Investigation on Erosion Resistance of Downhole Throttle with Ultra-high Pressure

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Abstract. The throttling nozzle, the core element of downhole throttling tool, is seriously eroded in the producing-sand gas well. In this paper, the fixed downhole throttle developed by Petro China Southwest Oil and Gasfield Company is taken as the research object, and the flow state of gas and the movement of sand particles are expressed by RNG $k-\varepsilon$ model and DPM model respectively. Through Fluent numerical simulation, the internal flow field distribution rule of throttle with diameter of 70mm is discussed, the most serious erosion area of throttle is obtained, and the influence of solid particle velocity, solid particle diameter and solid particle mass flow rate on the erosion of throttle are analyzed. It is meaningful to design and improve throttle according to working parameters of gas well. According to the simulation, it is believed that the fixed downhole throttle will contribute to a better understanding for erosion resistance of downhole throttle with ultra-high pressure.

Keywords: Downhole throttle; fluent; erosion; gas-solid two-phase.

1. Introduction
As an important energy substitute in the current stage of the world energy transition, natural gas has the advantage of abundant reserves, cleanliness and environment-friendly feathers. Downhole throttling technology has been utilized to reduce the pressure of gas below the ground during gas extraction. It can reduce influence of high pressure on surface pipeline, playing a significant role in cost reduction, safe operation, energy conservation and efficient production [1]. Therefore, failure of downhole throttle tool is a problem worthy of attention. In the high temperature, high pressure and high sulfur environment, the erosion phenomenon of throttle nozzle with long service-period is serious. Erosion is the accumulation of micro-damage caused by the impact of a large number of particles on the wall, causing volume damage to the wall, such as wall pits, wall thinning, wall perforation and other phenomena. Erosion usually occurs on the wall of a fluid field with solid particles, so the problem of erosion also involves two-phase flow or even multi-phase flow. At present, a large number of scholars have studied erosion problems of throttle nozzles. Erosion is a complex process affected by many factors, such as solid parameters[2], fluid parameters[3], wall parameters[4] and so on. Wang adopted finite element
method on research of erosive wear mechanism on ductile and brittle materials [5]. Many scholars had studied the effects of various factors on target erosion, including the relationship between material properties and erosion mechanism [6]; the relationships between impact properties and erosion mechanism [7]; and the relationships between erodent (particle) properties and erosion process [8]. Jie Zhang discussed erosion wear mechanism of bent pipes, and analyzed impact of curvature-to-diameter ratio, particle velocity and assembly angle of the double elbow bend on maximum erosion rate [9]. Hongjun Zhu explored the erosion rate and deformation of valve core in gas-particle flow under different operating and structural conditions with different fluid parameters [10]. A variety of erosion models have been developed to simulate erosion behavior and predict maximum erosion rate, which have been applied to engineering design as an important reference quantity [11]. A. Mansouri utilized combined CFD/experimental methodology to research motion of solid particle in gas-solid and liquid-solid flow, and found prediction model of erosion by taking erosion depth as objective function [12]. Guo R Wang investigated erosion of the throttle valve of managed pressure drilling, by a discrete phase model (DPM) and a semi-empirical material removal model, which was verified by experiment [13]. Liu feng [14] discussed the erosion effect of gas-solid two-phase flow on the valve filter. Wei C X [15] analyzed erosion of buckling tubing string in high-pressure gas wells. Hu D [16] performed a systematic analysis of downhole throttling device suitable for the acidic gas field in east Sichuan and put forward the structural improvement, which was feasible in the test. Cao xuewen [17] investigated the influence of solid phase particle properties on the erosion effect of bending pipe.

In this paper, based on the analysis of a fixed downhole throttles and throttles of CNPC, Fluent is used to simulate the flow field law of the restrictor in the ultra-high pressure environment, and the DPM model is used to simulate the sand movement in the flow to explore the erosion of the throttle in the gas producing well, and the influence of single factor on erosion is discussed. According to these, the improvement suggestion of erosion prevention of throttle is put forward.

2. Problem Description of Erosion

As is presented in Figure.1, When fluid passes through a small cross-section hole, the movement of the fluid is stagnated on the wall, and a dramatic change happens in fluid field of the small hole. The energy of fluid is absorbed and consumed by other structures such as throttles and tubing. Because of the friction of the pipe wall and the existence of fluid viscosity, there will be a loss of kinetic energy on the wall of the fluid. The faster the flow velocity and the higher the upstream pressure, the more the loss of energy. An obvious pressure drop will appear between upstream and downstream. On the other hand, as the flow section becomes smaller, the downstream flow of the throttle will decrease and the static pressure will decrease, thus achieving the purpose of throttling and reducing the pressure.

![Figure 1. Throttling phenomenon of small cross-section holes.](image)

In the past design, because of unreasonable material selection, worse working environment and other reasons, the larger partial diameter often appears in throttle nozzle after a working period, and material erosion on the internal wall is serious. Erosion is essentially a cumulative damage phenomenon caused by solid particles impacting wall media under the action of flow field. When the solid particles pass through the throttle nozzle, they get larger kinetic energy to impact the surface of the material, which results in local stress concentration, plastic deformation and micro-cracks. Action of multiple alternating loads and accumulation of microscopic damage result in volume failure of the material. The solid particles of erosion are generally carried by fluids, with large kinetic energy and small-scale particles. Generally speaking, the smaller the solid particles are, the greater the velocity of the flow field is, and the flow field can change the motion state of the particles. The larger the solid particles, the greater the damage effect on the wall. Nozzle erosion often has the characteristics of partial diameter-expansion of circular pipe and worse quality of surface. In oil and gas wells of large sand production, sand particles
impact the pipe wall and phenomena of tool erosion is more serious.

3. Numerical Simulation of High-pressure Water Jet

Simplified tubing in oil and gas wells is a circular tubing channel, which is derived from the formula.

\[ R_e = \frac{ud}{v} \]

Where, the kinematic viscosity coefficient of natural gas is \( v = 2.5 \times 10^{-5} \text{m}^2/\text{s}(150^\circ \text{C}) \) and the output is \( 5 \times 10^4 \text{ m}^3/\text{d} \). By calculation, \( R_e = 48000 \) (when \( \text{Re} > 8000 \sim 12000 \), it must be turbulent), so natural gas flow in oil pipeline is turbulent.

The Eulerian-Lagrangian methodology is applied to simulate the multiphase flow that involves the gas and solid particles and interaction among them. The flow status of the gas is treated as a continuum phase and expressed by Navier–Stokes equations. The \( \text{RNG} \) turbulent model is utilized to capture the turbulent status of the gas flow. Due to its Lagrange algorithm that can be used to track particles and simulate the flow state of discrete particles, the DPM model (discrete phase model) is simulate sand motion. All equations are then integrated using as implicit method to calculate the behavior of the particles in the flow domain. Furthermore, rebound velocity model and erosion model are respectively employed to describe type of wall and erosion degree during solid particles impinge wall.

3.1. Numerical Model

3.1.1. \( \text{RNG} \ k - \varepsilon \) model. Two equations models are historically the most widely used turbulent models in computational fluid dynamic (CFD). The standard \( k - \varepsilon \) model is the most widely used turbulence model. The \( \text{RNG} \ k - \varepsilon \) model, derived from instantaneous navier-stokes equations by using a mathematical technique called “renormalization group” methods (RNG), is an improved form of the standard \( k - \varepsilon \) model, with higher accuracy of time-homogenized strain flow and eddy current, and can better deal with flows with high strain rate and larger streamline bending degree. RNG \( k - \varepsilon \) model is expressed by formula[13]:

\[
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial X_i}(\rho k u_i) = \frac{\partial}{\partial X_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial X_j}\right) + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]

\[
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial X_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial X_j}\left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial X_j}\right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon
\]

Where, \( G_k \) is the generation of turbulence kinetic energy due to the mean velocity gradients, \( G_b \) is the generation of turbulence kinetic energy due to buoyancy, and \( Y_M \) is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. \( \alpha_k \) and \( \alpha_\varepsilon \) are the inverse effective Prandtl number for \( k \) and \( \varepsilon \), respectively. \( S_k \) and \( S_\varepsilon \) are user-defined source terms, \( C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon} \) are constants, \( C_{1\varepsilon} \) = 1.42 and \( C_{2\varepsilon} \) = 1.68 were obtained by RNG \( k - \varepsilon \) model.

3.1.2. Discrete phase model (DPM). Fluent predicts trajectory of discrete phase particle by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the force acting on the particle inertia with the force acting on the particle, and can be written as [9]:

\[
\frac{d\vec{u}_p}{dt} = F_p(\vec{u} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}
\]

The additional acceleration terms

\[
\vec{F} = C_{vm} \rho \frac{\vec{u}_p \nabla \vec{u} - d\vec{u}_p}{dt}
\]

The drag force:
\[ F_d = \frac{18 \mu}{24 \rho_p d_p^2} C_d R_e \]

The relative Reynolds number:
\[ R_e = \frac{\rho d_p (\bar{u}_p - \bar{u})}{\mu} \]

The drag coefficient:
\[ C_d = \frac{24}{Re} (1 + ARe^B) + \frac{C}{1 + D/Re} \]

Where, \( \bar{u} \) is the fluid phase velocity, \( \bar{u}_p \) is the particle velocity, \( \mu \) is the molecular viscosity of the fluid, \( \rho \) is the fluid density, \( \rho_p \) is the density of the particle, and \( d_p \) is the particle diameter, \( \vec{g} \) is gravitational acceleration. \( R_{ep} \) is the relative Reynolds number, \( C_{vm} \) is the virtual mass factor, \( A, B, C \) and \( D \) are empirical correlated constants, related to the shape of the solid particles.

3.1.3. Erosion model. Most of the erosion models used at present are empirical formulas. This paper adopts the erosion model of N particles under the action of flow field:
\[ R_{erosion} = \sum_{p=1}^{N_{particles}} \frac{\bar{m}_p C(d_p) f(\gamma) v^{b(v)}}{A_{face}} \]

Where, \( C(d_p) \) is the sand particle diameter function, \( \gamma \) is the impact angle of sand particles on the wall surface; \( f(\gamma) \) is the impact angle function; \( v \) is the velocity of sand relative to the wall surface, \( b(v) \) is a function of relative velocity; \( A_{face} \) is the unit erosion area of tubing surface.

3.1.4. Discrete phase reflection coefficients. They bounce off the wall after the particles hit the wall. A loss of energy arise during this period, which the angle of reflection will change, thus have an influence on the trajectory of particles, and the change of which is determined by the rebound coefficients. In Fluent, they are defined as the normal coefficient of reflection and the tangential coefficient of reflection[18]:
\[ e_n = \frac{v_{z,n}}{v_{1,n}} \]
\[ e_t = \frac{v_{z,t}}{v_{1,t}} \]

Where, \( v_n \) is the particle velocity normal to the wall and the subscripts 1 and 2 refer to before and after collision. Similarly, \( v_t \) is the particle tangential velocity to the wall. Based on experiment data, literature[19] proposed empirical formula:
\[ e_n = 0.993 - 0.0307\gamma + 4.75 \times 10^{-4} \gamma^2 - 2.61 \times 10^{-6} \gamma^3 \]
\[ e_t = 0.998 - 0.0290\gamma + 6.43 \times 10^{-4} \gamma^2 - 3.56 \times 10^{-6} \gamma^3 \]

Impact angle function \( f(\gamma) \) is defined with piece-wise function:
\[
 f(\gamma) = \begin{cases} 
 0 & (\gamma = 0^\circ) \\
 0.8 & (\gamma = 20^\circ) \\
 1 & (\gamma = 30^\circ) \\
 0.5 & (\gamma = 45^\circ) \\
 0.4 & (\gamma = 90^\circ) 
\end{cases}
\]
3.2. Calculation Parameters

Hufutang [20] analyzed the sand production of serious sand-production wells in Sebei Gas Field and established a sand production model. Deng Shaoqiang [21] analyzed the production and sand production of S-19 well and other sand production wells, and the results were good. Therefore, this paper uses their research results on sand production wells.

The throttle pressure-drop and throat diameter data of GKJL59-70-G20 in Mo 030-H25, Mo 030-H24, Mo 004-H8 and KJL59-70-G20 in Huanglong 004-X3, Tiandong 007-X3 and Qili 22 for field applications of are shown in Table 1. Lin Lin [22] through literature research and analysis, it is concluded that when the particle size of sand is greater than 0.2 mm, the damage to equipment will increase greatly. This paper formulates the research object of solid particle size based on the research results. Therefore, 0.025 mm, 0.05 mm, 0.1 mm, 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm and 1.0 mm are selected for numerical simulation.

| Name of gas wells   | Diameter of nozzles mm | Pressure drop of holehead MPa | Production of gas 10^4 m^3/d | Type of throttles |
|---------------------|------------------------|-------------------------------|------------------------------|------------------|
| Mo 030-H25          | 3.8                    | 18.5→5.2                      | 5                            | GKJL59-70-G20    |
| Mo 030-H24          | 3.5                    | 20.5→5.2                      | 5                            |                  |
| Mo 004-H8           | 4.2                    | 16.5→5                        | 3                            |                  |
| Huanglong 004-X3    | 6.3                    | 17.5→7.2                      | 9.5                          | KJL59-70-G20    |
| Tiandong 007-X3     | 8.8                    | 36→8.5                        | 38                           |                  |
| Qili 22             | 4.6                    | 48.8→6                        | 5                            |                  |

There is a critical velocity of carrying sand in sand production of gas wells, which is the minimum velocity at which sand particles can be carried out from the bottom of the wellbore along with the fluid flow in the gas wells. The following is the calculation formula [22]:

$$ u_{cf} = \left[\frac{4gd(\rho_s - \rho_g)}{3C_d \rho_g}\right]^{0.5} $$

Where, the meaning of each parameter is as above. The critical velocities of particles with different diameters $d$ can be obtained. The calculated results are shown in Table 2.

| Diameter of solid particles $d$ (mm) | 0.1 | 0.2 | 1 |
|-------------------------------------|-----|-----|---|
| The critical flow velocity $u_{cf}$ (m/s) | 3   | 4   | 9 |

3.3. Geometry and Grids Model

In the paper, a throttle suitable for the 70mm string is selected and simplify the structure as shown in Figure.2, the internal channel model was established in Solidworks, and grid generated with the Gambit program. The minimum size of the grid was 0.5mm at the flow channel position of the throttle nozzle, the minimum size of the grid was 1.0mm at the adjacent area, and the minimum size of the grid is 2mm at other positions. The total number of grids was 647083, as shown in Figure.3 below. Set pressure inlet, pressure outlet as boundary conditions, wall type of reflect. In the following analysis, calculation...
parameters of solid particles are defined in DPM, and the particle shape is simplified to spherical particles.

Figure 2. Diagram of throttle structure.

Figure 3. Flow field and grid in throttle.

4. Numerical Result and Discussion

The above model is applied to simulate the erosion of downhole throttle in ultra-pressure wells. Here are the simulation results and analysis of erosions.

4.1. Model Verification

Gas flowing through the throttle nozzle, the following happens: When the pressure at both inlet and outlet reaches a critical value, the flow flux will not increase, and the gas flow flux through the throttle reaches a maximum value. At this point, the flow state of gas reaches a critical state, which can be judged by formula [23]:

\[ \frac{P_1}{P_2} < \left( \frac{2}{k + 1} \right)^{k-1} \]

In the paper, methane is regarded as an compressible ideal gas, the viscosity as a constant. When the gas passes through the throttle nozzle in a critical state, the flow flux of the gas, the nozzle diameter of the throttle, and the pressure meet formula [23]:

\[ Q_{\text{max}} = \frac{0.408P_1 d^2}{\sqrt{\gamma g T_1 Z_1}} \left( \frac{k}{k-1} \right)^{\left( \frac{2}{k+1} \right)^{k+1} - \left( \frac{2}{k+1} \right)^{k-1}} \]

Where, \( Q_{\text{max}} \) is the flow flux through the throttle nozzle(under standard condition), \( 10^4 \text{m}^3/\text{d} \); \( P_1, P_2 \) the pressure at both inlet and outlet, MPa; \( d \) is the nozzle diameter of the throttle, mm; \( T_1 \) is temperature in entrance of throttle, K; \( Z_1 \) is gas deviation coefficient; \( \gamma_g \) is gas relative density; \( k \) is adiabatic coefficient, \( k = 1.3 \) (nature gas); according to formula (1), \( (P_2/P_1)_c = 0.546 \).

Based on the actual working conditions, \( P_1 = 50\text{MPa} \), \( P_2 = 10\text{MPa} \). When the pressure ratio is 0.2, the gas of throttle nozzle section is in critical state. In order to verify the model, the calculation of \( P_1 = 50\text{MPa} \), pressure ratio of 0.1, 0.3, 0.4, 0.5 is set in this paper. The mass flow of the throttle is calculated by taking the stable data of the internal density and velocity of the throttle nozzle. The results are in Figure 4:

Figure 4. Mass flow of calculating value of the model and theoretical value.

The error of mass flow calculated by the model is less than 2%, which is in good agreement with the theoretical value and can be used as the calculation model of erosion.
4.2. Internal Flow Field Analysis of Ultra-high Pressure Downhole Throttle

The above model is applied to simulate the erosion of downhole throttle in ultra-pressure wells. Due to the small volume and mass of solid particles, the movement inside the throttle is completely affected by the flow field. The analysis results of the flow field parameters in the throttle under the working condition $P_1 = 50MPa$, $P_2 = 10MPa$ are shown in the following Figure 5.

**Figure 5.** Simulation results of internal flow field of downhole throttle under ultra-high pressure.

As shown in Figure 5, Figure 5(a) (b) is the contour of density and velocity distribution of gas, and Figure 5 (c) (d) is the curve of density and velocity with displacement on the central axis. The gas density decreases along the axial direction, but the velocity is opposite. In Figure 5 (c) (d), due to the sudden change of the size of the flow field, the change rate of density and velocity at the inlet of the throttle is the largest, there is fluctuation and tends to be stable after entering the throttle, and the density and velocity of the gas will fluctuate again after leaving the outlet. The change of the flow field near the inlet and outlet of the throttle is dramatic, and the violent change of the flow field will lead to the violent change of the movement of solid particles.

4.3. Erosion Behavior Analysis of Ultra-high Pressure Downhole Throttle

The above model is applied to simulate the erosion of downhole throttle in ultra-pressure wells. Here are the simulation results and analysis of erosions.
Figure 6. Simulation results of erosion of ultra-high pressure downhole throttle. The erosion contour of the throttle nozzle diameter 5.5mm is shown in Figure 6 (a). The largest erosion zone is located at the axial 30~42mm of the outlet of throttle nozzle, and the erosion rate at sides of inlet and outlet of the throttle nozzle is much relatively higher than that at other locations. The result of erosion is in agreement with erosion phenomenon of real condition and result of literature [24]. The pipe diameter at the throttle nozzle is sharply reduced, the fluid velocity is increased to several times, and the kinetic energy of the solid phase particles is increased. In addition, the turbulence characteristics of the fluid drive more particles to impact the wall surface. At this condition, the probability of particle collision wall at the throttle nozzle is the highest, and the energy of the impact wall is greater, so the erosion is the most serious.

4.4. The Effect of Single Factor on Erosion Rate of Throttle Nozzle

The sand production of gas Wells is complicated, with different sand production amount, different geological structure, different sand particle size, different formation pressure and different well depth, all of which will affect the change of flow field in the wellbore, affect the movement of solid particles, and thus affect the erosion effect of throttle nozzle. To sum up, the influence of mass flow rate of solid phase, velocity of solid phase particles, diameter of particles and number of particles on erosion rate will be analyzed below.

With the above grid model, the nozzle diameter is 5.5mm, and other parameters are given as follows. Fluent was used for analysis and calculation, and the maximum erosion rate of each example was taken for data statistics. The results were shown in the figure. Figure 7(a) shows that, when other factors are constant, the erosion rate of the choke is positively correlated with the mass of the solid particles passing through in unit time. In Figure 7(b), the erosion rate of the choke first increased and then decreased with the particle velocity. When the velocity was relatively small, the kinetic energy of the particles increased with the increase of the velocity, and the impact damage effect on the wall surface was stronger. In the calculation model in this paper, the axial length of the nozzle is 42mm. As the flow rate continues to increase, the particles carried by the turbulence are quickly carried away from the internal flow channel of the nozzle, and only fewer particles avoid contact with each other. Therefore, the erosion rate decreases with the increase of the flow rate of the particles.
In Figure 7(c), with the same mass of particles passing through the wall in unit time, the erosion effect of solid particles on the wall surface decreases as a logarithmic function with the particle diameter, but only because the number of solid particles decreases in the vertical way of diameter ratio. The number of particles of 0.2mm is 0.002 times of 0.025mm, and the impact probability on the wall surface is greatly reduced. Figure 7(d) shows that when the number of solid particles is consistent, the erosion rate increases exponentially with the change of particle diameter. The erosion effect of 0.2mm particles is much greater than that of 0.15mm particles, which is consistent with the research results in literature [22]. In conclusion, erosion is more obvious in gas wells with large sand production, coarse grain, high ground stress and large working pressure drop.

5. Summary and Conclusions

In this paper, the erosion of the throttle under high pressure is studied, and the representative working conditions are selected in the research content to verify the validity of the model. The analysis results are basically consistent with the actual engineering application. The above research can be summarized as follows:

(1) According to simulating the erosion analysis of downhole throttles in high-pressure gas wells, it was found that The flow field at the inlet and outlet of the choke changes most dramatically, and the velocity and density have large fluctuations.

(2) The largest erosion zone of the throttles occurred in the region of 30~42mm of the outlet of throttle nozzle. Sides of inlet and outlet of the throttle nozzle is easy to be eroded.

(3) The analysis results of the influence of single factor on the erosion rate, emerge that the erosion phenomenon of the throttle is more serious in the gas well with large sand production amount, coarse grain, high ground stress and large working pressure difference. The erosion of throttle can be decreased by reducing the passing rate of coarse sand and working pressure drop.

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