Computational Analysis of Erosion Wear Rate in a Pipeline Using the Drift Flux Models based on Eulerian Continuum Equations

Joseph I. Achebo, *Member,IAENG*

***Abstract*—This paper clearly explains the use of drift flux models based on Eulerian continuum equations in predicting erosion wear rate in a transmission pipeline. In this case, a pipeline with a diameter of 0.5m was investigated. It was found that there was a large sand particle concentration on the welded parts of the pipe which has affected the internal geometry of the pipe. From physical examination, the reduction in the nominal thickness of the pipe was related to erosion wear. Wallace et al (2000) erosion wear prediction equation was applied to determine the rate of erosion wear (E) which was found to be 9.9×10^{-4} mg/g at a fluid velocity of 9.45m/s. The high erosion wear value could be attributed to the state of the pipe material and the brittle and hard nature of the sand particles.**

***Index Terms*— Erosion wear, fluid velocity, particle velocity, drift flux model, pipeline**

I. INTRODUCTION

Erosion can be defined as the wear that occurs when solid particles entrained in a fluid stream strike a surface [1]. The erosion of a solid surface due to particle impacts can be due to deformation wear and cutting wear [2], [3]. Deformation wear occurs when repeated particle impacts at high impact angles plastically deform the surface layers of the material, eventually causing material loss through surface fragmentation. Cutting wear occurs due to particle impact at small angles, with a scratch or cut being formed on the surface if the shear strength of the material is exceeded. [4]

This research work investigates a two-phase, particle-liquid turbulent flow interaction system. The fluid velocity and the particle velocity were determined and used in the prediction of the erosion wear rate of the internal surface of the pipeline, using the equations developed by Wallace et al [5].

Bahr et al [1] observed that a number of erosion models have been developed for erosion prediction by other researchers [6]- [8]. Some researchers have used computational methods to predict erosion [5], [9]. In this study drift flux or algebraic slip models were used to predict erosion wear rate in the fluid pipeline. These models involve the solution of Eulerian continuum equations for a single fluid phase which exhibits a variable density based upon the local particle volume fraction summed across all particle sizes. The particles are assumed to be continuously slipping with respect to the conveying fluid at constant velocity due to gravitational and/or centrifugal forces and the distribution of particles is obtained through the solution of a single scalar transport equation for the volume fraction of each particle size considered [4].

J.I.Achebo is a lecturer with the Department of Production Engineering , University of Benin, Nigeria.(email: josephachebo@yahoo.co.uk)

II. THE CONTINUOUS FLOW MODEL

To study the flow behaviour in a continuous flow pattern, the conservation equations for mass and momentum in combination with transport equations for turbulence model are applied.

The governing equations for axisymmetric turbulent flow were expressed as follows [1], [10]

$$\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0 \tag{1}$$

Where u_j is the average velocity component and ρ is the fluid density.

$$\frac{\partial}{\partial x_j}\left(pu_iu_j\right)=\frac{-\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{dx_j}\right)-\frac{\partial}{dx_j}\left(\rho u_iu_j\right) \tag{2}$$

Where P is the static pressure and the stress tensor

$$-\rho u_iu_j=\left[\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_j}\right)\right]-\frac{2}{3}\rho k\delta_{ij} \tag{3}$$

Where δ_{ij} is the Kronecker delta and $\mu_{eff}=u_t+\mu$ is the effective viscosity. The turbulent viscosity, μ_t, is obtained using the high-Reynolds number form as

$$\mu_t=\rho C_p\frac{K^2}{\varepsilon} \tag{4}$$

And $\mu=\upsilon\rho$ (5)

Where υ is the Kinematic viscosity

$$\upsilon = \frac{u_m d}{\mathrm{Re}_x} \quad \left(\mathrm{Re}\, x = \frac{u_m d}{\upsilon} > 2300 \text{ for turbulent flow} \right) \tag{6}$$

With $C_p = 0.0845$ [11], k and ε are the kinetic energy of turbulence and its dissipation rate. The kinetic energy of turbulence, k = $0.01U^2$ while the dissipation rate of turbulent kinetic energy could be obtained using (4) with μ_t expressed in terms of a length scale L, where L was taken to be equal to the inlet pipe diameter. Kinetic energy of turbulence and its dissipation rate are determined from the equations of the law of the wall.

$$\dot{m} = \rho U_m A \tag{7}$$

Where $\dot{m}$ is the mass rate of flow, U_m is the mean velocity, A is the cross sectional area of the pipe and d is the diameter of the pipe.

The mass velocity, $G = \frac{\dot{m}}{A} = \rho U_m$ (8)

Where ρ = water density at 4.44°C = 999.8 Kg/m^3

III. PARTICLE EQUATION OF MOTION

In deriving this equation, two assumptions are adopted.

1. the solid particles do not interact with each other, and
2. the influence of particle motion on the fluid flow field is very small and can be neglected.

This assumptions were also adopted by Edwards et al [12] and Wallace et al. [5].

The governing particle equation of motion is given as

$$\frac{du_p}{dt} = F_D\left(u - u_p\right) + \frac{g\left(\rho_p - \rho\right)}{\rho_p} + \sum F_x + \Delta p + F_d \tag{9}$$

Where $F_D\left(u - u_p\right)$, is the drag force per unit particle mass, and

$$F_D = \frac{3C_D \mu \mathrm{Re}_p}{4\rho_p d_p^2} \tag{10}$$

$$\mathrm{Re}_p = \frac{r_f \rho_f d_p \left(u_p - u\right)}{\mu} \tag{11}$$

Re_p is the particle Reynolds number. U can be obtained from Eq. (2)

$$C_D = \frac{24}{\mathrm{Re}_p}\left(1 + 0.15\,\mathrm{Re}_p^{0.687}\right)\left(0 < \mathrm{Re}_p \le 1000\right) \tag{12}$$

Where C_D is the drag coefficient and r_f is a volume fraction of the fluid [4]

$\frac{g(\rho_p - \rho)}{\rho_p}$ is the particle buoyancy force term

F_d is the Saffman lift force [13]

$$\sum F_x = \frac{d\left(mU\right)x}{d\tau} \tag{13}$$

Where $\sum F_x$ is the increase in momentum flux in the fluid around the particles and τ, is the shear force due to flow

$$\Delta p = f \frac{L}{d} \rho \frac{u_m^2}{2g} \tag{14}$$

Where Δp is, the pressure gradient encountered, f is the frictional force and g is the acceleration due to gravity.

IV. THE EROSION PREDICTION EQUATION

In this study, the erosion rate, E, in mg/g developed by Wallace et al [5] is used.

$$E = \left\{ \frac{\frac{1}{2}u_p^2 \cos^2\alpha \sin 2\alpha}{\Upsilon} + \frac{\frac{1}{2}u_p^2 \sin^2\alpha}{\sigma} \right\} \text{ for } \alpha \le 45^\circ \tag{15}$$

and

$$E = \left\{ \frac{\frac{1}{2}u_p^2 \cos^2\alpha}{\Upsilon} + \frac{\frac{1}{2}u_p^2 \sin^2\alpha}{\sigma} \right\} \text{ for } \alpha > 45^\circ \tag{16}$$

Where Υ and σ are the cutting wear and deformation wear coefficients having the values 33316.9 and 77419.7 respectively. U_p can be obtained from n (9) and α could be determined insitu. From the study made by Bitter [3] peak erosion rates have been measured to occur at impact angles of 25 – 30°, indicating that cutting wear dominates.

V. DISCUSSION OF RESULTS

The drift flux models were used to predict the rate of erosion wear in a water transportation pipeline. The diameter of the pipe was 0.5m and its length that was investigated was 30m. The solid particles that settled in the pipeline are spherical shaped pa2rticles between the diameters of 75 μm and 150 μm. They were transported in the pipe conveying water in a mass flow rate of 4724kg/m.s. The fluid flow velocity was measured to be 9.45m/s . The drag force per unit particle mass was 0.6 kg/m^2 with a corresponding drag coefficient of 0.3. The measured average impact angle of 27^o was used for this study. Applying the Wallace et al [5] erosion rate, E, equation for $\alpha \leq 45^{\circ}$, E was found to be 9.9 x 10^{-4} mg/g. The high value of E, shows that the particle size was large and the particle was hard and brittle. It also confirms that the carbon steel pipe would have been plastically strained by the effect of the repeated impact of the sand particles on it. However, the effect of gravity on particle motion was negligible at high fluid velocity of 9.45 m/s

VI. CONCLUSION

The drift flux model has been successfully applied to predict the erosion wear rate of pipelines. The continuous flow model was developed to determine the flow velocity, which aided the computation of the particle velocity in the development of particle equation of motion which eventually leads to the prediction of the erosion wear rate. This research study shows that the water pipeline under study was greatly affected by wear which lead to early leakages at various locations on the pipeline. Proper measures have been taken to eliminate the entrance of sand particles. This process can be applied to predict the level of wear in other fluid transportation pipelines containing some concentration of hard particles, where wear has been suspected to occur.

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