Numerical study on the flow field of self-propelled multi-orifices nozzle jetting bit

Xiaoning Zhang¹*, Libao Shi¹, Chenghu Bao², Dongzhu Sun³, Zhenguo He¹, Lulin Kong¹
¹Research Institute of Petroleum Exploration & Development of CNPC, Beijing, China
²CNPC International Coorporation (Aktobe), Kazakstan
³Daqing Drilling Coorporation, Daqing, China

*Corresponding author:E-mail:zhangxn1981@petrochina.com.cn

Abstract. Ultra-short radius radial jet drilling (USRRJD) is a beneficial method to develop the coal bed methane and conventional oil and gas resources. Jetting bit is a self-propelled nozzle and key tool for USRJD, which could rapidly jet and erode the formation, and then form to regular hole to evaluate oil and gas. Multi-orifice nozzle jetting bit is a special self-propelled bit. This paper introduced flow field characteristics studied by numerical method for multi-orifice nozzle jetting. Combined with the mathematical and RNG k-ε turbulent model, physical model is established according the bit shapes and working condition. The simulated self-propelled force coincides well with the reported experimental data. The simulated results show that the flow field includes four regions, such as forward flow, cross flow, backward flow and low velocity. Forward orifices enlarges bottom hole impact zone which is beneficial to enlarge hole diameter, the maximum axial velocity of forward orifices is distanced due to absorb of central orifice. Backward orifices can further enlarge hole diameter and generate self-propelled force. Wall attachment in backward orifices results in low velocity of backward jetting, which would decrease the propelled force. This study provided the reference for optimizing multi-orifice nozzle and operation parameters.

Key words: USRRJD, multi-orifices nozzle jetting bit, flow field, numerical simulation, self-forward force

1. Introduction
Ultra-short radius radial jet drilling (USRRJD) was developed rapidly over the last two decades, which is particularly beneficial for developing depleted reservoirs, fault block oil reservoirs, margin reservoirs and heavy oil reservoirs and coal bed methane and so on. The key equipment of USRRJD mainly includes a bit, high pressure hose, and a whip stock (shown in Fig.1). It just depends on hydraulic energy to break rock and drill ahead in formations by overcome drag. The whip stock is small enough to avoid under reaming and enter the main hole smoothly, and provide the passage for bit and hose to turn from vertical to horizontal. A flexible high-pressure hose is used to complete the
diversion from vertical to horizontal in the casing and convey fluid with high energy to bit for breaking rock. Jet nozzle is the key component to break rock and provide force to overcome drag and pull the hose moving forward, which largely affect the extension of horizontal holes and ROP. USRRJD has been successfully applied or tested in the USA, Canada, China, Bolivia, Argentina, Egypt, and Russia, and so on [1]-[8].

The multi-orifice nozzle (shown in Fig. 2) is an efficient nozzle applied as bit to break rock in USRRJD. The multi-orifice nozzle is divided into two parts. The forward orifices generate the high pressure jetting impact on bottom of hole to break rock and deepen the hole, while the backward orifices form backward jetting to generate the self-propelled force and meanwhile expand hole. Many researchers have studied the self-propelled force and rock break of multi-orifices nozzle. Beset [2] analyzed the mechanism of rock breaking and the self-propelled ability of multi-orifice nozzles; Guo et al. [9] and Li et al. [10] studied the self-propelled forces of multi-orifice nozzles by theoretical and simulated method without considering the effect of jetting on propelled force; Liao et al. [11] experimented the effect of the number of forward orifices and hydraulic parameters on the rock-breaking properties. Due to the complex flow field of self-propelled multi-orifices nozzle, there is no references report about. But the several researchers have simulated the flow field of round jetting and swirling jetting. By numerical simulation, Sheen [12] studied the flow field of three-orifice nozzles and swirling jetting, and Liao et al. [13][14] mainly studied flow field of swirling combined with straight nozzles. Because flow field is very important to nozzle design, this paper will introduce the flow field by numerically simulating.

Figure 1. Diagram of ultra-short radius radial jetting drilling

Figure 2. Schematic of multi-hole nozzle
2. Mathematical and physical model

2.1. Control Equation
Traditionally, control equation includes continuity, Navies-stokes and energy equations. During the progress of rock breaking by water jetting of multi-orifices nozzle, the effect of heat transferring between fluid and formation on flow field could be ignored. Flow field has little relationship with time. Besides, the density of water is constant. Thus the characteristics of multi-orifices nozzle jetting perform as:

1. The fluid is incompressible.
2. The flow is steady.

So the basic control equation just includes continuity equation and Navies-stokes equation for simulating flow field of multi-orifices nozzle.

2.2. Turbulent Model
Due to high velocity of submerged jetting and complex of nozzle structure, there exists severely bent streamline in outlet and inlet and vortex in annulus. There are several turbulent models established by certain assumption and experience, but one model can't gain the exact results to all problems. Where, RNG k-ε model considers the influence of small scale flow by simulating large scale flow and modifying vicious item. Thus, high accurate results could be gained to simulate flow field of large bending streamline and high strain rate by RNG k-ε model. Besides, this mode is easier to convergent and save simulating time than other models by reducing the oscillation frequency of convergence. Thus RNG k-ε model is used to simulate the flow field.

2.3. Physical model and mesh
There are many designs for multi-orifices nozzle, particularly with 1 central orifice and 3, 6, or 8 forward orifices. In this paper, the nozzle with 6 central orifices, 1 central orifice and 8 forward orifices. The structure parameters and photo of multi-orifices nozzle is shown as Fig.3 and Fig.4 respectively. The key parameters of nozzle are the angle of 30º between axial of nozzle and forward orifices, D1=0.011m, D2=0.018m, D3=0.007m, L=0.0302m, d1=0.007m, d2=0.006m, d3=0.008m.

![Figure 3. Structure of multi-orifices nozzle](image-url)
When the nozzle operate in drilling, these exits distance between the front of nozzle (the distance named jetting distance assumed 0.010m) and bottom of hole and annulus between nozzle and hole (hole size assumed 0.030m). The flow area of flow field includes: inner of nozzle, nozzle and annulus between borehole and nozzle.

The model of flow area is meshed by software GAMBIT. Due to the flow area is complex, it’s difficult to mesh structuring grid. So the calculated area is separated to several blocks meshed by tetrahedron/hexahedron grid. Due to the complex flow area, the severe turbulent flow exists. To gain more accurate results, the girds are in filled in the area with high velocity gradient (shown as Fig 5.).

2.4. Boundary conditions

The boundary conditions of simulation model include inlet, outlet and wall, and flow area full of water. Combined with computer and actual operation parameters, boundary conditions are velocity inlet, pressure outlet and no-slip wall. According to the operation of drilling, the flow rate is 0.1-2.0L/s, and pressure at bottom is 1.0-10.0MPa.

3. Results of Simulated Flow Field

3.1. Numerical results verified by experiment

To confirm the validity of established numerical model, simulated self-propelled forces are compared to that experimented by Goo et al.[9] With the flow rate of 0.1-2.0L/s (shown in Fig.6). The difference between numerical and experimental values is less than 5.5%, which indicates that the mathematical and physical model used in the numerical simulation is reasonable. When flow rate is higher than 1.0L/s, the self-propelled force may reach 2kN.

Due to the drag and propelled force largely affect the length of horizontal section, the drag resulting from hose will be calculated by software Well plan[15]. The following data are used, the outer diameter of hose of 0.063mm, the thickness of hose of 0.004mm, density of hose of 2.5g/cm3, the frictional coefficient of 0.25-0.50, the density of fluid of 1.0 g/cm3. Fig.7. shows that the drag changes with the length of horizontal section under different whole condition. When the horizontal section is 200m, the drags changes between 290-580N without considering the drag in whip stock. Thus, to generate higher propelled force and guarantee smoothly drill ahead, flow rate is recommended to as high as possible.
3.2. Distribution of flow field

With inlet flow rate of 1.5L/s and outlet pressure of 5MPa, the flow field structure of multi-orifices nozzle is shown as Fig.8, which is divided into cross flow area, forward jetting area, backward jetting area and low velocity area according to the nozzle structure and distribution of velocity.

According to the experimental results of round nozzle jetting, the structure of parallel multi-orifices nozzle free jetting includes four sections, initial section, transient section, essential section and mixing section. But for submerged non-free jetting, the flow field just includes initial section, transient section and essential section. With the impinging of forward and backward jetting, multi-orifices nozzle could break rock and form and enlarge a hole and propelled force is also generated to overcome drag and guarantee to smoothly drill ahead.
3.3. Flow field of forward jetting

To the forward jetting, the attenuation of axial velocity, distribution radial velocity and velocity distribution of jetting area near wall are the important indexes of utilization ratio of jetting energy. If the axial velocity gradient is lower, the jetting energy decays lower. Thus, the utilization ratio of jetting energy could be improved, but the impinging area could decrease. If the radial velocity extends fast, jetting has higher ability to absorb the surrounding fluid, which could enlarge the impinging area. If the jetting extends too fast, the effective distance of erosion by jetting would shorten. As, the forward jetting of multi-orifices nozzle consisted by many round jetting, central orifice has larger size and less resistance coefficient than the other forward orifices. The jetting velocity of central orifice is higher than that of other forward orifices (shown in Fig.8). Jetting bundle of multi-orifice nozzle impacts on bottom of hole and generate larger impinging area than single jetting. The jetting of uniformly distributed orifices shrinks towards to the central due to absorbing of the other forward orifice jetting which results in largely difference of velocity distribution between central orifice and the other forward orifices.
Fig. 9 shows the velocity attenuation curves along axis of forward orifices. The velocity is about 15.79 m/s on the axis of central and the other forward orifices. When the fluid flows near the inlet of orifices, the velocity on axis of central orifice is higher than that on axis of the other forward orifices due to the effect of internal wall of nozzle and higher resistance coefficient. The velocity of orifice could be improved by optimizing the internal shape of nozzle and forward orifices. The fluid is accelerated by orifices and impinges to bottom of hole. Due to the larger size of central orifice, the velocity attenuation is lower than that of the other forward orifices. When the fluid reaches to bottom, the axial velocity becomes zero. The resistance coefficient of central orifice is lower than that of the other forward orifices, so the jetting energy of central orifice is higher. Due to the inter absorbing between central orifice and edged orifices, the potential core of edged orifice displaces from the axis. Thus the velocity attenuation of forward orifices is different with that of central orifice.

3.4. Cross flow area
Due to the velocity is zero at the bottom, the velocity distribution in the place with distance from bottom 1mm will be analyzed. As shown in Fig. 10, jetting flow field of multi-orifices nozzle jetting performs as gear shape and gradually decreases from central to edge due to radial diffusion with the limitation of wall. The impinging area of multi-orifices obviously increases compare with that of single orifice which is in favor of enlarging hole. The heterogeneous flow field could improve the rate of break rock, but meanwhile would form an irregular hole.

Fig. 10. Flow field at place with 1mm to the bottom of hole
Figure 11. Velocity curves at the plane with distance 1mm from the bottom hole

As shown in Fig.11, jetting flow velocity is mainly axial and radial velocity, the tangential velocity is nearly zero at the radial direction of plane with distance from the bottom of the hole. The horizontal axis with the value of zero is the central of bottom, the value of 0.015m is the wall of hole. When the radial velocity is positive, it indicates that the direction of radial velocity is from central to edged wall. The direction of radial velocity is from edged wall to the central when the radial velocity is negative. This phenomena result from the limitation of flow by wall. The change trend of axial velocity and velocity magnitude is nearly similar when the radial distance is less than 7mm. When the radial distance is longer than 7mm, the curve of radial velocity is coincided with that of velocity magnitude, which indicates that axial velocity is almost zero. The jetting velocity is mainly axial velocity when the radial distance is less than 7mm while the jetting velocity is mainly radial velocity when the radial distance is longer than 7mm.

3.5. Backward jetting area
Partial fluid flows from internal of nozzles into the backward nozzle and jet into annulus, then form the back jetting (shown as Fig.12). The distribution of backward jetting is different to that of forward jetting due to certain angles between direction of maximum axial velocity and wall of hole. Thus, the backward jetting impacts larger area than forward jetting. High velocity gradient near wall will result in higher strain rate which is favor of breaking rock. On the basis of hole drilled by forward jetting, backward jetting would break rock further and enlarge hole. When the water flows into nozzle and jets from backward orifices, wall attachment and large bent streamline results in separation and backward flow area, and the velocity isn’t symmetrical at the axis of backward orifices, which largely increases the frictional factor. Thus the average velocity of backward jetting (max. velocity is 76m/s) is much lower than that of forward jetting (max. velocity reaches 140m/s).
4. Conclusion

(1) The established mathematical and physical model is favor of design and optimizing the structure of multi-orifice nozzle.

(2) The forward jetting of multi-orifices increase the impinging area, which is favor of form large hole. Due to the flow field performing as gear shape, the turbulent intensity increases, which is favor of sweeping the cutting from bottom.

(3) The wall attachment in backward orifice increases the local resistance coefficient, thus the size of backward orifices should be larger than that of forward orifices to provide higher self-propelled force and stability of nozzle for drilling ahead.

(4) Due to the drag in whip stock is difficult to determine, further study and test should be performed to optimize the structure of multi-orifice nozzle and flow rate to guarantee the self-propelled force achieve the requirement of designed horizontal section. To smoothly control the well trajectory, special tool should be considered to adjust the azimuth and inclination.

References

[1] Dickinson, E. The Ultra short Radius Radial System Applied to Thermal Recovery of Heavy Oil. Presented at the SPE Western Regional Meeting, Bakersfield, California, 30 March-1 April. SPE-24087-MS(1992).

[2] Buset, P., Riiber, M., Eek, A. Jet Drilling Tool: Cost-Effective Lateral Drilling Technology for Enhanced Oil Recovery. Presented at the SPE/ICOTA Coiled Tubing Roundtable, Houston, Texas, 7-8 March. SPE-68504-MS(2001).

[3] Shi, L., Li, Y., Guo, H. Application of radial horizontal well drilling techniques in Jin 45-Jian 1 well. Pet. Drill. Tech. 30 (5), 23-24(2002).

[4] Bruni, M.A., Biasotti, J.H., Salomone, G.D. Radial Drilling in Argentina. Presented at the Latin American &Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina, 15-18 April.SPE-107382-MS(2007).

[5] Cirigliano, R.A., Blacutt, J.F.T. First Experience in the Application of radial Perforation Technology in Deep Wells. Presented at the Latin American &Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina, 15-18 April. SPE-107182-MS(2007).

[6] Ursegov, S., Bazylev, A., Taraskin, E. First Results of Cyclic Steam Stimulation of Vertical Wells with Radial Horizontal Bores in Heavy Oil Carbonates(Russian). SPE Russian Oil and Gas Technical Conference and Exhibition, Moscow, Russia, 28-30 October. SPE-115125-RU (2008).

[7] Abdel-Ghany, M.A., Siso, S., Hassan, A.M., Pierpaolo, P., Roberto, C. New Technology Application, Radial Drilling Petro, First Well in Egypt. Presented at the Offshore
Mediterranean Conference, Ravenna, Italy, 23-25 March. OMC-2011-163, (2011).

[8] Steven, D.C., Ahmed, H.K. Novel Technique to Drill Horizontal Laterals Revitalizes Aging Field. Presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands, 5-7 March. SPE-163405-MS (2013).

[9] Guo, R., Li, G., Huang, Z., Tian, S., Zhang, X., Wu, W. Theoretical and experimental study of the pulling force of jet bits in radial drilling technology. Pet. Sci. 4 (6), 395-399 (2009).

[10] Li, J., Li, G., Huang, Z., et al. The self-propelled force model of a multi-orifice for radial jet drilling. Journal of Natural Gas Science and Engineering 24, 441-448 (2015).

[11] Liao, H., Niu, J., Cheng, Y., Huang, Z., Ma, D. Experiment study on water jet breaking rock by multi-orifice nozzle. J. China Coal Soc. 36 (11), 1858-1862 (2011).

[12] Shen, Z. Theory and Technology of Water Jet, first ed. China U. of Petroleum Press, Dongying, pp. 269-270, 1998.

[13] Liao, H., Li, G., Li, J., et al. Flow field study on intergrating straight and swirling jets for radial horizontal drilling. JOURNAL OF CHINA COAL SOCIATY, 37(11):1895-1900 (2012).

[14] Liao, H., Wu, D., Wang, Lei, et al. Comparisons of spraying structure and rock breakage characteristics of round straight jet, wirling jet, and straight swirling integrated jet[J]. Atomization and Sprays, 2013, 23: 363-377 (2013).

[15] Landmark Graphics Corporation. Using WELLPLAN R2003.11.0.1. Part No. 162163, Rev. A, V2003.11, (2014).