Analysis on vibration characteristics of tubing under pressure operation

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Abstract: Pressure operation is a kind of advanced downhole technology which can be used to lift and lower the string under the condition of maintaining a certain pressure in the wellbore, not killing the well or releasing the pressure. However, due to the pressure fluctuation at the front end of the string, the string vibration is caused, which is extremely unfavorable to the operation with pressure. According to industry data, in a series of oilfield safety incidents from 2008 to 2015, nearly 65% of the total was due to vibration in the downhole string. Therefore, it is necessary to further study the factors affecting the vibration of the pipe string, so as to reduce the influence of the pipe string vibration, which is also an important means to avoid accidents. In this paper, the dynamic grid method is applied to the numerical simulation analysis of the pipeline, and the pressure fluctuation at the front end of the pipe string is obtained. At the same time, the influence of different shapes at the front end of the pipe string on the vibration of the pipe string is studied, which provides a certain theoretical background for relevant scholars.

1. INTRODUCTION
Pressure operation technology is a method of operating under the condition of keeping the original pressure in the well as far as possible. At present, the application rate of this technology in foreign gas Wells has reached more than 90%, and the number of Wells constructed every year is more than 5000, which has brought huge economic and social benefits to oil companies\textsuperscript{1-3}. In the 1960s, China also began to study the technology of operation with pressure, and gained certain research and development experience and operation effect. However, due to insufficient understanding of operation with pressure, low level of process safety, matching and equipment manufacturing, it was not popularized\textsuperscript{4}. Pressure operation is the process of drilling, completion, workover, or other operations performed by specialized technical personnel operating special systems and equipment under conditions of in-hole pressure. At present, it has been widely used in underbalance drilling, side drilling, small hole drilling, well completion, perforation, oil testing, testing, acidification, fracturing and workover operations abroad\textsuperscript{5}.

The application of this technology provides a new idea for the exploration and development of oil and gas fields. In traditional operations, the first step is to kill the well to balance formation pressure and prevent blowout. So it's hard to meet many of the geological requirements that affect geological
analysis. And the technology of operation with pressure can lift and lower the string under the condition of pressure, accurately and truly complete various evaluation tests, work system changes and other operating procedures. However, due to the vibration of the lower string, safety accidents are often caused during operations with pressure. In a series of field safety accidents from 2008 to 2015, nearly 65% of them were caused by the vibration of the inlet string \cite{6-8}. Therefore, it is necessary to further study the factors affecting the vibration of the pipe string, so as to reduce the influence of the pipe string vibration, which is also an important means to avoid accidents.

2. CFD SIMULATION MODEL

2.1. Model governing equation

The transport equation of the standard model is:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \nu + \frac{\mu}{\sigma_k} \frac{k}{\rho} \right] \frac{\partial k}{\partial x_j} + G_k + G_p - \rho e - Y_e + S_k \tag{1}$$

$$\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho u_i e)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \frac{\mu}{\sigma_\epsilon} \frac{\partial e}{\partial x_j} \right] + C_\epsilon k \frac{\partial k}{\partial x_j} + C_{\epsilon 2} \frac{E}{k} - C_{\epsilon 3} \rho \frac{e^2}{k} + S_\epsilon \tag{2}$$

Among them:

$$G_k = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \tag{3}$$

$$G_p = \beta \rho \frac{\partial u_i}{\partial x_j} \frac{\partial T}{\partial x_j} \tag{4}$$

$$\beta = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} \tag{5}$$

$$Y_e = 2 \rho e M^2 \tag{6}$$

$$M_i = \sqrt{k/a^2} \tag{7}$$

$$a = \sqrt{\gamma RT} \tag{8}$$

$G_k$ is the turbulent kinetic energy generated by the average velocity gradient, $G_p$ is the turbulent kinetic energy caused by buoyancy, $Y_e$ is the influence of compressible turbulent pulsation expansion on the total dissipation rate; $C_\epsilon$, $C_{\epsilon 2}$, $C_{\epsilon 3}$ is the empirical constant, The default values in FLUENT are used throughout this article $C_\epsilon = 1.44$, $C_{\epsilon 2} = 1.92$, $C_{\epsilon 3} = 0.99$, $\sigma_t$, $\sigma_\epsilon$ are the prandtl coefficients corresponding to the dissipation rate of turbulent kinetic energy and turbulent kinetic energy respectively, The FLUENT default is used $\sigma_t = 1.0$, $\sigma_\epsilon = 1.3$, $Pr_t$ is the turbulent prandtl number, $Pr_t = 0.85$, $g_i$ is the component of gravity acceleration in the direction of $i$, $\beta$ is the coefficient of thermal expansion, $M_i$ is turbulent Mach number, $a$ for the speed of sound.

The transport equation of turbulent kinetic energy in the standard $k-\epsilon$ model is derived from the exact equation, but the equation of dissipation rate is derived from the physical reasoning and mathematical simulation of the similar prototype equation. This model assumes that the flow is completely turbulent, and the effect of molecular viscosity can be ignored. Therefore, the standard $k-\epsilon$ model is suitable for the simulation of the flow process with complete turbulence.

2.2. Dynamic mesh theory

Model the shape of the moving grid method are adopted to simulate the fluid field due to the moving boundary changes over time, the border area of the grid fluid domain deformation with spring fairing method and grid reconstruction, in the spring fairing method for grid update process, the boundary displacement is too large, the refactoring, with mesh distortion rate is too large or too severe grid size change together with a local grid.
The smoothing method of the spring is to regard the boundary between any two grid nodes as a spring connected to each other. After the displacement of the grid boundary nodes occurs, a force proportional to the displacement will be generated, and the magnitude of the force is calculated by hooke's law. The nodes connected by springs will regain the balance of forces in the new position. Starting from the displacement of the boundary node, according to hooke's law, after iterative calculation, the new grid node position that makes the net force on each node zero can finally be obtained. The force on the grid node can be written as:

$$ F_i = \sum_j k_{ij} (\Delta x_j - \Delta x_i) $$

(9)

Where, $\Delta x_i$ and $\Delta x_j$ are the displacements of node $i$ and node $j$ respectively, $n_i$ is the number of nodes connected to node $i$, and $k_{ij}$ is the spring stiffness coefficient of node $i$ and node $j$. The spring stiffness coefficient of its adjacent nodes is defined as:

$$ k_{ij} = \frac{k_{fsc}}{\sqrt{|x_i - x_j|}} $$

(10)

Where, $k_{fsc}$ is the spring constant factor, whose value ranges from 0 to 1.

When in equilibrium, the resultant force of all spring forces connected to node $i$ is 0, which can be calculated through iteration:

$$ \Delta x_i^{n+1} = \frac{\sum_j n_i k_{ij} \Delta x_j^n}{\sum_j n_j k_{ij}} $$

(11)

Where, $m$ is the number of iterations. When the iterative calculation converges, the position update method is:

$$ \Delta x_i^{n+1} = \Delta x_i^n + \Delta x_i^{\text{converged}} $$

(12)

Where, the superscript $n+1$ and $n$ respectively represent the location of the next time step node and the current time step node.

2.3. The boundary conditions

The inlet and outlet are set as open boundaries, and the inlet and outlet are both pressure boundaries. The fluid density is , the dynamic viscosity is set to according to the conversion of 10cPa, the inlet pressure is 4.5m/s, and the outlet pressure is 0.5MPa. The other surfaces are determined by the wall surface condition, which is determined by the wall function method, and the solid surface is determined by the non-slip boundary condition. When calculating the turbulent kinetic energy near the wall, the $k$ equation is used, and the wall dissipation rate is zero.

3. Simulation analysis of the influencing factors of string vibration

3.1. Effect of vibration of flat end string

During the downgoing process of the pipe string, different front end shapes of the pipe string will cause the change of the pressure at the front end of the pipe string, which will cause the vibration of the pipe string during the downgoing process. The cloud diagram of pressure change in the downgoing process of the flat end pipe string is as follows:

(a)
It can be seen from figure 1 and figure 2 that during the downgoing process of the flat-end string, the pressure at the front end fluctuates greatly, reaching a stable state of 1.66MPa after a certain period of time. This is because the shape of the flat end is subject to a large resistance. When entering the pipe string, the drainage area changes suddenly, and the pressure on the front end changes greatly, and the pipe string vibrates greatly.

3.2. Influence of vibration of convex end string

During the downgoing process of the convex end pipe string, the resistance of the front end is small, and the change of its shape will affect the pressure change, thus affecting the vibration of the pipe string. In order to understand the downgoing pressure change of the convex end pipe string, the simulation cloud diagram obtained is shown in figure 3:

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FIG. 1 total pressure cloud diagram of the front end of the flat end string

FIG. 2 pressure change curve at the front of the flat end string

FIG. 3 total pressure cloud diagram of the front end of the convex end pipe string
FIG. 4 pressure change curve of the front end of the convex end string

It can be seen from FIG. 3 and FIG. 4 that the pressure at the front of the convex end string changes little, but the pressure changes show some differences when the convex end string enters different sections. This is because when the convex end string enters the bottom, it suffers less resistance and has less influence on the pressure at the front of the string, so the downflow of the string becomes more stable.

3.3. Effect of pipe string vibration at concave end
During the downgoing process of the concave end string, the resistance of the front end is relatively large, and the change of its shape will affect the pressure change, thus affecting the vibration of the string. In order to understand the downgoing pressure change of the concave end string, the simulation cloud diagram obtained is shown in figure 5:

FIG. 5 cloud diagram of the total pressure at the front end of the pipe string with concave end
FIG. 6 pressure change curve of the front end of the pipe string with concave end

It can be seen from figure 5 and figure 6 that the pressure at the front of the concave end string changes greatly, and the pressure changes show certain differences when the pipe string enters different sections. This is because when the pipe string at the bottom enters, the resistance suffered by the convex end string is larger, which has a greater impact on the pressure at the front of the pipe string, so the pipe string entering becomes more unstable.

3.4. Influence of vibration of convex end string
During the downgoing process of the tip string, the resistance of the front end is relatively small, and the shape change of the tip string will affect the pressure change, thus affecting the vibration of the string. In order to understand the downgoing pressure change of the tip string, the simulation cloud diagram obtained is shown in figure 7:

FIG. 7 total pressure cloud diagram of the front end of the tip string
FIG. 8 pressure change curve of the tip string

It can be seen from figure 7 and figure 8 that the pressure change at the front of the cusp string is relatively small, the pressure change at the bottom 10m and the pressure at the bottom 50m is relatively small, and it tends to be stable when reaching 1.68MPa. This is because when the cusp string enters the bottom, the resistance at the front end is relatively small, which has less impact on the pressure at the front of the string, so the pressure at the front of the string becomes more stable.

4. SHAPE ANALYSIS OF FRONT END OF STRING

Through simulation analysis can be seen that the second chapter content, different string front shape change, will cause different pressure changes, which cause vibration string under the zha is fashionable, in order to get down into the best shape of pipe string to prevent vibration, get the front shape of stress change curve as shown in figure 9:

FIG. 9 pressure change curves of the front shapes of different strings

It can be seen from figure 9 that the pressure change of the convex end string is small, and the pressure is 16.3MPa to reach the stable state. This is because the resistance of the convex end string is lower than that of the flat end and concave end, and the pressure fluctuation is smaller. Compared with the tip string, although the resistance is less, but the convex end of the fluid disturbance is less, the pressure change is less. Therefore, the pressure change and vibration of the pipe string are the least when the convex end pipe string enters the pipe string.

5. CONCLUSION

In this paper, the dynamic grid method is applied to the numerical simulation analysis of the downhole string under pressure operation, and the pressure fluctuation changes of the downhole string are
obtained. At the same time, the influence of different shapes of the downhole string on the vibration of the string is studied, and the following conclusions are obtained:

1) the dynamic grid method is applicable to the numerical simulation calculation of the downtime of the pipe string under pressure operation, and can accurately obtain the pressure fluctuation curve of the front end of the pipe string.

2) the influence of different front end shapes of the string on the vibration of the string is analyzed, and the pressure fluctuation curves of the front end of the string are obtained when the string enters different sections.

3) when the convex end pipe string goes down, the pressure fluctuation is the least, and the resistance is smaller. The fluid exerts less force on the pipe string, and the vibration of the pipe string is the least.

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