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Anti-Thixotropic Analysis of Pipeline Metal Losses in Welded Locations due to Particulate Wear

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Abstract

This paper examines the causes of metal loss induced by cutting wear within the internal walls of pipelines which could lead to unpredicted and unexpected pipeline failure and the attendant oil spillage in Nigeria. To determine the rate of wear, the flow properties were determined. Flow was found to be turbulent containing sand particles with an average size of 3.8.µm. These particles in their agglomerated form possess a drag coefficient of $8.75x10^{-5}$ when they interact with the internal walls of the pipe, moving with a mass flow rate of 47.06 kg/m.s. Eventually the calculated erosion wear rate was $4.94x10^{-4}$mm/g. This wear rate suggests an immediate replacement of the pipe before a catastrophic occurrence. This investigation was verified by measuring the metal losses using the Ultrasonic Thickness Measurement Gauge. The Ultrasonic Thickness Measurement Gauge was used to measure pipe wall thicknesses at the wellhead 0.05m and 0.10m spool piece at 3, 6, 9, and 12 O'clock positions. The nominal thicknesses of the pipes are 5.5mm and 6.0mm, however, the variance between the measured thickness values and the nominal thickness value was very high. The pipe wear was found to be caused by the presence of large slurry of aggregates of sand stones in the pipelines. Particle size distribution analysis was done and the effective size of the sandstone was found to be 3.8µm. This investigation showed that the sand trap built insitu to sieve the sand and stones from the oil reservoir had failed.

Keywords: erosion wear rate, metal losses, sand particles, pipeline, UTM

1.0 Introduction

Pipeline wear is a major problem in the oil industry. Many researchers have investigated the cause of wear and have linked it to the interaction between large angular, semi rounded and rounded solid particles and the internal surface of the pipe during turbulent flow process [1-3]. Cutting wear often results in pipeline failure and usually takes a long period of time to occur [4]. The time dependent increase in shear stress, even when the shear rate becomes constant makes this investigation anti-thixotropic.

Pipelines in the oil and gas industry especially the ones connected to the separator are used to transport a complex multiphase mixture of gas, liquid and particulates (sand and proppant). The pipeline studied in Nigeria was examined and found to have been affected by erosion wear. Erosion often causes localized grooves, pits or other distinctive patterns in locations that experience persistent elevated slurry velocity.

Barton [5] was of the opinion that the extent of wear depends on the weight of the particle, the amount of drag imparted on the particles by the fluid as they pass through the elbows and pipes, the hardness of the particles, the elbow material, and the fluid velocity. Light particles require less drag to change direction of movement; therefore they tend to follow the flow. However, larger heavier particles possess a relatively higher momentum, and will barely be deflected by the fluid flow. Large particles would therefore tend to travel in straight lines, thus bouncing off the elbow walls as they go.

Venkatesh [6] wrote that component parts that are susceptible to erosion damage are the ones placed where the flow direction changes suddenly; high flow velocities are caused by high volumetric flow rate and other flow restrictions.

Crude oil wells produce a considerable amount of sand and proppants along with the crude, the volume of these unwanted impurities tends to increase as the well ages. Sand Traps and filters are usually installed by Oil and Gas Companies, to sift out and thereby reduce the amount of sand entrants transported to the Separator. However, although

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these Sand Traps may prove effective for large particles sizes of between 50 to 500 microns, minimizing their entrance into the pipeline, they are generally not designed to sift out the more minute particle sizes of less than 10 microns, and these smaller particles easily pass through the Sand Traps. Some of these particles thereafter agglomerate into large paste-like build ups in areas where flow is slow. A paste is a substance that behaves as a solid until a sufficiently large load or stress is applied, at which point it flows like a fluid. Thus once undisturbed this build up, over time, reduces the internal volume of the pipeline leading to more flow restrictions with the attendant increase in momentum. Inconsistent flow rate in the pipes is responsible for the increase of erosion wear at certain locations in the pipe, than at other locations, considering the fact that sand has a particle density of $2600kgm^{-3}$. Any increase in momentum is far more acute at elbows and T-joints, and eroding welded joints, and compromising the internal walls

Salama and Venkatesh [7] wrote that if a well produces less than 2.1×10^{-5} to 5.2×10^{-5} kgs^{-1} daily, it is often regarded as being sand free. Barton [5] said that the primary factor controlling wear in ductile materials is the material's hardness. In the Oil and Gas industry, heat treated, ductile steel is often the material of choice for pipeline design. Barton [5] also wrote that particulate erosion in ductile materials erosion is primarily caused by a process known as micro machining. In this process, he observed that particles impacting at an angle to the surface scoop away material. On the issue of whether the variation in steel hardness can affect erosion resistance, Haugen et al [8] suggested that the difference between different grades of steel is negligible for impact velocities of less than $100ms^{-1}$.

Experimental and computational methods have been applied to investigate the extent of wear [6, 9] in a pipeline. In this study, a physical test is taken insitu with the ultrasonic thickness measurement gauge as a confirmation test, to measure the thickness of the pipe at different locations and compare same with the nominal pipe thickness value. Particle size distribution analysis would be carried out and the effect of the particle impact on the walls of the pipe would be explained. This investigation is aimed at evaluating the performance characteristics of the gauge.

2.0 Description of the Ultrasonic Thickness Measurement Gauge

Ultrasonic thickness gauges are used to make precise dimensional measurements on a wide variety of coatings and materials. Ultrasonic thickness gauges operate in a manner similar to radar or sonar to measure the thickness of material from one side. An ultrasonic transducer introduces a short burst of sonic energy into a test piece. It has electronic sensors designed to receive the return echo from the back surface of the test piece or any irregularity or discontinuity within the test piece. The characteristics of ultrasonic waves are such that they propagate through a homogeneous media at a given velocity until they strike an acoustic boundary, commonly called an interface, where they reflect and propagate the waves in a reverse direction and at the same speed. This is generally accomplished by converting an electric pulse applied to a piezoelectric transducer into ultrasonic waves and then the returning ultrasonic waves are then converted to an electrical impulse by the transducer which then displays on a display screen.

3.0 Methodology

To determine the wear rate of the 1.5D elbow and pipeline investigated, the flow properties that induce wear, the sand particle size that tend to be responsible for wear, and a confirmation test of the extent of wear by measuring the metal losses were determined as follows:

3.1 Flow Properties

Reynolds number (dimensionless) is defined as

$$\mathrm{Re}_d = \frac{\rho_f D_p V_s}{\mu_f} \qquad (1)$$

where ρ_f is the density of fluid, kgm^{-3} , D_p is the particle diameter in m, V_s is the particle settling velocity, ms^{-1} and μ_f is the fluid viscosity in Pas^{-1}

In the Stoke region of settling for a spherical rigid particle, the coefficient of drag, C_D can be related to the Reynolds number, Re_d as

$$C_D = \frac{24}{\mathrm{Re}_d} \qquad (2)$$

The particle settling velocity, V_s is expressed as

$$V_s = \frac{\omega^2 r\left(\rho_s - \rho_f\right) D_p^2}{18\mu_f} \qquad (3)$$

Where ω is the angular velocity of the centrifuge, rads^{-1}, r is the radial position of the centrifuge, m, ρ_s is the density of the solid particles, ρ_f is the density of the fluid, D_p is the spherical diameter of the settling particle, m and μ_f is the fluid viscosity in Pas^{-1}. Viscosity is a measure of the ability of a fluid to resist flow by means of internal friction [10].

The mass flow rate, $\dot{m}$ is determined through

$$\dot{m} = \left(\rho_s - \rho_f\right) U_m A \tag{4}$$

U_m is the mean velocity, ms^{-1}, A is the cross sectional area of the pipe
Shear stress between fluid layers, τ is expressed as

For Re_d ⍰ 10^7 [11]

$$\tau = 0.0296 \left(\frac{\mu_f}{U_m x}\right)^{\frac{1}{5}} \rho_s U_m^2 \tag{5}$$

Shear rate, $\dot{\gamma}$ is defined as

$$\dot{\gamma} = \frac{8U_m}{d_i} \tag{6}$$

where U_m is the mean velocity of the fluid, in m/s and d_i is the inner diameter of the pipe in m.
The boundary fluid-particle layer thickness, δ is defined by applying Eq (7) [11].

$$\frac{\delta}{x} = 0.381\,\mathrm{Re}_d^{-\frac{1}{5}} - 10,256\,\mathrm{Re}_d^{-1} \tag{7}$$

Table 1 shows the parameters used for the computation of the flow properties

Table 1: Parameters Used for the Computation of the Flow Properties

Angular velocity of the centrifuge, ω	$= 8.0\ rad/s$
Radial position of the centrifuge, r	$= 3.0\ cm$
Density of the solid particle, ρ_s	$= 2650\ kg/m^3$
Density of the fluid, ρ_f	$= 898\ kg/m^3$
Particle diameter, D_p	$= 3.8\ \mu m$
Fluid viscosity, μ_f	$= 1.12\ x\ 10^{-5}\ Pa/s$
Elbow diameter, d_i	$= 60\ mm$
Elbow r / D	$= 1.5$

3.2 Ultrasonic Thickness Measurements (UTM)

A DM2E type ultrasonic thickness measurement instrument was used to determine the pipe wall thickness of both the wellhead spool piece and the flowline. The measurements were taken at:

i. The wellhead 0.05m spool piece, measurements were taken 1.5cm upstream and downstream of every weldment on the spool piece
ii. The 0.10m flowline measurements were taken at points on the flowline about 30m – 40m from the wellhead.
iii. Reports of the above measurements at 3, 6, 9 and 12 0'clock positions were made.
iv. Final presentation of measurement data were presented on:
   - the percent nominal thickness, and
   - the percent loss of both the wellhead spool piece and the flowline.

3.3 Well Test Sand Production

The sand which flows from the reservoir to the transportation pipeline is collected by the sand trap. An adequate quantity of sand is used to carryout the particle size distribution analysis. Equation (8) and (9) were used to determine particle uniformity coefficient and concavity coefficient.

$$\text{Uniformity coefficient} = \frac{D_{60}}{D_{10}} \tag{8}$$

Concavity coefficient = $\dfrac{(D_{30})^2}{D_{60} \cdot D_{10}}$ (9)

D_{10}, D_{30} and D_{60} are sand particle sizes. These represent 10%, 30% and 60% of the sand particle sizes respectively that are finer, as represented by the sand particle size distribution curve in Fig 1.

3.4 Erosion Wear Rate

The Erosion wear rate, E [5] is defined as

$$E = F_m F_s m_p V_p^n F(\alpha) \quad (10)$$

where $F(\alpha)$ is a material dependent function of the impact angle between 0 and 1. For $\alpha = 45^o$, $F(\alpha) = 0.97$ [12]

V_p is the particle impact velocity, ms^{-1}, m_p is the mass flow rate of particles impacting in an area kgs, n is a material dependent index = -1.75, Typical values of F_m of a number of steels ranging from 0.833 to 1.267 [13]. F_s is a coefficient that accounts for sand sharpness:
For Sharp sand grain, $F_s = 1$; Semi-rounded grain, $F_s = 0.53$; Rounded grain, $F_s = 0.2$

4.0 Discussion of Results

From the findings, having determined the flow properties, a dimensionless Reynolds number of 2.74 x 10^5 was determined; this value indicates that the flow is turbulent, moving with a mean velocity of 9.5 m/s. The force, with which the fluid flow drags the sand particles along the internal walls in the pipeline, leading to cutting wear, has a coefficient of 8.75 x 10^{-5}. Cutting wear was found to be more apparent where the fluid is most agitated; being elbow and welded joints, therefore those regions tended suffer a higher erosion rate. The particle size of 3.8 μm was determined with the aid of a mechanical sieve analysis method. The agglomerated particles are a mixture of fluid and sand particles churned up together. These agglomerated particles were calculated to have a mass flow rate of 47.06 kg/m.s. The thickness of each layer (fluid/sand particle) relative to the other was calculated to be 0.023μm, applying the equation provided by Holman [11]. The erosion wear rate of the eroded pipe was calculated to be 4.94 x 10^{-4} mm/g. This value indicates that the erosion wear has not yet reached the catastrophic state, but suggests immediate replacement of the eroded sections of the pipe.

To confirm the findings of this investigation, the ultrasonic thickness gauge was used to determine the metal losses both at the elbow and welded joints of the internal walls of the pipeline, being a non destructive testing method. Ultrasonic Measurements (UTM) readings at the 0.05m wellhead spool piece of nominal thickness of 5.5 mm, is presented in Table 2.

Table 2: Ultrasonic Thickness measurements at the 0.05m well head spool piece.

Locations	Thickness values at 0'Clock positions			
	3	6	9	12
A	5.3	5.2	5.4	5.4
B	5.4	5.0	5.4	5.5
C	5.1	5.4	5.4	5.5
D	4.5	5.3	4.9	5.5
E	4.7	5.4	5.3	5.0
F	5.3	5.1	5.4	5.4
G	5.5	5.5	5.5	5.2
H	4.2	4.7	4.7	4.9
I	5.3	5.2	5.4	5.5
J	5.4	4.9	5.4	5.5
K	5.9	5.1	5.4	4.9
X	5.5	5.0	5.4	5.4
Y	4.7	5.5	5.3	5.4
Z	5.5	5.1	5.5	5.4

Where locations A – Z are positions on the downstream wellhead where measurements were taken.
Table 3 tabulates the summary of the readings and calculations of Table 2.

Table 3: The Percent Nominal Thickness, and Percent loss calculation, of measured positions on the wellhead.

Location	Minimum Residual Thickness	Percent Nominal thickness	Percent loss
A	5.2	94.55	5.45
B	5.0	90.91	9.09
C	5.1	92.73	7.27
D	4.5	81.82	18.18
E	4.7	85.82	14.55
F	5.1	92.73	7.27
G	5.2	94.55	5.45
H	4.2	76.36	23.64
I	5.2	94.55	5.45
J	49	89.09	10.91
K	4.9	89.09	10.91
X	5.0	90.91	9.09
Y	4.7	85.45	14.55
Z	5.1	92.73	7.27

The ultrasonic measurement readings at the 0.10m flowline taken at different points at about 30 – 40m from the wellhead of 6.0mm nominal thickness is presented in Tables 4

Table 4: Ultrasonic measurement Readings at 0.10m flowline.

Locations	Thickness values at 0'clock positions			
	3	6	9	12
1	5.9	5.8	5.9	5.9
2	5.4	5.9	5.3	5.9
3	5.5	5.5	5.8	5.9
4	5.8	5.2	5.3	5.4
5	5.8	5.9	5.8	5.7
6	5.8	5.2	5.4	5.8
7	5.4	5.4	5.3	5.1
8	5.5	5.2	5.5	5.9
9	5.2	5.2	5.4	5.8
10	5.1	5.3	5.3	5.0

Where Locations 1 – 10 are positions on the flowline where measurements were taken.

Table 5 presents the summary of the readings and calculations in Table 4

Table 5: The Percent Nominal thickness, and percent loss calculation, of measured positions on the flowline.

Location	Minimum Residual thickness	Percent nominal thickness	Percent loss
1	5.8	96.67	3.33
2	5.3	88.33	33.67
3	5.5	91.67	8.33
4	5.2	86.67	13.33
5	5.7	95.00	5.00
6	5.2	86.67	13.33
7	5.1	85.00	15.00
8	5.2	86.67	13.33
9	5.2	86.67	13.33
10	5.0	83.33	16.67

From the ultrasonic thickness measurement analysis, the percent losses of metal from the carbon steel pipes indicate that the wear was severe and that the sand particle impact on the pipe walls is high. Fig.1 shows the sand particle size distribution curve obtained from the production sand tests conducted. The interaction of these sand particles with the internal walls of the pipes is responsible for the wear resulting to metal loss. The average size of these particles is found in Fig 1. The size of the particles would help to find the solution to eliminate metal loss as a result of wear in the pipeline. Thus a method for a more effective isolation of sand particles of these sizes becomes very imperative.

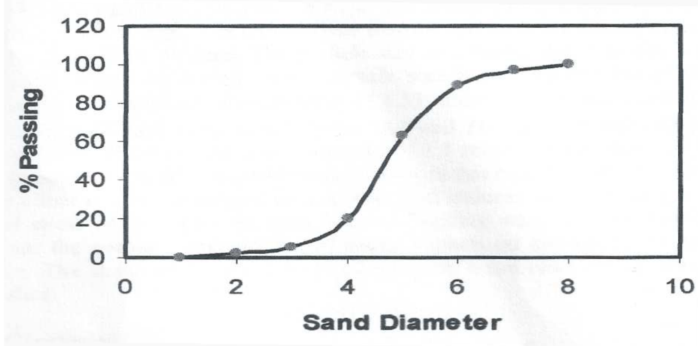

Fig. 1.sand particle size distribution curve.

The particle size distribution analysis was carried out on the sand removed from the pipeline. The particle size distribution curve in Fig 1 was very steep. This shows that the average sand particle size is uniform and has an effective size of $3.8\,\mu m$ and coefficient of uniformity of 1.53, these explain that since the value of the coefficient of uniformity is not large, it means that D_{60} and D_{10} sand particle sizes do not differ appreciably. The coefficient of concavity of 1.1 measures the shape of the distribution curve between D_{60} and D_{10} sand particle sizes; in this case, the value of the coefficient shows that the particles are round in shape.

5.0 Conclusion

The effect of particle impact on the internal walls of the pipeline causes strain on the pipe material and the effect exposes it to cutting wear. It has also been shown that the greater the percent concentration of sand impact on the internal walls, the greater the shear stress and the corresponding shear rate, as established from the ultrasonic thickness test results. From the investigation, it was found that erosion wear has eroded the pipe studied and this was verified using the ultrasonic thickness measurement gauge which is a non destructive testing method. The result from the tests showed that several locations in the internal walls of the pipeline, particularly the welded joints and elbows have suffered wear. It was recommended that the compromised pipe sections be replaced as at the earliest opportunity to prevent pipeline failure and possible catastrophic oil spill. This failure of the pipeline if not controlled would lead to great losses to the company, in terms of litigation by host communities, idle time due to flowline shutdown, maintenance time, and other sundry issues. The results are encouraging, the method of investigation is simple and the time used for the thickness measurement is short.

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