Analysis of improving ways for dual nozzle negative pressure chip removal device in deep hole processing

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Abstract: In order to solve the problem of chip removal of the large-length-diameter ratios deep-hole machining, the negative pressure jet model is established on the basis of analysing the mechanism of DF system's negative pressure chip removal. To solve the energy loss caused by the eddy current phenomenon in the front separation zone, this paper adopts two-stage injection method. The pre-nozzle is added in the front separation zone so that part of the jet fluid enters the front separation zone through this nozzle, reducing unnecessary energy in the front separation zone and increasing the negative pressure value. Through theoretical analysis and fluent simulation optimization experiments, the paper proved that jet angle of the new jet nozzle is 33 degree and the clearance is 0.4mm has the best effect. The negative pressure zone is the largest, and the pressure value in the negative pressure zone is reduced by about 50.7%, which minimizes the energy loss in the front separation zone and enhances the negative pressure chip removal capability.

1.INTRODUCTION
In the mechanical manufacturing industry, the hole machining accounts for about 1/3 of the total machining. In terms of processing cost and workload, deep hole machining accounts for more than 40% of the hole machining[1].Chip removal is the key in all the problems of deep hole machining. There are three common ways to solve the problem of chip removal: (1) expanding the chip removal space; (2) controlling the chip shape; (3) enhancing the chip removal power[2]. The negative pressure chip removal system is a device designed to solve the problem of chip evacuation. It adopts the third way mentioned above to enhance the chip's chip power by the negative pressure generated by the suction effect[3].Guan Shixi and others have made a theoretical analysis of the structure and working principle of the existing DF deep hole drilling system[4].Zhao Liqin and others have studied the optimal design of the negative pressure system for deep hole processing[5].At present, there is no research on the energy loss caused by the swirl of the nozzle front. The structure of the existing negative pressure chip removal device is shown in Figure 1.

In this paper, after analyzing the structure and working principle of the existing deep hole machining negative pressure chip removal device, the method of reducing the energy loss of the front separation zone is put forward by putting a nozzle in the position of the front separation zone. Therefore, the unnecessary energy loss is reduced and the DF system's chip removal ability is enhanced[6].
2. INTRODUCTION
The current common technology is the DF internal chip system. The cutting fluid supplied by the oil pump is divided into two parts. The previous fluid is the Chip flow. It flows through the cutting edge, carries the Chip into the throat of the drill bit, enters the drill pipe through the drill cavity, and flows into the negative pressure device. The latter liquid flow is the main jet, which flows through the jet gap at the nozzle of the negative pressure device. Because the jet flow channel is narrow and the flow velocity and energy are high, the end of the drill rod will generate a negative pressure region. The area of negative pressure causes the Chip flow to be sucked in and mixed with the accelerated main jet, creating a shear action that increases the speed and energy of the Chip flow and accelerates the discharge of the chips.

In the existing deep-hole negative pressure chip evacuation device, the two-phase flow of the cutting fluid and the jet fluid exchange energy near the nozzle. At the nozzle, six zones consisting of a vacuum zone, front separation zone, rear separation area, jet zone, energy conversion zone, and mixed flow zone will be formed. The negative pressure jet model is shown in Figure 2.

1-Front Separation areas 2-Jet Zone 3-Rear separation area 4-Cutting fluid flow direction 5-The mixed flow area 6-Energy conversion zone 7-Vacuum Zone

Figure 2. Negative pressure jet model

(1) Separation areas - The junction of the outside of the jet area with the main chip evacuation channel. In the process of Jet zone fluid flow from the nozzle into the chip removal channel, the channel cross-section is dramatically enlarged, and the fluid and the solid wall surface are separated to form a separation zone. This zone has strong turbulence. The fluid will decrease in speed or even form a backflow by a great loss of energy;

(2) Jet Zone - Nozzle fluid Channel.

(3) The mixed flow area - the middle part of the rear chip removal channel. The two cutting fluids are fully mixed and the energy conversion is completed.

(4) Energy conversion zone - the intersection of the outside of the jet zone and the rear chip removal channel. The two-phase flow in this area performs energy conversion so that the fluid velocity in the main chip removal channel increases;

(5) Vacuum Zone - Cone streamer at the front of the nozzle. The negative pressure zone is formed by the fluid energy exchange between the jet and the main chip channel. The negative pressure in the negative pressure region plays a suction effect on the cutting fluid in the chip passage.

Figure 1. Schematic diagram of the existing negative pressure chip extraction device
Based on the above analysis, it can be seen that there is a front separation zone and a vacuum zone in the front of the jet nozzle. By reducing the energy loss in the pre-separation zone and increasing the suction capacity in the vacuum zone, this method has a positive effect on enhancing negative pressure chip removal. Therefore, it is proposed to increase the nozzle structure in the front separation zone. This structure reduces the energy loss by reducing the eddy current caused by the former separation zone through the imported jet oil\cite{8}. The newly designed dual nozzle annular structure vacuum device is shown in the figure 3.

![Figure3. Dual nozzle annular structure](image)

### 3. THEORETICAL ANALYSIS

We understand the mechanics principle of the negative pressure effect more conveniently by studying the cutting fluid between the cuttings of the cutting area and the negative pressure nozzle. Double nozzle negative pressure chip removal device model is shown in Figure 4.

![Figure4. Double nozzle negative pressure chip removal device model](image)

Theoretical analysis

The mathematical model of the negative pressure jet energy conversion can be expressed by the fluid dynamic momentum equation as\cite{9}:

\[
P_1 \cdot A_1 + P_2 \cdot A_2 \cdot \cos(K_1) + P_3 \cdot A_3 \cdot \cos(K_2) - P_4 \cdot A_4 - N = \rho \alpha_{04} \cdot Q_4 \cdot V_4 - \rho \cdot \alpha_{01} \cdot Q_1 \cdot V_1 - \rho \alpha_{02} \cdot Q_2 \cdot V_2 \cdot \cos(K_1) - \rho \cdot \alpha_{03} \cdot Q_3 \cdot V_3 \cdot \cos(K_2)
\]

(1)

In the formula: $P_1, P_2, P_3, P_4$ —average pressure value on the 1-1 section of the vacuum zone, 2-2 section of the front nozzle structure, 3-3 section of the original nozzle structure, 4-4 section of the mixed area, unit MP; $Q_1, Q_2, Q_3$ and $Q_4$ —flow over $A_1, A_2, A_3$ and $A_4$, unit liters per minute; $A_1, A_2, A_3$ and $A_4$ —Area of vacuum zone $A_1$, pre-nozzle structure $A_2$ section, original nozzle structure $A_3$ section and mixed zone $A_4$ section, unit is $m^2$; $V_1, V_2, V_3, V_4$ —the average velocity on the cross section of $A_1, A_2, A_3$ and $A_4$, unit m/s; $\rho$ —fluid density, unit $kg/m^3$; $K_1$ and $K_2$ respectively are the jet Angle of the front nozzle and the original nozzle structure, unit is the degree; $N$—force in the chip direction, which acts on the unit fluids in the $A_1, A_2, A_3$ and $A_4$ cross sections, unit is N; $\alpha_{01}, \alpha_{02}, \alpha_{03}$ and $\alpha_{04}$ —The momentum correction coefficients at sections $A_1, A_2, A_3$ and $A_4$. As the flow state is turbulent, take $\alpha_{01} = \alpha_{02} = \alpha_{03} = \alpha_{04} = 1$. 
From the mathematical model of the negative pressure jet region energy conversion, it can be seen that the main factors affecting the negative pressure effect under the conditions of the structure of the chip evacuation channel are the fluctuating channel flow volume $Q_1$, the upstream jet channel flow volume $Q_2$, and the jet annular channel flow volume $Q_3$, section of pre-nozzle $A_2$, section of original nozzle structure $A_3$, the negative pressure injection angle $K_1$, $K_2$ and the fluid properties.

The improvement measures proposed in this paper are based on the existing structure, so as to ensure that the original nozzles are unchanged, the discharge channel flow volume $Q_1$ is constant, and the total flow volume of negative pressure cavity is negative pressure unchanged. Considering the existing fuel tank structure, a nozzle passage is added at a position of 10 mm in front of a single annular jet passage into the main chip discharge passage. According to the above theoretical analysis, the flow volume $Q_2$, injection angle $K_1$, nozzle cross section $A_2$ and flow volume of the rear nozzle $Q_3$ will affect the negative pressure effect. Because of the linear relationship, the paper mainly studies the change of negative pressure and the optimal parameters of the front nozzle after adding the front nozzle.

4. SIMULATION OPTIMIZATION

4.1 Physical Model

The model of the negative pressure device is established in a small diameter DF deep hole drilling system with a diameter of 4 mm at the inlet and 4.5 mm at the outlet of the main channel. The main channel chip cutting fluid flow rate is 1.51L/min, that is, the flow rate is 2m/s. The inlet diameter of the negative pressure oil chamber is 0.6mm, and the inlet flow rate is 0.34L/min, that is, the flow rate is 5m/s. The negative pressure annular nozzle gap is 0.4mm, and the nozzle spray angle is 30 degrees. Without considering chip existence, fluent is used to carry out simulation test. The nozzle structure is arranged at the front 10 mm of the original annular jet nozzle. The structure shares the negative pressure oil with the original nozzle structure. The jet angle and clearance of the front nozzle may affect the negative pressure effect. Therefore, the structure of the front nozzle is optimized. The jet angle range is chosen from $25^\circ$ to $30^\circ$ and the gap range is chosen from 0.1 mm to 0.4 mm. The single variable method is used to simulate the nozzle. The simulation data of different size combinations are analyzed, as shown in Table 1.

| gap | Group number | Injection angle |
|-----|--------------|-----------------|
| 25  | (1)          | (2)             | (3) | (4) |
| 27  | (5)          | (6)             | (7) | (8) |
| 29  | (9)          | (10)            | (11)| (12)|
| 30  | (13)         | (14)            | (15)| (16)|
| 31  | (17)         | (18)            | (19)| (20)|
| 33  | (21)         | (22)            | (23)| (24)|
| 35  | (25)         | (26)            | (27)| (28)|

4.2 Calculation Method

(1) Model selection: adopt the pressure-based implicit solver, and select the standard k-ε turbulence model;

(2) Fluid material properties: the sulfide cutting fluid Sulfur-Liquid is adopted, the fluid density is 2000kg/m$^3$, the viscosity is $1.72\times10^3$kg/m·s;

(3) Wall condition selection: set to no-slip condition, the wall surface roughness maintains the default value of 0.5, and for all other scalars, impermeable wall conditions are chosen;

(4) Select the numerical calculation difference scheme:
The pressure interpolation keeps the default standard method; The SIMPLEC algorithm is selected by pressure - velocity coupling method, and Second Order Upwind Scheme is used for momentum, turbulent kinetic energy and turbulent dissipation rate.

(5) Relaxation factor setting: Set the stress item relaxation factor to 0.3, density\, quality item to 1, momentum item to 0.5, turbulent energy item to 0.5, turbulent dissipation rate item to 0.5, turbulent viscosity item to 0.5;

(6) Boundary conditions selection: the liquid inlet speed of the chip removal channel is 2m/s, The jet port velocity is 5m/s;

(7) Convergence criterion setting: set the difference between the continuous equations on the two sides represented by the difference equation is less than 0.0001.

### 4.3 Analysis of Simulation Results.

In this paper, by monitoring the three-dimensional model plane pressure cloud map, the symmetry axis and the negative pressure change curve, the existing structure and the negative pressure device of the front nozzle structure are compared and analyzed to determine the optimal solution.

As shown in Figure 5, original structure negative pressure device pressure distribution is shown. It is obvious that there is a negative pressure zone near the symmetry axis of the front part of the nozzle, and no negative pressure is formed at the front separation zone of the nozzle.

![Figure 5. original structure negative pressure device pressure distribution](image1)

As shown in Figure 6, original structure negative pressure device symmetrical axis pressure curve is shown. The negative pressure drops sharply at the nozzle (15mm position) to the mixed flow area (17.5mm position), and then gradually reaches the stable value, taking the pressure value P at 17.5 mm as a reference point, $P = -1771.6\text{pa}$.

![Figure 6. original structure negative pressure device symmetrical axis pressure curve](image2)

### 4.3.1 Pressure cloud comparison

As shown in Figure 7, double nozzle negative pressure device pressure distribution contrast is shown. It is observed from the diagram that the area of negative pressure area of the dual nozzle structure negative pressure device is obviously larger than that of the existing structure negative pressure device. The negative pressure area of the dual nozzle structure extends to both sides of the symmetrical axis and covers the occupied area.
Figure 7. Comparison of pressure distribution for double nozzle negative pressure device of the front separation area. Compared with the data in table 1, the negative pressure area of the front nozzle of group (24) can be observed to be the largest, the former separation area is the smallest, the effect is the best, the effect of group (4) and (27) take second place.
4.3.2 Comparison of Pressure Curves of Symmetrical Axis

Figure 8. Comparison of negative pressure variation of symmetric axis in double nozzles negative pressure device
As shown in Figure 8, double nozzle negative pressure device symmetrical axis pressure curve contrast is shown. Observing the changes in the pressure curve in Figure 8, the comparative analysis shows that the negative pressure effect at the symmetry axis of the double nozzle negative pressure device is more significant than the existing negative pressure device. From the nozzle (15mm position) to the mixed flow area (17.5mm position), the (24) group showed a greater decline.

By observing the pressure value at the 17.5mm position of the symmetrical axis (the stable negative pressure formed after the energy conversion is completed in the mixed flow region), the data of Table 2 can be obtained, and the minimum pressure value of group (24) can be obtained, $p_{24} = -2669\text{Pa}$

| Injection angle | Pressure gap |
|----------------|-------------|
| 25             | -1697.1     |
| 27             | -1877       |
| 29             | -1710.7     |
| 30             | -1775.7     |
| 31             | -1647.4     |
| 33             | -1745.2     |
| 35             | -1736       |
| 2              | -2457.7     |
|                | -1832.6     |
|                | -2564.4     |
|                | -1715.6     |
|                | -1814.9     |
|                | -2431.2     |
|                | -2376.5     |
| 3              | -1977.1     |
|                | -1940.6     |
|                | -1935.2     |
|                | -2027.6     |
|                | -2579.2     |
|                | -2525.1     |
|                | -2636       |
| 4              | -2668.8     |
|                | -2576.3     |
|                | -1985.6     |
|                | -2108.9     |
|                | -2161.1     |
|                | -2669       |
|                | -2152.9     |

5. CONCLUSION

1. In order to solve the problem of deep hole removal difficulty with large aspect ratio, based on the analysis of the original negative pressure jet model, the original negative pressure chip removal device was proposed to increase the new structure of the front nozzle. The new structure reduces the energy loss caused by the front separation zone, increases the volume occupied by the negative pressure zone, and enhances its negative pressure chip removal capability.

2. Through theoretical analysis, the main factors affecting the capacity of the new dual nozzle negative pressure device are the jet angle and clearance of the front nozzle.

3. The structure of the double nozzle was optimized by fluent simulation. When the jet angle of the front nozzle was 33 degree and the gap was 0.4mm, the effect was the best and the negative pressure area was the largest. The minimum negative pressure of the symmetrical axis at 17.5mm was - 2669Pa. On the basis of the existing structure, the negative pressure value was reduced by about 50.7%.

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