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Effect of the gas–solid two-phase flow velocity on elbow erosion

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ABSTRACT

Because of the rapid development of oil and gas pipelines and the increasing number of pipeline accidents, pipeline safety has garnered more attention around the world. Erosion on the inner diameter of pipes is one of the main factors in pipeline failure. Since experimental methods for wall thickness inspection of pipelines are expensive, an accurate model for predicting erosion rate of pipelines under working conditions is needed. A new erosion prediction model is proposed in this research which combines the theoretical and Lagrange discrete phase models for erosion. The model considers effects of gas–solid multiphase velocity and gas pressure. It is applied to elbows under the working conditions of a gas station of the Daqing Oil and Gas Company in China. The results are considerably closer to measured erosion of elbows than the results calculated using existing models. The comparison between erosion under high and low gas pressures shows that the effect of gas-phase velocity on erosion rate is more significant in elbows under high-pressure conditions.

Particles can be found in gas pipelines because debris particles can fall off from pipeline walls during transport (Tsochatzidis and Maroulis, 2007). Erosion occurs on pipelines because of these particles and may even lead to pipeline accidents. Studies show that erosion on high-pressure pipelines mainly occurs on elbows, and the mass loss due to erosion on elbows is 50 times larger than that on straight pipelines (Li and Dong, 1987). Several theoretical models and erosion mechanisms have been proposed in recent years (Ilmar and Priit, 2008; Huang et al., 2010). A simple equation for calculation of erosion on elbows was given in the criterion of the American Petroleum Institute (API-14E), which considered the particle velocities and quantities (API Recommended Practice 14E, 2007). By considering the material density, Tilly (Tilly, 1979) proposed a method for calculating erosion rate. Another modified equation for calculating erosion that considers the particle size and mixture density was put forward by Salama (Salama,1998). Paris et al.(Paris et al., 2014) introduced research on the solid particle erosion of pipelines. Shirazi et al.(Shirazi et al., 1995) proposed a stagnation region to be included in the calculation of erosion, Zhang et al. (Zhang et al., 2007) took the flow field into consideration when computing particle erosion in water and air flow, and Chen et al.(Chen et al., 2006) proposed a method to estimate erosion in multiphase flow based on mechanistic analysis and numerical simulation. Since the influence on particles in gas pipelines by gas-phase velocities cannot be ignored when analyzing erosion in high-pressure pipelines, gas density under high pressure is much higher than that under standard pressure, an erosion model of pipelines under working conditions that considers the effect of the gas phase is needed for predicting pipeline life.

Based on a theoretical model and different particle erosion behavior under high and low gas pressure, a new method to predict solid particle erosion on pipelines is proposed in this paper. In this method, effects of gas pressure, gas velocity and solid velocity on erosion are taken into consideration. Results of the proposed model were compared with the API-14E model, the modified model proposed by Salama and inspection report data under field conditions. Furthermore, the erosion effects on pipelines under high and low pressure with different velocities of gas–solid two phases were analyzed, and the relationship between the velocities of the inlet and erosion rates is summarized to obtain a prediction model which closely matched field data.

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1. Theoretical model

1.1. Erosion model

The erosion rates of the walls caused by particles can be calculated as follows (Edwards et al., 2000):

$$R_{erosion} = \sum_{p=1}^{N_{particles}} \frac{m_p c(d_p) f(\alpha) v^{b(u)}}{A_{face}} \quad (1)$$

where $R_{erosion}$ is the erosion rate, m_p is the mass flow rate, $C(d_p)$ is a function of particle diameter, $f(\alpha)$ is a function of impact angle α, $v^{b(v)}$ is a function of relative velocity, and A_{face} is the area of the cell face on the wall. Parameters of the model for spherical particles were determined by Lee (Lee and Tu, 2002), where $b(u)$ is 2.4.

1.2. Lagrange discrete model

The Euler-Lagrange method is typically adopted to study two-phase gas and solid flow (Darmana, 2006). Gas is considered as a continuous phase, solid particles are regarded as a dispersed phase, and particle tracks are described using the Lagrange coordinate (Fluent Inc, 2006). Solid particles of the dispersed phase are described using the Lagrange method, and the movement of these particles follows Newton's second law (Zhong et al., 2006) as follows:

$$\frac{du_p}{dt} = \frac{3uC_D \mathrm{Re}_p (u - u_p)}{4\rho_P d_P^2} + \frac{g(\rho_P - \rho)}{\rho_P} \quad (2)$$

where u_p and u are the solid particle velocities of the dispersed phase and gas of the continuous phase, respectively; C_D is the drag coefficient; Re_p is the relative Reynolds number; ρ_P and ρ are densities of the particle and gas phase respectively; d_p is the diameter of the particles; and g is the gravitational acceleration.

2. Prediction model of erosion

2.1. Two common methods for calculating erosion rate

One equation commonly used for calculating erosion on elbows was presented in API-14E (API Recommended Practice 14E, 2007) as follows:

$$R_{erosion} = 5.33MV^2 \Big/ D^2 \quad (3)$$

where M is the output rate of particles, V is the velocity of the flow, and D is the diameter of pipelines.

A second erosion equation modified the API-14E equation (Salama,1998). The particle sizes and mixture flow densities are considered in this modified model as follows:

$$R_{erosion} = \frac{1}{S_P} \frac{v^2 d}{D^2 \rho_m} \quad (4)$$

where d is the diameter of a pipeline, ρ_m is the density of mixture flow, and Sp is the geometric constant with a value of 2000 when the range of r is from 1.5 D to 5 D.

2.2. New prediction model for erosion rate

Only the particle velocity was considered when calculating the erosion rates in the erosion model (1) described above. In the commonly used calculation methods (3) and (4), the velocity of the mixture flow was assumed to be the velocity parameter. Thus, effects on erosion rates under different velocities of the gas and particle velocities could not be analyzed by this method. The gas–solid two phases influence each other when particles move in the gas pipeline. Because the gas density under the high pressure of working conditions is much higher than that under standard pressure, the influence of gas flow on particles is more significant in high-pressure pipelines. Therefore, if the influence of the gas-phase and solid-phase velocities on erosion is considered separately when calculating solid particle erosion rates of gas pipelines, the results calculated by the prediction model for erosion rates are expected to be closer to the actual working conditions.

For the present research, the $v^{b(u)}$ parameter in model (1) was separated into the gas and solid velocities. The influence of the gas-phase velocity on the particle-phase velocity was also considered. The gas phase is the main part of the gas–solid two phase flow, and the modified prediction model is shown as follows,

$$R_{erosion} = \sum_{p=1}^{N_{particles}} \frac{m_p c(d_p) f(\alpha) \left[v^{b(u)} + a\sqrt{\frac{P_g}{P}} (\Delta v)^{\frac{4}{3}} \right]}{A_{face}} \quad (5)$$

In addition, the influence of gas-phase velocity on particle-phase velocity $a\sqrt{\frac{P_g}{P}}(\Delta v)^{\frac{4}{3}}$ was added to the prediction model, where $\Delta v = u - u_p$ and a is a constant (a>0), P_g is the pressure of the gas pipeline, and P is the standard pressure. When the gas-phase velocity is higher than the solid-phase velocity ($\Delta v > 0$), the particle velocity is increased by the gas phase. When the gas-phase velocity is lower than that of the solid phase ($\Delta v < 0$), the particle velocity is decreased by the gas phase. When gas velocity is the same as the solid velocity ($\Delta v = 0$), no influence exists between the two phases and the modified model is the same as equation (1).

Operating pressure, temperature, and other parameters are usually used to describe gas pipelines under working conditions. Δv can be obtained by combining the resistance equation (6) and disperse phase equation (3) (Fan et al., 1998; Hou et al., 2001), along with the consideration of densities and other factors to give:

$$F_D = \frac{1}{2} \Delta v^2 \rho C_D A \quad (6)$$

where F_D is the gas resistance, and A is the cross sectional area of particles.

The gas velocity, densities (which can be affected by the operating pressure, temperature), pipeline sizes, and other factors are included in the model proposed above. Thus, the erosion rate of gas pipelines can be predicted using equation (5).

3. Application of the new calculation model

The new erosion prediction model was applied to gas pipelines under working conditions of the gathering station for the Daqing Oil and Gas Company in Daqing, China. Parameters of the pipelines are shown in Table 1(China Special Equipment Inspection and Research Institute, 2011).

Kaye and Boardman (Launder and Spalding, 1972) found that the free settling of particles is prevented when the particle percentage by volume φ is more than 5%. The influence between particles can be ignored when φ < 0.08, and the suspensoid can be regarded as the dilute phase. In the multiphase mixture suspension system, the proportion of particles in the unit volume of the mixture and the share of each phase in the mixture can be calculated by the following equation (Gidaspow, 1994):