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Flow erosion and flow induced vibration of gas well relief line with periodic fluctuation of boosting output

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ABSTRACT

Gas well relief line plays the key role in timely discharging high-pressure particle-laden gas flow to ensure safe test and exploitation. However, the boosting output is usually fluctuation, intensifying the flow erosion and flow induced vibration of relief line. In this work, numerical investigation was carried out to examine the effects of fluctuation amplitude and fluctuation period of discharge capacity on the flow erosion and flow induced vibration. Unsteady Reynolds- Averaged-Navier-Stokes (URANS) equations are employed to describe the hydrodynamic characteristics of continuous phase (compressible gas), and discrete phase model (DPM) is utilized to describe the kinematics and trajectory of discrete solid particles (sand particles). The erosion rate and flow induced displacement of relief line are obtained by an empirical erosion model and a fluid-structure interaction (FSI) model, respectively. The results indicate that the flow properties, flow erosion and flow induced vibration are sensitive to the fluctuation of boosting output. Large displacement and severe erosion present in relief line with large fluctuation amplitude or small fluctuation period of discharge capacity.

1. Introduction

High-pressure high-speed particle-laden gas flow should be discharged through relief line of gas well timely and safely in the well testing and exploitation process (Zhu et al., 2014a). Due to the space restraint of well site and the whole layout of large equipment, elbows are usually installed in the relief line to bypass devices and other obstacles. However, elbows introduce a change in flow direction and are known to be responsible for various problems such as high pressure loss, pipe vibration and pipe wear (Chu and Yu, 2008). Gas well usually has a large boosting output, which ranges from 0.2 million to 1.5 million m^3/d. In the relief line bearing such a large discharge, compressible gas flow expands continuously along the relief line and usually reaches the speed of sound in the outlet. This high speed gas flow brings about large swing of pipeline in the downstream of the last elbow, because it is not fixed in actual well site. Due to the instability in the well testing and exploitation process, the boosting output is usually fluctuation, which intensifies the flow induced vibration. The swing of relief line constitutes a huge threat to the field operations, even causing casualties.

Moreover, the great majority of gas wells have formation sand production. The formation sands are carried out by high-speed gas flow into the relief line. In elbows, particles' inertia causes they to deviate from the streamlines of the carrying gas, resulting in particle impingement on the pipe walls (Derrick and Michael, 2012; Jong et al., 2009). Severe erosion takes place on the elbow of relief line under the impingement action of high-speed particle-laden gas flow, causing a significant reduction of its life-span. Flow erosion is a complicated problem due to a number of parameters affecting the erosion severity. The fluctuation of boosting output further exacerbates the complexity. Once the relief line is failure because of erosion, not only the maintenance costs but also environmental burden will be increased. Particularly for high-sulfur gas wells, relief line failure may cause disastrous consequences. Therefore, comprehensive analysis of flow erosion and flow induced vibration of relief line bearing fluctuation discharge of high-pressure high-speed gas flow is urgently needed.

Flow induced vibration, as a representative fluid-structure interaction issue, has attracted many investigators to make efforts to better understand the pipe vibration induced by internal flow or external flow (Zhang et al., 2003; Rinaldi et al., 2010; Wang, 2010; Zhang et al., 2010; Alijani and Amabili, 2014). A great many researchers proposed that pipe vibration appears when internal flow rate is beyond a critical value. As summarized by Paidoussis and Li,

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(1993); Paidoussis (1998), the structural frequency of a clamped-clamped pipe decreases with the increasing of the internal flow rate, and the buckling instability occurs when the flow rate beyond a critical value. The weakly nonlinear equations of motion were employed by Modarres-Sadeghi and Paidoussis (2009) to study the nonlinear dynamics of extensible pipes conveying fluid. Numerical studies have been conducted by Jin (1997), Wang and Ni (2006) and Wang (2009) to examine the stability and complicated dynamics of a restrained pipe conveying fluid. In studies of Xu and Yang (2006a, 2006b), the mechanism of flow-induced internal resonances in pipe has been attempted to analyze, and the minimum critical velocity has been found out. However, straight pipes are the main objects in these investigations, and the two ends of the pipes are either fixed or articulated. Few literature have discussed the flow induced vibration of a pipe located downstream of an elbow, not to mention the outlet end of the pipe being freedom. Particularity of high-pressure high-speed particle-laden gas flow in pipe further increase the complexity of this problem.

Both physical and numerical modelling of flow erosion of pipe bends, elbows, tees and related geometries have been performed by many researchers (Suzuki et al., 2008; Li et al., 2010; Stack and Abdelrahman, 2011; Tan et al., 2012; Zhang et al., 2012; Zhu et al., 2015a). Carrying fluid properties, particle content and particle size have been recognized as the key factors affecting flow erosion (Tang et al., 2009; Ferng and Lin, 2010). Deng et al. (2005) and Mazumder et al. (2008a, 2008b) have carried out experimental studies to identify the location and magnitude of erosion in elbows. Zeng et al. (2014) have experimentally investigated the erosion-corrosion behavior of X65 pipeline elbow by array electrodes technique, and computational fluid dynamics (CFD) simulation were also conducted to cover shortages of experiment. Several empirical models have been proposed based on experiments for gas flow contained solid particles (Oka and Yoshida, 2005; Zhang et al., 2007). However, most of these researches focus on incompressible fluid flow in atmospheric pressure or low pressure environment, such as pneumatic conveying and slurry transportation. The high-pressure gas flow is compressible in relief line, whose density and velocity are changing along the pipe and the velocity may even reach the sonic speed. It highlights the complexity of flow erosion.

Until now, few literature have taken flow erosion and flow induced vibration into account together. In our previous research, a mutual influence between erosion and vibration has been found (Zhu et al., 2014b, 2014c, 2014d, 2015b). Therefore, coupling analysis of fluid-structure interaction (FSI) vibration and flow erosion is important for compressible gas-solid two-phase flow in relief line. Due to the complex circumstance of high-pressure gas well relief line, it is a great challenge to conduct experimental study on flow erosion and flow induced vibration of relief line. CFD model has demonstrated performance in simulating multi-phase flows (Sun et al., 2004; Fan et al., 2004; Zhu et al., 2012a; 2012b, 2013). A large number of studies about flow erosion or flow induced vibration have been reported by using CFD (Jin, 1997; Oka and Yoshida, 2005; Wang and Ni, 2006; Zhang et al., 2007; Wang, 2009; Tang et al., 2009; Ferng and Lin, 2010; Zeng et al., 2014; Zhu et al., 2015a, 2015b). Zhu et al. (2015b) have numerically studied the effects of inlet flow rate, pipe diameter and discrete phase content on the location and magnitude of flow erosion and flow induced swing of relief line. However, the boosting output is stable in the study.

Therefore, in this work, unsteady CFD model coupling with discrete phase model (DPM) and FSI numerical methods is employed to investigate the flow erosion and flow induced vibration of relief line bearing fluctuation discharge of high-pressure high-speed gas-solid two-phase flow. The effects of fluctuation amplitude and fluctuation period of discharge capacity on the flow erosion and flow induced vibration are discussed in detail.

2. Problem description

A three-dimensional horizontal elbow pipe is selected as the computational domain, which contains three sections: front straight pipe, elbow and rear straight pipe, as shown in Fig. 1. The lengths of front straight pipe (L_f) and rear straight pipe (L_r) are 5 m and 20 m, respectively, and the two straight pipes are connected by a 90° elbow with ratio of curvature and diameter of 1.25. The outer diameter (d_o) of the pipe is 73 mm with wall thickness (δ) of 4 mm.

The inlet flow rate fluctuates periodically with the average value of 800000 m^3/d. The fluctuation amplitude and period are set as variables ranging from 50000 m^3/d to 250000 m^3/d and from 2 s to 10 s, respectively. The discrete phase content is fixed at 5% (weight percent) of the average discharge capacity. Table 1 lists the detailed parameters for all simulation cases. In the table, the inlet volume flow rates are the values under standard state (101325Pa and 293.15 K), which are obtained by well field record of discharge capacity. The inlet mass flow rate is defined as:

$$Q_m = \frac{\rho_0 Q}{24 \times 3600} \quad (1)$$

where Q is volume flow rate, Q_m is mass flow rate, ρ_0 is the density of gas under standard state. As a basis for comparison group, case 1 is a stable case without fluctuation.

The physical and mechanical properties of fluid and pipe are listed in Table 2. In order to facilitate calculation and comparison, sand particles are seemed as spherical particles with uniform diameter, and only the pressure gradient force and drag force are considered for the phase interaction.

3. Model formulation

3.1. Governing equations

Eulerian-Lagrangian approach is employed to capture flow properties of gas flow and particle tracking of sand particles. Unsteady Reynolds-Averaged-Navier-Stokes (URANS) equations are employed to describe the hydrodynamic characteristics of continuous phase (compressible gas), while discrete phase model (DPM) is utilized to describe the kinematics and trajectory of discrete solid particles (sand particles).

URANS model is well established and can be found in many CFD literature (He and Li, 2005; He et al., 2005; Khurram and Arif, 2006; Arif and Ramon, 2009; Zhu et al., 2015a). Therefore, it is not described in this paper to avoid repetition. The turbulence of gas-solid flow is simulated by the realizable k-ε turbulence model. The detail of this model including the kinetic energy (k) and its energy dissipation rate (ε) transport equations can be found in Kimura and Hosoda (2003), Rohdin and Moshfegh (2007) and Zhu et al. (2015b).

DPM model is treated in a Lagrangian framework with particle motion equation expressed as (Sun et al., 2004; Farnoosh et al., 2010; Zhu et al., 2012b):

$$\frac{dv_p}{dt} = \frac{C_D \mathrm{Re}_p}{24\tau_t}\left(v - v_p\right) + \frac{g\left(\rho_p - \rho\right)}{\rho_p} + 0.5\frac{\rho}{\rho_p}\frac{d\left(v - v_p\right)}{dt} \quad (2)$$

in which,