Investigation of the factors affecting the self-propelled force in a multi-orifice nozzle using a novel simulation method

Yumei Li | Tao Zhang

Beijing Key Laboratory of High Dynamic Navigation Technology, Beijing Information Science & Technology University, Beijing, China

Correspondence
Yumei Li, Beijing Key Laboratory of High Dynamic Navigation Technology, Beijing Information Science & Technology University, Beijing 100101, China. Email: liyumei3680238@163.com

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Abstract
A multi-orifice nozzle is the primary actuator of radial jet drilling for the stimulation of unconventional and low-permeability reservoirs. This research developed a 3D flow field simulation model to investigate the self-propelled force of a multi-orifice nozzle based on ANSYS-CFX. To evaluate the self-propelled ability of the nozzle, investigation was performed on the effects of the angle, number, the diameter of the forward and backward orifices of the multi-orifice nozzle, and the diameter of the micro-hole in the radial well on its self-propelled ability by sensitivity analysis.

The results revealed that the self-propelled force slightly increased with the angle of forward orifice increasing, and decreased with the angle of backward orifice increasing; and that the self-propelled force had a tendency to decrease significantly with the number of forward orifices increasing, and increased slightly with the number of backward orifices increasing. The self-propelled forces for different combinations of forward and backward orifices were obtained by the simulation method, which agreed well with those obtained by the calculation method, with an average accuracy of 95.82%. It was observed that the self-propelled force increased substantially with the angle of forward orifice increasing, and decreased with the angle of backward orifice increasing; and that the self-propelled force had a tendency to decrease significantly with the number of forward orifices increasing, and increased slightly with the number of backward orifices increasing. The self-propelled forces for different combinations of forward and backward orifices were obtained by the simulation method, which agreed well with those obtained by the calculation method, with an average accuracy of 95.82%. It was observed that the self-propelled force increased substantially as the value of $K (d_2/d_1)$ increased, but tended to slow down when the flow rate was within a certain range. Besides, with the increase in the diameter of the micro-hole, the self-propelled force reduced, and increased substantially as the inlet flow rate increased, but tended to slow down as the inlet flow rate further increased. Thus, to ensure the self-propelled ability of the jet nozzle, a set of optimal structural parameters can be used to generate the target self-propelled ability. The research improves the working performance of multi-orifice nozzles and provides theoretical guidance for hydraulic radial jet drilling process.

KEYWORDS
CFX, multi-orifice nozzle, radial jet drilling, self-propelled force
1 | INTRODUCTION

In recent years, a large proportion of newly discovered oil and gas resources in China has the characteristics of low porosity, low permeability, and low fluidity. The task of stabilizing oil production in old oilfields is arduous, and a cost-effective technology is urgently needed to tap the potentials of such resources, increase the production and injection, and increase the ultimate recovery of oilfields.

High-pressure water jets have played important roles in increasing the drilling penetration rate. In 1985, with the support of Petrophysics and Bechtel companies in the United States, W. Dickinson et al proposed the first-generation hydraulic radial jet drilling (RJD) technology. The main feature of the technology was that after the casing was opened, it could realize a turn of 90° from vertical to horizontal. The research results showed that drilling depth was one of the main factors affecting productivity. When the drilling depth exceeded 15 m in radial jet drilling, the productivity ratio was 2-3 times that of conventional perforation. One application of radial jet drilling guided by a high-pressure water jet was developed to provide multiple lateral micro-holes with a length of 30-100 m and a diameter of 25-50 mm along radial directions in a vertical wellbore. The reservoir plane in a vertical borehole was radially drilled and distributed in a radial pattern. After that, a coiled tubing was used to connect the high-pressure hose. Horizontal oil and gas passages were opened to establish high-diversion channels for the remaining oil and gas zones in the far-well zone, thereby increasing the well production. Compared with conventional perforating-fracturing technology, the advantages of hydraulic radial jet drilling technology are obvious: pollution-free, hydraulic fracturing, rock tensile failure, and cavitation for reservoir modification, etc. The schematic of a conventional RJD system is shown in Figure 1. Radial horizontal well technology has been applied in China, the United States, Canada, Russia, Argentina, Bolivia, Egypt, and other countries since its introduction and has achieved different effects.

A radial jet nozzle is the most critical actuator of an RJD system. The force generated by the jet nozzle to pull the high-pressure hose moving forward, breaking the rock, and forming multiple lateral micro-holes to enhance the production is called the self-propelled force. The structural parameters of a multi-orifice nozzle play an important role in controlling the self-propelled force, rock breaking force, jet pressure, and maximum drillable length. The forward orifice mainly completes the rock breaking relying on high-pressure jetting, while the backward orifice with the function of assisting the reaming and stabilizing the jet nozzle has the function of expanding the radial hole by generating the self-propelled force. The angle of the backward orifice dominates the component of the momentum in the axial direction. Jingbin Li et al constructed a model to calculate the self-propelled force and defined a factor to characterize the self-propelled ability of the nozzle. They investigated the effects of the number, angle, and the diameter of orifice on its self-propelled ability. Based on the operational condition of radial horizontal jet drilling, Huanpeng Chi et al proposed a model for calculating the maximum drillable length of micro-holes. The model considered the pressure loss of the circulation system, the pressure and flow rate of the pump, and the self-propulsion effect of the multiple-jet nozzle. The results indicated that the flow rate was the dominant factor affecting the radial horizontal jet drilling process. Xuelin Yang et al established a simplified model for water jetting process through the computational fluid dynamics software Fluent. The effects of geometric structure and parameters on the flow field of the water jetting were examined through simulation.

Since conducting a high-pressure water jetting experiment is very dangerous, it is difficult to obtain the internal characteristics of the flow field by indoor laboratory test. Also, indoor laboratory test is a time-consuming and costly process. Thus, to evaluate the self-propelled force of a multi-orifice nozzle, a 3D flow field simulation model of the nozzle was established using ANSYS-CFX software which has excellent calculation convergence and numerical accuracy. Sensitivity analysis was performed to investigate and compare the effects of the nozzle structure parameters, including angle, number, the diameter of the nozzle, and the diameter of the micro-hole on the self-propelled force and spray characteristics of the jet nozzle. Finally, the indoor experiment of casing windowing was conducted with the multi-orifice nozzle, and the performance well met the engineering requirements in field. This research provides a theoretical basis for improving the rock drilling performance of radial jet drilling, and optimizing the design of radial wellbores and the jet parameters.

FIGURE 1 Schematic of an RJD system with high-pressure water
2 | MATHEMATICAL MODEL OF SELF-PROPELLED FORCE

According to the momentum theorem, the amount of change in the momentum of the control body is equal to the sum of the external forces acting on the control body. The momentum control equation of the control body in the horizontal direction under the condition of steady flow is given by:

\[
\int_S \rho v_x v_x dA = \sum F_x
\]

where \( \rho \) is the fluid density, \( \text{kg/m}^3 \); \( v_x \) is the velocity in the horizontal direction, \( \text{m/s} \); \( F_x \) is the resultant force acting on the control body in the direction of the horizontal axis, \( \text{N} \).

The left term in Equation (1) represents the momentum change in the horizontal direction inside the control body and is the momentum value in the horizontal direction at the exit of the hole in front of and behind the jet nozzle minus the momentum value in the horizontal direction at the entrance of the internal channel.

The right term in Equation (1) represents the sum of the external force vectors acting on the boundary of the control body, and the pull force of the high-pressure hose against the jet nozzle.

\[
\sum \rho \cdot v_i^2 A_i \cos \theta_i - \sum \rho \cdot v_j^2 A_j \cos \theta_j - \rho v_0^2 A_0 = F_h + (P_{in} - P_{out}) \sum A_i
\]

The pulling force of the high-pressure hose against the jet nozzle can be obtained from Equation (4):

\[
F_h = -\sum \rho \cdot v_i^2 A_i \cos \theta_i + \sum \rho \cdot v_j^2 A_j \cos \theta_j - \rho v_0^2 A_0 - (P_{in} - P_{out}) \sum A_i
\]

The pulling force of the high-pressure hose against the jet nozzle is equal to the self-propelled force generated by the jet nozzle. According to the principle of acting force and reacting force, the self-propelled force \( F_z \) generated by the jet nozzle can be expressed as:

\[
F_z = \sum \rho \cdot v_j^2 A_j \cos \theta_j - \sum \rho \cdot v_i^2 A_i \cos \theta_i + \rho v_0^2 A_0 + (P_{in} - P_{out}) \sum A_i
\]

Since the internal pressure exists only in the system consisting of a pump, a high-pressure hose, and a jet nozzle, the thrust generated by the internal pressure on the jet nozzle is an internal force for the system and cannot be directly converted into traction. Therefore, the self-propelled force can be calculated by:

\[
F_z = \sum \rho \cdot v_j^2 A_j \cos \theta_j - \sum \rho \cdot v_i^2 A_i \cos \theta_i - P_{out} \sum A_i
\]

3 | MODELING OF THE MULTI-ORIFICE NOZZLE

3.1 | Geometry

In this research, a standard multi-orifice nozzle was used for simulation. The geometry of the nozzle is the basis for
further simulation, and accurate measurement is the prerequisite for the accurate design and drawing of its geometry. The geometry of a multi-orifice nozzle is shown in Figure 2. A three-coordinate measuring instrument (CROMA Series) was used to measure the geometry of the jet nozzle, as shown in Figure 3. The basic geometry parameters of the jet nozzle are as follows: The diameter of the micro-hole is \( \Phi \), the total length of the jet nozzle is \( L = 17.5 \) mm, the outer diameter of the jet nozzle is \( d' = 12.5 \) mm, the inner diameter of the jet nozzle is \( d_0 = 8.6 \) mm, the inlet pressure of the orifice is \( P_0 \), the inlet flow rate is \( Q_{in} \), the diameter of the forward and backward orifices of the jet nozzle are \( d_2 \) and \( d_1 \), respectively, and the angle of the forward and backward orifices of the jet nozzle is \( \theta_2 \) and \( \theta_1 \), respectively. The physical geometry of the jet nozzle was obtained through multiple measurements. Specifically, the 3D model of the jet nozzle was drawn, then a cylinder model of micro-hole size was used to cut the model of jet nozzle. Finally, the

flow field model was established by 3D modeling software SolidWorks, as shown in Figure 4.

3.2 | Meshing and boundary

To simplify model calculations, the following assumptions are made: (a) Heat transfer is not considered in the whole simulation process, and the energy equation is in the closed state; (b) working fluid is incompressible and steady; (c) gravity is not considered.

The diameter of the forward and backward orifices is smaller than that of the micro-hole, thus the main part of jet nozzle is partitioned to facilitate the refinement of the mesh accuracy of each part. The 3D flow field of the jet nozzle was meshed by the ANSYS-ICEM grid processor. The number of grids was 64 688 and the number of nodes was 125 686. According to the constraint conditions, the working pressure of the pump as a power source during the drilling process was 50 MPa and its certified capacity was 100 L/min. The working fluid in the entire simulation environment was clean water with a fluid density of 1000 kg/m\(^3\). The simulation of the jet nozzle only considers the boundary conditions of the inlet, outlet, and wall, as shown in Figure 5.

After the boundary conditions were set, the discrete format and relaxation factor in the solver were debugged. During the operation, the residual monitoring window was opened to observe the changes in multiple physical quantities. After the model and boundary conditions were set, the solver and model were also set subsequently. The solver was opened to set the discrete format and relaxation factor. In order to obtain high calculation accuracy, the relaxation factor and step size should be reduced, leading to increased calculation amount and calculation time.
4 | SENSITIVITY ANALYSIS

4.1 | Angle of the forward and backward orifices

The angle of the forward and backward orifices mainly influences the diameter and shape of the radial micro-hole. In the simulation process, it was assumed that the diameter of the micro-hole was $\Phi = 30$ mm, the bottom confining pressure was $P = 40$ MPa, the diameter of the forward orifice was $d_2 = 0.50$ mm, the diameter of the backward orifice was $d_1 = 0.70$ mm, the number of the forward orifice was 3, and the number of the backward orifice was 6. The angle of the forward and backward orifices: (a) the angle of the forward orifice was $\theta_2 = 20^\circ$, and the angle of the backward orifice was set to $\theta_2 = 30^\circ, 35^\circ, 40^\circ$; (b) the angle of the backward orifice was $\theta_1 = 30^\circ$, and the angle of the forward orifice was set to $\theta_1 = 15^\circ, 20^\circ, 25^\circ$. The influence of the angle of the forward and backward orifices on the velocity field was investigated by numerical simulation, as shown in Figure 6.

At the inlet flow rate $Q = 40$ L/min, the effects of the angle of the forward and backward orifices on the self-propelled force and jet velocity were investigated and illustrated in Figures 7 and 8, respectively. It is observed that
the self-propelled force slightly increases with the angle of the forward orifice increasing, which explains that the angle mainly influences the pattern of the micro-hole in the radial jet drilling. So, the angle of the forward orifice has small effect on the traction power of the jet nozzle, and can only be used as a reference when designing the multi-orifice nozzle. In addition, the self-propelled force and jet velocity have a tendency to increase substantially as the flow rate increases. For the angle of the backward orifice, as shown in Figure 8, the self-propelled force decreases with the angle of the backward orifice increasing. To obtain large driving force from backward flow and a wider radial hole, the angle of the backward orifice cannot be too large when designing the multi-orifice nozzle. Besides, the larger the angle of the backward orifice, the greater the jet velocity. Thus, there is an optimal angle that can generate the target self-propelled force ability to complete the jet rock breaking.

4.2 Number of forward and backward orifices

In this simulation, the diameter of the micro-hole was $\Phi = 30.0 \text{ mm}$, the bottom confining pressure was $P = 40 \text{ MPa}$, the diameter of the backward orifice was $d_1 = 0.70 \text{ mm}$, the diameter of the forward orifice was $d_2 = 0.50 \text{ mm}$, the angle of the forward orifice was $\theta_2 = 20^\circ$, and the angle of the backward orifice was $\theta_1 = 30^\circ$. The number of the forward and backward orifice was as follows: (a) (F + B) 3 + 4, 3 + 5, 3 + 6; (b) 4 + 4, 4 + 5, 4 + 6; (c) 5 + 4, 5 + 5, 5 + 6. The simulation models with the above number combinations were established, as shown in Figure 9. Figure 10 shows the jet velocity distributions for the different numbers of forward and backward orifices being 3 + 6, 4 + 6, and 5 + 6. It is found from Figure 10 that the velocity of the flow field has the largest value at the forward and backward orifices of the
multi-orifice nozzles, and that the jet velocity at the backward orifice is greater than that at the forward orifice.

Research should be done to investigate the spatial layout of the orifices of the multi-nozzle as well as the effect of the number of orifices. Figures 11 and 12 show the relationship between the self-propelled force curve and flow rate for different numbers of forward and backward orifices, respectively. Result indicates that the self-propelled force has a tendency to decrease significantly with the number of forward orifices increasing, which can be explained by that the larger the number of forward orifices, the higher the outlet pressure, leading to a high-pressure loss in the hose. In addition, the self-propelled force has a tendency to increase substantially as the flow rate increases and to increase slightly with the number of backward orifice increasing. This indicates that the larger of the number of backward orifices, the larger backward flow rate, and the larger driving force in rock breaking process. Therefore, on the premise of ensuring the self-propelled force ability, to improve the rock breaking efficiency of the multi-nozzle, there exists an optimal number of forward and backward orifices that can achieve the best performance in radial jet drilling.

Figure 13 shows the comparison between the numerical simulation and calculation results of the self-propelled force, respectively. As shown in the figure, $F_{z_n}$ and $F_{z_c}$ represent the numerical simulation results and calculation results, respectively. It is obvious that the numerical simulation
results agree well with the calculation results, with an average accuracy of 95.82%, which indicates that the simulation method in this research can be used as the basis of choosing the self-propelled force during horizontal radial jet drilling process.

4.3 Diameter of forward and backward orifices

In this simulation, the diameter of the micro-hole was $\Phi = 30.0$ mm, the bottom confining pressure was
$P = 40 \text{ MPa}$, the angle of the forward orifice was $\theta_2 = 20^\circ$, and the angle of the backward orifice was $\theta_1 = 30^\circ$. The combination of the number of the forward and backward orifices was $F + B = 3 + 6$. Changing the diameters of the forward and backward orifices, multiple simulation models were established, as shown in Figure 14. Figure 15 shows the jet velocity distributions with different diameters of forward and backward orifices.

Here, we investigated the effects of the diameters of the forward and backward orifices on the self-propelled force, and the curves obtained for different ratios of $K = d_2/d_1$ are shown in Figure 16. As shown in the figure, the self-propelled force increases substantially as $K$ increases for the flow rate $Q_{in} < 60 \text{ L/min}$, but tends to slow down as the inlet flow rate increases for the flow rate $Q_{in} > 60 \text{ L/min}$, and finally tends to reach an equilibrium state. This phenomenon results from that the diameter of the forward orifice is too large to increase the jet pressure, and the diameter is too small, easily causing the blocking and the concentration of the jet pressure. Thus, to obtain satisfying self-propelled force, the diameter of the forward orifice should be larger than that of the backward orifice within a certain range, and there exists an optimal ratio $K$ for the best self-propelled force.

### 4.4 Diameter of the micro-hole

The angle of the forward and backward orifices mainly influences the diameter and shape of the radial micro-hole. In this...
simulation, it was assumed that the bottom confining pressure was \( P = 40 \) MPa, the diameter of the forward orifice was \( d_2 = 0.50 \) mm, the diameter of the backward orifice was \( d_1 = 0.70 \) mm, the number of the forward orifice is 3, and the number of the backward orifice was 6. The diameters of the micro-hole of multi-orifice nozzle were set as 25 mm, 30 mm, 35 mm, and 40 mm. Based on the parameters presented above, the models with different diameters of the micro-hole were established, as shown in Figure 17. Figure 18 shows the jet velocity distributions with different diameters of the micro-hole at different inlet flow rate. Figure 19 shows the self-propelled forces with different diameters of the micro-hole. It is obviously from Figure 19 that with the diameter of the micro-hole increasing, the self-propelled force reduces. Besides, the self-propelled force increases substantially as the inlet flow rate increases, but tends to slow down as the inlet flow rate further increases. This phenomenon can be explained by that a sufficient contact space gradually formed between the work fluid and the well as the diameter of the micro-hole increased, resulting in serious filtration.

5 | EXPERIMENT DESCRIPTION

Indoor experiment was conducted to verify the simulation results. We constructed a radial horizontal well at a depth of 2000 m, with the pump pressure of 40 MPa, and the displacement of 15-45 L/min. The work fluid was clean water, with a density of 1000 kg/m\(^3\) and a viscosity of 0.549 mPa s. The diameter of the wellbore was 139.7 mm, the inner diameter of the multi-orifice nozzle was 20.0 mm, and the outer diameter of the multi-orifice nozzle was 12.2 mm. The number of the forward orifice is 3 and the number of the backward orifice was 6. The diameter of the forward orifice was \( d_2 = 0.50 \) mm, and the diameter of the backward orifice was \( d_1 = 0.70 \) mm. The angle of the forward orifice was \( \theta_2 = 20^\circ \), and the angle of the backward orifice was \( \theta_1 = 30^\circ \). The working pipe string was the tubing with an outer diameter of 0.06 mm and the steering gear was put into the predetermined position.

In the experiment, the rule of the casing windowing was researched, and the time was recorded. The experiment of casing windowing was conducted with the multi-orifice nozzle under the condition of high-pressure jet in radial horizontal wells. The cement and water were mixed into a slurry according to a certain ratio, and then fixed on the periphery of the casing, with a thickness of 8 cm and a height of 10 cm. The cement was kept solidified for 24 hours before the drilling cement ring test. The experimental results of casing window-opening are shown in Figure 20. As can be observed, the multi-orifice nozzle relying on self-propelled force could drill through the casing completely. The opening with high construction quality was smooth and uniform, and the edges were free of burrs and bulges. The quality of these opening completely met the engineering requirements in field. Displacement is also one of the important factors affecting the casing window-opening. Increasing the displacement would increase the screw speed and shorten the window-opening time, but when the screw speed was too fast,
bit bouncing would easily occur and the screw life might be shortened.

Figure 21 shows the comparison of numerical simulation results \(F_{z-n}\), calculation results \(F_{z-c}\), and experiment results \(F_{z-e}\) of the self-propelled force. It is obvious that the difference between the three results of \(F_{z-n}\), \(F_{z-c}\), and \(F_{z-e}\) is very small, which proves that the numerical simulation method and the indoor experiment method are highly feasible.

6 | CONCLUSION

In this research, a 3D flow field simulation model was established to investigate the self-propelled force of a multi-orifice nozzle based on ANSYS-CFX. We investigated the effects of the angle, number, the diameter of the forward and backward orifices of the multi-orifice nozzle, and the diameter of the micro-hole in the radial well on the self-propelled ability by sensitivity analysis. The effectiveness of the proposed model was verified by theoretical analysis and field experiment. The conclusions of this research are summarized as follows:

1. The self-propelled force slight increases with the angle of forward orifice increase, and decreases with the angle of backward orifice increases. In addition, the self-propelled force and jet velocity have a tendency to increase substantially as the flow rate increases. To obtain large driving force from backward flow and a wide radial hole, the angle of the backward orifice cannot be too large when designing the multi-orifice nozzle.

2. The self-propelled force has a tendency to decrease significantly with the number of backward orifices increasing. This indicates that the larger the number of backward orifices, the larger the backward flow rate, and the larger the fluid driving force in rock breaking process. Comparison between the simulation results and calculation results of the self-propelled force at different combinations of forward and backward orifices shows that the simulation results agree well with the calculation results, with an average accuracy of 95.82%.

3. The self-propelled force increases substantially as the value of \(K\) increases for the flow rate \(Q_{in} < 60\) L/min, but tends to slow down as the inlet flow rate increases for the flow rate \(Q_{in} > 60\) L/min, and finally tends to reach an equilibrium state. This phenomenon can be explained by that the diameter of the forward orifices is too large to increase the jet pressure, and the diameter is too small, easily causing the blocking and the concentration of the jet pressure. Thus, to obtain satisfying self-propelled force, the diameter of the forward orifice should be larger than that of the backward orifice within a certain range, and also there exists an optimal value for the best self-propelled force.

4. With the diameter of the micro-hole increasing, the self-propelled force reduces. The self-propelled force increases substantially as the inlet flow rate increases, but tends to slow down as the inlet flow rate further increases. This phenomenon can be explained by that a sufficient contact space gradually forms between the work fluid and the well as the diameter of the micro-hole increases, resulting in serious filtration.

5. The difference between the three results of \(F_{z-n}\), \(F_{z-c}\), and \(F_{z-e}\) is very small, which proves that the numerical simulation method and the indoor experiment method are highly feasible. The experimental results of casing window-opening show that the multi-orifice nozzle relying on self-propelled force can drill through the casing completely. The opening with high construction quality is smooth and uniform, and the edges are free of burrs and bulges, which meets the engineering requirements in field.

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CONFLICT OF INTEREST

None declared.
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