Effect of flow field on particle erosion in eroded square elbows

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Abstract. Erosion often occurs on the inner wall of gathering pipelines. Even if the particle size is small, the cumulative erosion may also cause serious erosion on pipelines and even leads to leakages. In order to learn erosion on elbows of pipelines in natural gas stations, mechanisms analysis and computational fluid dynamics (CFD) method were used to investigate erosion on square elbows based on a case of elbows erosion in a gas gathering station. The results show that there are erosion sensitive areas on the eroded surface of elbows which are more likely to be eroded, erosion prediction of elbows could be obtained through CFD method. It is concluded that researches on erosion are important in oil and gas gathering industry and could be a good guiding for life prediction, inspection and operational safety protection of gathering pipelines.

1. Introduction
Solid particles often cause erosion on pipelines and equipment accessories in oil and gas industry and may even lead to the failure of them. According to the researches, micro particles can still cause accumulating erosion on the internal wall of pipes and equipment during a long-term operation. A large number of particles with large size are often carried in gathering pipelines before filtered, which easily cause more serious erosion on pipelines. In addition, the corrosion products of the upstream pipe wall will fall off and may also cause erosion on the steel and PE (poly ethylene) pipe walls [1, 2] in natural gas industry and coal chemical industry [3, 4]. Safety problems caused by the failure of the pipelines and equipment are often occur [5].

2. Introduction of a case background
Erosion becomes more serious on the inner wall of pipelines as the operation condition of the natural gas pipelines in production stations getting worse. A picture of eroded square elbow of a natural gas gathering station. One of the surfaces has been perforated and the maximum erosion depth is about 1/6 of the thickness. The connected straight pipeline busted and the straight pipe wall is obviously eroded as shown in Figure 1. The transmission medium is natural gas which contains a lot of solid particles. The size of the connection straight pipe is Φ 22 × 5mm which is a non-standard high pressure forging made of 316L. The design pressure of the pipeline is 32 MPa. The failure method should be obtained according to erosion mechanism analysis, material performance analysis and simulation analysis as follow.
3. Erosion mechanism

3.1. Plastic material
When the particles colliding the target, material accumulation occurs on the other side of the particle movement direction under the cutting effect of the collision [6]. These materials accumulate and fall off from the target surface during the particle colliding, which cause the material loss (Figure 2).

(a) before the impact (b) crater formation and piling material at one side of the crater (c) separation of material from the surface

Figure 2. Schematic of erosion procedure in ductile material.

3.2. Brittle material
Different from the plastic materials, cracks occur when particles colliding on brittle materials. When the solid particles collide with the target, the cracks will be formed and expanded by further impact of the particles [7, 8]. The material surface is divided into smaller pieces and falling off from the surface during this process (Figure 3).

(a) growth of cone crack and median cracks (b) closure of median and creation of lateral cracks, (c) eroded crater formed

Figure 3. Expected mechanism of erosion in brittle material.

4. Result and Discussion

4.1. Failure analysis
According to the macro morphology of the eroded elbow, the failure are caused by materials brittle fracture and particles erosion. The brittle fracture may be caused by the insufficient internal pressure of the pipe fittings where obvious wall thickness thinning were found. The residual morphology conforms to the characteristics of brittle fracture. Further, it is inferred that the fracture of the elbow
may be related to the high-speed impact of solid particles; for particles were found attached. The deepest groove on the elbow is about 6 mm.

4.1.1. Metallographic analysis. The morphologies of the specimens are shown in Figure 4 and Figure 5. It can be seen that there are obvious differences between the welding area and the base metal area, some grain boundaries are obvious in the base metal area. According to the metallographic phase, the structure of the base metal is single-phase austenite.

![Figure 4. Metallographic phase of the base metal.](image)

![Figure 5. Metallographic phase of the weld area.](image)

4.1.2. Mechanical property analysis. The mechanical properties test results of the full wall thickness tensile samples obtained from the failure samples are shown in Table 1. The test results show that the mechanical properties of the samples are in accord with the GB 1220–8400Cr17Ni14Mo2.

**Table 1. Tensile test results of full wall thickness samples.**

| Standard value | Thickness of sample (mm) | Width of sample (mm) | tensile strength (Rm/MPa) | Plastic extension strength (Rp/MPa) | Elongation after fracture (A/%) |
|----------------|--------------------------|----------------------|--------------------------|-----------------------------------|--------------------------------|
| 1              | 5                        | 6                    | 595.8                    | 255.78                            | 56                             |
| 2              | 5                        | 6                    | 579.95                   | 269.18                            | 55.67                          |
4.1.3. EDS analysis. The analysis results are shown in Table 2, the content of C (carbon), Si (silicon) and Mn (manganese) is high and the content of Mo (molybdenum) in the weld area is very low. This result is obtained based on the point test which can only show the content at the test point. The low content of Mo will cause the erosion resistance of the material reduced. (Fe is iron, Cr chromium is and Ni is nickel).

Table 2. Results of EDS analysis of the failure samples.

|          | C (Wt%) | Fe (rest) | Si (1.00) | Mo (2.0-3.0) | Cr (16.0-18.0) | Mn (≤2.00) | Ni (10.0-14.0) |
|----------|---------|-----------|-----------|--------------|----------------|------------|---------------|
| Standard | ≤0.03   | ≤1.00     | 2.0-3.0   | 16.0-18.0    | ≤2.00          | 10.0-14.0  |               |
| Base metal |         |           |           |              |                 |            |               |
| Weld     | 61.50   | 0.14      | 0.28      | 18.38        | 2.91           | 13.95      |               |

4.1.4. Chemical composition analysis. The analysis results are shown in Table 3, the chemical composition of the material meets the requirements. The content of C in the weld is obviously high. Although the high carbon content can improve the strength of the material, it will also increase the brittleness of the material and even the risk of brittle fracture. (P is phosphorus and S is sulfur).

Table 3. Results of chemical composition analysis of the failure samples.

|          | C (Wt%) | P (≤0.035) | Si (1.00) | Mo (2.0-3.0) | Cr (16.0-18.0) | Mn (≤2.00) | Ni (10.0-14.0) | S (≤0.03) |
|----------|---------|------------|-----------|--------------|----------------|------------|---------------|-----------|
| Standard | ≤0.03   | ≤0.035     | ≤1.00     | 2.0-3.0      | 16.0-18.0      | ≤2.00      | 10.0-14.0     | ≤0.03     |
| Base metal | 0.018   | 0.032      | 0.39      | 2.08         | 16.28          | 0.92       | 12.21         | 0.006     |
| Weld     | 0.050   | 0.032      | 0.31      | 2.08         | 16.74          | 1.41       | 10.26         | 0.0023    |

According to the macroscopic appearance, the crack initiation position is in the weld area. The failure reason may be the insufficient wall thickness of the pipe fitting. The static fluid in the elbow turns into high-speed flow fluid after the valve open. The gas carries a large number of sands, which will further erode the pipe wall. In addition, the content of C in the weld area is high, the possibility of brittle fracture increases. When the strength is insufficient, pipe walls may burst under high-pressure.

4.2. Analysis of flow field in elbow

In order to analyze erosion the square elbow in gas gathering station, the CFD method is used to obtain the gas flow field and particle movement regulation in elbows. The erosion morphologies of the square elbow are shown in Figure 7. Obvious erosion occurs on the surface of the inner wall of the upstream side (as shown in the red circle) and the corresponding simulation models of the square elbows are setup.
4.2.1. Theoretical model

4.2.1.1. Turbulence model

The turbulent viscosity $\mu_t$ can be expressed as a function of $k$ and $\varepsilon$ [9]:

$$\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \quad (1)$$

where $\rho$ is the density of fluid, $C_{\mu}$ is an empirical constant with a usual value of 0.09, $k$ is the turbulent kinetic energy, and $\varepsilon$ is the dissipation rate of turbulent kinetic energy. The transport equation of the standard $k$-$\varepsilon$ model is given by [10, 11]:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_y + S_k \quad (2)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} \left( G_k + C_{3\varepsilon} G_b \right) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (3)$$

where,

$$G_k = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (4)$$

$$G_b = \beta g_j \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (5)$$

where,

$$\beta = - \frac{1}{\rho} \frac{\partial \rho}{\partial T} \quad (6)$$

$$Y_y = 2 \rho \varepsilon M_t^2 \quad (7)$$

$$M_t = \sqrt{k/\alpha} \quad (8)$$

$$a = \sqrt{\gamma RT} \quad (9)$$

where $G_k$ is the generated item of turbulent kinetic energy $k$, which is caused by the average velocity gradient and can be calculated using Equation (4). $G_b$ is the generated item of turbulent kinetic energy $k$, which is caused by the buoyancy and can be calculated by Equation (5), where $Pr_t$ and $\beta$ are the turbulent Prandtl number and coefficient of thermal expansion, respectively. $Y_y$ is the effect of expansion on total dissipation rate in compressible turbulence and can be calculated using Equation (7), where $M_t$ and $a$ are the turbulent Mach number and velocity of voice, respectively. $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are empirical constants with typical values of 1.44, 1.92, and 0.09, respectively. $\sigma_k$ and $\sigma_\varepsilon$ are the Prandtl numbers of turbulent kinetic energy and dissipation rate of turbulent kinetic energy with the usual values of 1.0 and 1.3, respectively. $S_k$ and $S_\varepsilon$ are the source items defined by the user.

4.2.1.2. Lagrange discrete phase model

The Euler-Lagrange method is typically adopted for research on two-phase gas and solid [12]. The fluid is considered as a continuous phase, the solid particles are regarded as the dispersed phase, and
particle tracks are described using the Lagrange coordinate [13]. The solid particles of the dispersed phase are described using the Lagrange method, and the movement of these particles follows Newton’s second law [14]:

\[
\frac{du_p}{dt} = \frac{3u C_D Re_p (u - u_p)}{4 \rho_p d_p^2} + \frac{g (\rho_p - \rho)}{\rho_p}
\]

where \( u_p \) and \( u \) are the velocities of solid particles of the dispersed phase and fluid of the continuous phase, respectively; \( C_D \) is the drag coefficient; \( Re_p \) is the relative Reynolds number; \( \rho_p \) and \( \rho \) are densities of the particle and fluid phases, respectively; \( d_p \) is the diameter of the particles; and \( g \) is the gravitational acceleration.

4.2.2. Simulation model. According to the eroded square elbow in a gas gathering station, the CFD method is used to setup simulation models for analyzing erosion caused by solid particles. The boundary layer should be refined to ensure that the maximum size is smaller than the particle radius to ensure the particle collision process would not be miss during the calculation. The geometric sizes of the model are set according to the actual size of the pipeline and the front and rear straight sections are extended. The boundary conditions were set as Table 4 and the grid of the square elbow is shown in Figure 8.

| Category          | Velocity | Pressure | Diameter | Particle size | Sand flow rate |
|-------------------|----------|----------|----------|---------------|----------------|
| Value             | 5 m/s    | 32 MPa   | 22 mm    | 150 μm        | 0.5 g/s        |

(a) Elbow without erosion       (b) Elbow with erosion

Figure 8. Geometry model and mesh of the square elbow.

4.2.3. Calculation results analysis. The movement track of particles and erosion on square elbows are shown in Figure 9 and Figure 10 respectively. It can be observed that particles collide with the internal wall and then collide with the downstream straight pipe, which is consistent with the damaged square elbow. Comparing with Figure 9 and Figure 10, particle collision is more concentrated on eroded square elbows for the internal flow area changing. The particle track changes obviously for the flow field changing in the square elbow when the wall of the elbow is eroded. Particles are more likely moving vertically along the straight pipe and the erosion gradually occurs on the opposite side of straight pipe as shown in Figure 10, which is the same as the actual eroded elbow.

Figure 9. Simulation results of square elbow without erosion.
5. Conclusions
1. After the well open, gas carrying large numbers of solid particles with high pressure and speed may cause high erosion on the internal wall of pipelines and fittings, and even leads to burst when the strength is insufficient.
2. The metallographic structure are different in weld area, heat affected zone and base metal of the failure samples, the area with high content of C will lead to the brittle fracture.
3. According to the numerical simulation results, erosion will be more serious on eroded square elbows for the internal flow area changing. Also, due to the change of fluid area in the eroded elbows, the erosion position on the downstream straight pipelines changes.

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Figure 10. Simulation results of square elbow with erosion.