Mechanism and numerical simulation of pressure stagnation during water jetting perforation

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Abstract: When perforating with an abrasive water jet, it is possible that the pressure in the hole (perforation) will be higher than that in the annulus because of water jet blasting against the hole wall, which also is the theoretical basis for the technology of hydro-jet fracturing. This paper analyzes the mechanism of generating pressure stagnation in water jet hole, and puts forward a new concept of hydro-seal. Then, the distribution of pressure in the hole was simulated with the finite element method. The simulation results showed that the pressure in the hole was higher than that in the annulus. Also, the lower the annular pressure (confining pressure) and the higher the blasting pressure, the greater the pressure difference. An experiment indicated that the cement sample was lifted up under the pressure stagnation in the hole, which proved the finite element simulation results obviously.

Key words: Water jet, perforation, pressure stagnation, hydro-seal, mechanism

1 Introduction

When perforating with an abrasive water jet (AWJ), the AWJ will be pressurized through the tubing to the downhole tool's nozzle, exiting with high velocity to penetrate the casing and form a hole (perforation) in the formation. Compared with the conventional perforation, it can avoid decreasing the formation permeability because of the crushed zone existing in bullet perforation (Li et al, 2000), enhancing the oil well production and fracturing efficiency. Some laboratory experiments have been done to optimize the fluid and the abrasive parameters in the AWJ perforation (Li et al, 2002; 2004; 2006). Combining the AWJ perforation with fracturing, becomes a new technology, hydro-jet fracturing, in which packer can be eliminated, different intervals can be fractured, avoiding the risk of fracturing failure due to the packer sealing problem (East et al, 2005; McDaniel et al, 2004; Hoch et al, 2003; Rees et al, 2001; Surjaatmadja et al, 2007). The critical issue in this technology is that, at the blasting position, the pressure in the hole should be higher than that in the annulus (confining pressure). In the authors' viewpoint, it is the "hydro-seal" that brings about the pressure enhancement (pressure stagnation) in the hole to ensure the success of hydro-jet fracturing. In this paper, the finite element method and experimental data were used to analyze the pressure stagnation.

2 Mechanism of pressure stagnation

In blasting perforation, the AWJ is generally used to penetrate casing and formation. According to the previous

research, the AWJ can form a spindle-shaped hole (Fig. 1) in the formation when the stand-off distance is smaller than 10 mm (Li et al, 2002). When the high speed AWJ passes the casing wall and cement, and impacts the hole end, it has to return from the same path to the annulus. The hole in the casing wall, normally 10 mm diameter, not only is the way of the entering jet (red part in Fig. 1), but also provides the path for the returning fluid (green part in Fig. 1), which seemingly acts as a "seal" to increase the pressure in the hole (pressure stagnation), and consequentially fractures the formation. The finite element method is a practical way to calculate the pressure rise.

3 Finite element simulation

The effect of perforation parameters on fracturing is very complex (Li et al, 2005). The perforation configuration in this simulation was established, according to the experimental results (Li et al, 2002), as follows: Perforation depth 500 mm, maximum diameter 50 mm, the diameter of hole in the casing wall 10 mm, and the perforation is spindle-shaped. Drawing the half part of the perforation (Fig. 2), we calculated the pressure distribution when changing the nozzle inlet pressure but fixing confining pressure and changing confining pressure but fixing nozzle inlet pressure, respectively.

3.1 Distribution of pressure in the hole when changing nozzle inlet pressure but fixing confining pressure

The confining pressure was set at 5 MPa, while the inlet pressure was set at 30, 35, 40, 45 and 50 MPa, respectively. Fig. 3 depicts the velocity vector near the nozzle exit when the inlet pressure was 30 MPa. This figure shows that the

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Fig. 1 Schematic view of the AWJ hole

Fig. 2 Half profile of the hole

Fig. 3 Velocity vector near the nozzle exit

jet velocity attenuates rapidly after the jet exits the nozzle, decreasing from 198 m/s to approximately 60 m/s at the distance of 60 mm. This phenomenon is different from conventional free jet (blasting into the air), which has a longer constant velocity area, with axial distance 5-50 times as long as the nozzle diameter. However in this calculated region, as shearing action exists between the entering and returning fluids, energy exchange will occur at the contact layer, resulting in rapid velocity attenuation.

Fig. 4 shows the distribution of pressure in the hole at different inlet pressures when the confining pressure was constant at 5 MPa. This indicates that after the stand-off

distance of 0.1 m (25 times as great as the nozzle diameter), the pressure becomes stable, while at the end of the hole, the value goes up slightly. At an inlet pressure of 50 MPa, the pressure in the hole is approximately 12 MPa, 7 MPa higher than the confining pressure.

3.2 Distribution of pressure in the hole when changing confining pressure but fixing nozzle inlet pressure

When the inlet pressure was set at 35 MPa, the distribution of pressure in the hole was predicted at the confining pressures of 5, 10, 15 and 20 MPa, respectively. Fig. 5 shows

Fig. 4 Pressure distribution in the hole at different inlet pressures

Fig. 5 Distribution of pressure in the perforation at different confining pressures

that the pressure in the hole would increase with the confining pressure. When the confining pressure was 5.0 MPa, the pressure in the hole was 9.4 MPa, 4.4 MPa higher than the confining pressure. Similarly, the pressure difference values were 3.7, 2.9 and 2.2 MPa when the combinations were 10.0/13.7, 15.0/17.9 and 20.0/22.2 MPa, respectively. The above results show that, due to the formation of “hydro-seal”, the pressure in the hole was always higher than the confining pressure. However, the higher the confining pressure, the smaller the difference, this is unfavorable to zone isolation during hydro-jet fracturing.

3.3 Experiment of pressure rise in the hole

Fig. 6 is the picture of the experiment performed to prove the pressure enhancement in the hole. The experimental conditions are as follows: a cement sample, with a diameter of 2.0 m, a length of 1.2 m, was enclosed with a thin steel sheet. A 5 1/2" casing was cemented in the cement sample. A blasting tool, with a diameter of 108 mm and four nozzles (diameter being 4, 5, 6 and 8 mm, respectively) was used. Pump pressure was 45-50 MPa, and corresponding flow rate was 2.2 m³/min. During the experiment, the annulus between tubing and casing was open. From this picture, we could find that one side of the sample was lifted up by the high pressure in the perforation while blasting. This visual phenomenon could prove the occurrence of pressure enhancement (pressure

Fig. 6 Experiment of pressure stagnation in the perforation

stagnation) in the perforation, which was predicted previously by infinite element method.

4 Conclusions

1) During water jet blasting, the occurrence of pressure stagnation in the perforation was due to the formation of “hydro-seal”, which also is the theoretical basis to realize hydro-jet fracturing.

2) The simulated results show that the lower the confining pressure and the higher the blasting pressure, the greater the pressure difference between perforation and annulus.

3) Higher confining pressure is unfavorable to enhance pressure stagnation in the perforation and to perform hydro-jet fracturing in deeper wells.

4) In the experiment, the cement sample was lifted up on one side, which proved the occurrence of pressure stagnation in the perforation.

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