Numerical Simulation and Structure Optimization of the Sudden Expansion and Contraction Flow In Fracturing Tubing

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Abstract. For serious erosion of the sudden expansion and contraction (SEC) in fracturing tubing, numerical simulation of SEC flow field is carried out using CFD and reynolds stress model. The velocity flow field and sand concentration in calculation region is achieved. The flowfields indicate that a large recirculation zone exists and sand concentration increases in the SEC, which causes the mixture of fluid and sand to impact upon the wall at the certain angle, and aroused erosion. Based on the obtained erosion reason, the structure optimization of the SEC are proceeded. Which improved the flow in SEC, reduced the erosion of SEC, and extended the service life of the tool.

1. Introduction
During fracturing processing, the erosion problems of fracturing tubing have become more and more serious as high flow rates and sand volume injecting. Influence of the fluid flow on the fracturing tubing is gradually concerned, it has an important effect on erosion. The streamline change, recirculation and sand deposition on walls within the sudden expansion and contraction of tubing tends to cause the tools failure, leading to fracturing failure (Fig.1).

Fig. 1 The erosion picture of sudden expansion and contraction

Study on flow factors can improve to reveal the erosion mechanism[1-2]. Oliveira[3] studies on the axisymmetric sudden expansion pipe laminar flow with finite volume method, using numerical simulation, received recirculation zone length, intensity, and position of vortex center. N. J. Clem[4] analyzed the flow in fracturing tubing using CFD, J. Li and S. Hamid[5] studied on flow field around the fracturing tools with k−ε model, utilizing numerical simulation, and received the effects of the impact angle on the inner surface of the tools. As reported by Zunce Wang[6,7], reynold stress model...
have advanced in predicting disturbed turbulent flows in bypass crossover sub of horizontal wells, through analyzing with different turbulence models, and the velocity field have been measured by means of a LDA system.

In view of this practical engineering problem, the studies on the sudden expansion and contraction flow during pumping sand slurries is scarce. In this paper, the numerical simulation method are adopted to design the structure parameter of fracturing tool.

2. Numerical simulation method
The high velocity flow in sudden expansion and contraction is turbulence flow, and RSM is adopted to simulate complicated turbulent flow.

2.1. Basic Equations
Equation of continuity:
\[ \frac{\partial \bar{u}_i}{\partial x_i} = 0 \]  

Momentum equation:
\[ \rho \frac{\partial}{\partial t} \left( \bar{u}_i \bar{u}_j \right) + \frac{\partial}{\partial x_j} \left( \rho \bar{u}_i \bar{u}_j \right) = D_{ij} + p_{ij} + \phi_{ij} + \varepsilon_{ij} \]  

Where, \( \bar{u}_i \) (i = 1,2,3) represents coordinate component; \( u_i, u_j \) (i, j = 1,2,3) is time averaged velocity; \( p \) is time averaged pressure; \( \mu \) is fluid dynamic viscosity; \( \rho \) is fluid density; \( \bar{u}_i \bar{u}_j \) is Reynolds-stress value, it can be defined by turbulent model.

2.2. Reynolds Stress Transportation Equation Model
The basic equations can be solved by the following Reynolds stress transportation equation.
\[ \frac{\partial}{\partial t} \left( \rho \bar{u}_i \bar{u}_j \right) + \frac{\partial}{\partial x_k} \left( \rho \bar{u}_i \bar{u}_j \frac{\partial u_k}{\partial x_j} \right) = D_{ij} + p_{ij} + \phi_{ij} + \varepsilon_{ij} \]  

Where, on the right each part is as follows:
\[ D_{ij} = \frac{\partial}{\partial x_k} \left( \frac{\mu}{\sigma_k} \frac{\partial u_i}{\partial x_k} + \mu \frac{\partial u_i \bar{u}_j}{\partial x_k} \right) \]  

Where, \( \mu \) is turbulent kinetic viscosity; \( \sigma_k = 0.82 \).
\[ p_{ij} = -\rho \left( \bar{u}_i \bar{u}_j \frac{\partial u_k}{\partial x_k} + \bar{u}_i \bar{u}_j \frac{\partial u_k}{\partial x_k} \right) \]  

\[ \phi_{ij} = -C_1 \rho \varepsilon \left( \bar{u}_i \bar{u}_j - \frac{2}{3} k \delta_{ij} \right) - C_2 \left( p_{ij} - \frac{1}{3} P_k \delta_{ij} \right) \]  

Where, \( C_1 = 1.8 \), \( \delta_{ij} \) is Kronecker delta, \( k \) is turbulent kinetic energy, \( \varepsilon \) is turbulent energy dissipation rate.
\[ \varepsilon_{ij} = -\frac{2}{3} \rho \varepsilon \delta_{ij} \]  

These have formed the closed equation group.

2.3. Model, Mesh and Numerical Method
The geometric model is simplified, and the simulation regime and structured grid have been showed in Fig.2. The final grids have as many as 2.77×10^6. Mixture two phase model is adopted to calculate the
liquid-sand flow. The finite volume method is used for discrete governing equations, SIMPLE is adopted for Pressure-velocity coupling. Standard format is for pressure interpolation. The density of sand particle is $1.72 \times 10^3 \text{kg/m}^3$, its mean diameter is $5 \times 10^{-5} \text{m}$, the volume fraction is 30%. Dynamic viscosity of the fracture fluid is 100mPa·s, its density is $1.02 \times 10^3 \text{kg/m}^3$. Inlet is defined by velocity inlet, and outlet is considered as pressure outlet.

Fig. 2 The model and grids used in the calculations

3. Results and discussion

3.1. Visualisation of flowfield

3.1.1. Streamlines. Figure 3 and Figure 4 show the pictures of the streamlines for the cases of $Q=3\text{m}^3/\text{min}$ and $Q=6\text{m}^3/\text{min}$, $Q$ is the flowrate. Fluid emanating from the inflow tube separates at the expansion and moves towards the large cylindrical wall. It reattaches to the wall at the contraction tube, and the flow is constricted by contraction tube. It flows towards the opposite side of wall, and then flows upstream along the wall. In this way a large recirculation zone is formed and the azimuthal flow impact the wall. The streamline between $Q=3\text{m}^3/\text{min}$ and $Q=6\text{m}^3/\text{min}$ is not significant difference, so it is basically independent of the flowrate.

Fig.3 The streamlines in SEC ($Q=3\text{m}^3/\text{min}$) Fig.4 The streamlines in SEC ($Q=6\text{m}^3/\text{min}$)

3.1.2. Sand concentration. Figure 5 and Figure 6 show the pictures of the sand concentration for the cases of $Q=3\text{m}^3/\text{min}$ and $Q=6\text{m}^3/\text{min}$. The volume fraction of sand is relatively stable at the center of tubing, the sand distributes nonuniformly in the recirculation zone. The high concentration of sand occur outside of recirculation, the low concentration of sand occur in the center of recirculation, and the high concentration particle reattach at the contraction section, and flow along wall of tubing, and then flow downstream as the concentration of sand near the wall is almost the same with the center of the tubing. The azimuthal flow with high concentration sand impact the sudden contraction tubing and cause the erosion of inner wall, which agree well with the results of site fracturing operation (Fig.1). The maximum concentration of $Q=6\text{m}^3/\text{min}$ is higher than The maximum concentration of $Q=3\text{m}^3/\text{min}$. It means the erosion is more serious as the high flowrate.
3.2. Structure Optimization

In order to reduce the effect of the recirculation on erosion, the structure optimization have been carried out. At the sudden expansion section, design the expanding angle to be 15°. At the sudden contraction section, design the contraction angle to be 30° and the inner wall be iso-variable curve. The simulated results of optimized structure show as in Fig. 7. The velocity vector show the streamlines are basically along the wall, the recirculation flow is disappear. The sand concentration profile show the distribution of sand is relatively uniform. The optimized structure can effectively reduce impacting of fluid and erosion of sand on the inner wall.

4. Conclusions

Based on CFD, the Mixture Model in conjunction with RSM turbulence model has been used to predict the motion of fracturing fluid and sand in sudden expansion and contraction, investigate the position of highly localised erosion. The streamline and sand concentration profile were received. A large recirculation zone is formed and the azimuthal flow impact the wall. The streamline is basically independent of the flowrate. The high concentration of sand occur outside of the recirculation zone, and the concentration of sand increases with the increase of the flowrate. The azimuthal flow with high concentration sand impact the sudden contraction tubing and cause the erosion of inner wall. The adopted simulation method was able to successfully predict the cause and position of the erosion, and it agree well with the results of site fracturing operation. The optimized structure of SEC is designed as the expanding angle of 15°, the contraction angle of 30° with the inner wall of iso-variable curve. The new structure make the streamlines to be basically along the wall, the recirculation flow to be disappear, and to effectively reduce the fluid impacting and the erosion of SEC.

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