INTRODUCTION

Salvage operations account for a large proportion of oil well workover operations, which can reach two-thirds of the total workover operations. Salvage tools are the most widely and frequently used tools in the overhaul of oil and water wells.\(^1,2\) With the deepening of oilfield development, most of the oilfields have basically entered the middle and late stages of mining. As objects may fall and cases may deform during workover operation, the number of large oil and water wells to be repaired is increased year by year. However, suffering from the increased construction difficulty and long construction period, well treatment is confronted with ever-growing challenges. In severe cases, high operating cost could even cause oil and water wells to be scrapped. As for oilfield block in the middle and late stages of development, the washing fluid and clean water tend to cause loss of the formation due to insufficient formation pressure, and thus disabling some wells to establish washing circulation channel. Conventional well washing methods\(^5-7\) are prone to leave debris residue, and the washing medium is susceptible to freezing in winter. At present, most of the oilfields in China and abroad have developed a partial reverse circulation washing device for the loss of small pieces of lost oil. The design of such device adopted a reverse circulation slagging method to make the cuttings return along the central channel of the device,\(^8-10\) which is superior to the normal circulation slagging method in having a smaller consumption of the well washing medium. However, the debris residue left during the promotion and use of this type of washing device may cause stuck in the milling process, generating safety hazards in the construction operation.\(^11,12\) Besides, the partial reverse circulation washing device has a limited volume of sedimentation tubes. When objects fell at the bottom of the well are numerous, it is necessary to carry out multiple lifting operations in order to salvage the falling objects, whereas when operating in cold weather, the washing medium will freeze.
To address the above limitations, effort has been devoted to combining the artificial tornado principle\textsuperscript{13} with the introduction to air-washing technology using air as a well washing medium, which fundamentally solves the easy-to-freeze problem of the liquid washing medium in winter and reduces the cost of the well washing medium. According to the independently developed injector and cyclone reverse circulation continuous sampling technology of Jilin University, together with the use of double-walled drill pipe, the well washing gas can pass through the annulus between the double-walled drill pipes to reach the bottom. Therefore, the lack of resistance to circulation caused by a serious leak of the well is avoided. At the same time, the bottom debris from the bottom of the drill pipe to the ground have no volume limitation to the sedimentation pipe, so it can meet the requirements of site operation. Numerical simulation analysis of the flow field at the bottom of the device was carried out by using computational fluid dynamics (CFD) analysis software to verify the feasibility of the design. As a result, the structural parameters of the internal swirling orifice, which play a key role in the counter-circulation effect of the fisher, are determined.

2 \hspace{1em} {\textbf{STRUCTURAL DESIGN}}

The cyclone reverse circulation well washing device is designed on the basis of artificial tornado technology. According to the research on the induced mechanism of artificial tornado, the key to the formation of artificial tornado is to introduce a rising-induced swirl. Therefore, three internal swirling holes whose axes are at an angle of 45° to the bottom of the apparatus are provided inside the apparatus as the main structure for forming an artificial tornado during induction. In addition, three external injection holes are formed in the outer ring gap of the device at 45° to the central axis to increase the collection rate of the salvage debris. As shown in Figure 1, the structural diagram of the device model is depicted. When combined with the double wall drill pipe, the cyclone reverse circulation well washing device exhibits good performance in the salvage operation. The working principle is that the air enters the reduced diameter passage from the annular space between the inner and outer tubes of the double wall drill pipe and forms a high-speed jet through the reduced diameter passage. A part of the high-speed airflow flows through the outer orifice hole into the annulus between the well wall and the salvage, and the debris at the bottom of the hole bottom will be gathered to the center of the bottom of the hole. Another part of the high-speed airflow is jetted through the inner swirling orifice to the passage in the device, where it forms a rising vortex flow. The accumulated debris in this circumstance will be drawn into the chip evacuation passage and returned to the ground through the inner pipe of the double-walled drill\textsuperscript{14,15}

3 \hspace{1em} {\textbf{MODEL ESTABLISHMENT}}

As a CFD solver, Fluent\textsuperscript{16} can solve a variety of complex fluid calculation simulations. It cannot only apply to different solution methods but also capable of providing a multigrid method that accelerates the convergence speed. In the calculation process, it is difficult to obtain an exact solution of the equation by the numerical calculation method usually used. Discrete variables are therefore required to solve the approximate solution of the problem, and the discrete equations derived from the finite volume method have the advantages of both integral conservation and high computational efficiency. Hence, the finite volume method is used herein in the computational domain of discrete models. The discrete format means that when the finite volume method is used for discrete calculations, the discrete results can be obtained depending on the interpolation method used. Since the first-order upwind type is absolutely stable, the discrete precision can be improved. Considering the performance of the computer, the first-order upwind calculation is employed in the numerical simulation of the cyclone reverse circulation washing device flow field studied in this paper to calculate the spatial discrete calculation of the domain.

3.1 \hspace{1em} {\textbf{Mathematical model}}

3.1.1 \hspace{1em} {\textbf{Physical model}}

The hole diameter of the well is 120 mm, the outer diameter of the device is 114 mm, the diameter of the lower perforation...
is 6 mm, the angle between the inner and outer nozzle holes and the horizontal line of the bottom of the hole is 45°, and the gap of 5 mm height is set at the bottom of the hole for setting debris.

The internal flow field structure of the designed reverse circulation well washing device is more complicated. Structured grid and unstructured grid are combined in the grid division to improve the calculation accuracy and reduce the calculation cost. The meshing results in Figure 2 demonstrate the structural characteristics of the flow field model, the passage part and the outer annulus of the device connected with the inner and outer nozzle holes are drawn as unstructured meshes.

### 3.1.2 Control equation

The gas control equation includes continuity equation, momentum equation, and energy equation, and its general formula can be expressed as

\[
\frac{\partial (\rho \phi)}{\partial t} + \text{div} (\rho \mathbf{v} \phi) = \text{div} (\Gamma \cdot \text{grad} \phi) + S. \tag{1}
\]

In the formula \( \rho \) is the gas density, kg/m\(^3\); \( t \) is time, s; \( \phi \) is a general variable; \( \mathbf{v} \) is the solution variable; \( \Gamma \) is the general diffusion coefficient; and \( S \) is the generalized source term.

In the bottom hole flow field of the device, the solid debris particles are small in size and low in concentration, thus the interaction between solid debris particles is negligible.\(^{18} \)

The detritus particles are affected by various forces in the motion of the flow field, which are mainly divided into three categories. The first kind of force does not affect the relative motion of fluid and particle: gravity, pressure gradient force, inertia force, etc. The second one affects the relative motion of fluid and particle: resistance, nearby mass force, Basset force, etc. The last is the normal force perpendicular to the relative motion direction: Magnus force, Saffman lift force, etc. According to Newton’s second law, the particle motion equation of clastic particles in the Lagrange coordinate system can be defined as\(^{18} \)

\[
m_p \frac{d u_p}{d t} = F_D (u - u_p) + \frac{g_s (\rho_p - \rho)}{\rho_p} + F_x. \tag{2}
\]

In this formula \( M_p \) is the quality of cuttings. \( d u_p / d t \) is the debris acceleration. \( F_D (u - u_p) \) is the drag force of cuttings, \( F_D = 3 \mu C_p \rho u (g_p \bar{p}^2) \). \( C_p \) is the drag coefficient, \( \bar{p} \) is the Reynolds number. The \( u \) is the gas velocity, m/s. The \( u_p \) is cuttings speed, m/s. The \( g_s (\rho_p - \rho) / \rho_p \) is the debris gravity. The \( \rho_p \) is the density of the rock, kg/m\(^3\). The \( dp \) is the cuttings diameter, m; \( F_x \) is the other force of the cuttings.

### 3.1.3 Turbulence model

The standard k-\( \varepsilon \) model cannot handle strong vortices or flows with curved walls well. The RNG k-\( \varepsilon \) model not only corrects the Reynolds number but also accommodates the presence of swirl. Parameters that manifest the time-average strain rate are added to the dissipation rate equation to guarantee the accurate reflection of fluid flow offered by the generated items in the model and ensure higher precision. Because of the strong turbulent flow in the internal flow field when the liquid is washed underground, the RNG k-\( \varepsilon \) model is used for numerical simulation.

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \alpha_k \mu_{e\theta} \frac{\partial k}{\partial x_j} \right] + G_k + G_p - \rho \varepsilon \tag{3}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \alpha_\varepsilon \mu_{e\theta} \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} \left( C_{1\varepsilon} G_k - C_{1\varepsilon}^* \varepsilon \right) \tag{4}
\]

In the above equations: \( G_k = \mu_l \left( \frac{d u_i}{d x_j} + \frac{d u_j}{d x_i} \right) \frac{du_i}{d x_j} \); \( C_{1\varepsilon} = C_{1\varepsilon}^* \frac{1 - 1/\eta_0}{1 + \rho^\eta}; C_{2\varepsilon} = 1.42, \eta = (2E_j \cdot E_j)^{1/2} k / \varepsilon; \); \( C_{1\varepsilon}^* \) is 1.42, \( C_{2\varepsilon} = 1.68, \mu_{e\theta} = 1 + \mu \), \( \rho = 0.012, \eta_0 = 4.377, \eta = (2E_j \cdot E_j)^{1/2} k / \varepsilon, E_j \) is average strain rate.

### 3.2 Boundary condition setting

Two-phase fluid (gas phase and solid phase) is used in the simulation. The liquid phase material is ideal air with the density of 1.225 kg/m\(^3\) and the moving viscosity coefficient of 1.78 × 10\(^{-5}\) g/m/s The inlet boundary condition is set to mass flow, and the total gas mass flow rate is 0.12 kg/s. Therefore, the inlet flow rate of the three internal orifices is set to 0.02 kg/s after the exception of the spout. The exit
boundary is defined by setting the static pressure at the exit boundary.

Wall boundaries are used to define the flow regions of the gas phase and the solid phase. In this simulation, besides the two boundary conditions mentioned above, the remaining flow field surfaces are defined as wall boundaries. Under the no-slip wall condition, the standard wall method is used in the vicinity of the wall surface, and its expression is

\[
U^* = \frac{1}{k} \ln \left( E_y^* \right) \quad y^* > 11.225 \\
U^* = y^*^{1/12} \quad y^* \leq 11.225 \\
U^* = \frac{u_p \sqrt{k}}{\tau_w} \quad y^* = \frac{u_p y^{1/2}}{\mu}
\]

where \( k \) is the Von Karman constant, which is 0.42, \( E \) is the experimental constant as 9.81, \( k_p \) is the \( P \) point kinetic energy.

The solid phase particles enter the bottom flow field by means of a planar source, and the entered source surface is the bottom surface of the bottom spin hole. It is assumed that the cuttings entering the flow field are spherical inertial particles. The particle diameter is set to 0.01 m with the density ranging from 1200 to 2600 kg/m\(^3\). When the density reaches the highest level (2600 kg/m\(^3\)), it means the debris has completely covered the bottom of the device. The particle size satisfies the Rosin-Rammler particle size distribution function with an initial velocity of 0 m/s. The particles exhibit no rotation during the movement and there is no collision between the particles. The air is set as the main phase, and the solid phase particles are the secondary phase. We set the time step to 0.01 seconds. In the iterative calculation process, convergence is considered when the residual values of all physical variables are reduced to \( 10^{-3} \). In addition, we set the maximum number of iteration steps for each step to 15 steps. When the calculated value does not change greatly as the iteration progresses and gradually stabilizes, we also think that the calculation result also converges.

3.3 | Grid independence

The internal structure of the flow field at the bottom of the hole is complicated. In order to eliminate the effect of mesh on the numerical simulation results, grid independence must be verified.

According to different grid sizes, the flow field models at the bottom of the hole are divided into four different grid numbers: 580 000, 1 870 000, 2 380 000, and 5 460 000 and the numerical simulation results of each model are compared. Figure 3 shows the gas velocity on the axis in the flow field model. The distribution curve reveals that when the number of grids exceeds 238 000, the calculation results tend to be stable. As a result, the number of grids is chosen to be around 2,500,000 and the final accurate grid number is 2,358,981.

4 | NUMERICAL SIMULATION OF FLOW FIELD AT THE BOTTOM OF A HOLE

The movement trace of the solid phase particles is shown in Figure 4. As can be seen, the cleaning of the debris is mainly divided into three stages during the well washing process. The first stage is the debris accumulation (Figure 4A), in which, the outer ring gap and the external debris at the bottom of the hole are concentrated to the center of the bottom of the hole under the jet stream of the outer orifice. The airflow from the internal swirling orifice forms a rising spiral airflow in the chip evacuation passage and the accumulated debris is drawn to the ground. The second phase represents an unstable cleaning phase, as shown in Figure 4B. At this stage, the amount of debris in the center of the bottom of the hole is reduced. The airflow of the orifice begins to contact inside and outside, and the trajectory of the debris on the spoiler becomes irregular. However, as the time of contact prolongs, the ascending airflow formed by the airflow through the inner and outer orifices gradually becomes stable. The third phase is the residual debris cleaning phase, as illustrated in Figure 4C. At this stage, the amount of debris at the bottom of the hole is very small. The air flow mainly needs to clean the residual debris at the outer ring gap, and then the well washing operation is completed.

4.1 | Solid phase distribution

In the simulated well washing process, the well washing condition of the device is observed mainly through the distribution of the solid phase debris in the bottom flow field at different time periods. The solid phase distribution at different points in the device is shown in Figure 5. During washing, the bottom debris is firstly collected to the middle of the
bottom of the hole, and then the vortex formed by the internal swirl hole is pulled to the ground along the center of the device. The debris at the outer ring gap is carried by the external jet to the center of the bottom of the hole and then returned to the ground along the chip discharge passage through the internal swirl hole. Notably, there is no residual debris at the bottom of the well after well washing.

**4.2 Characteristics of gas phase turbulence**

From the schematic diagram of the longitudinal and lateral turbulent energy distribution in Figure 6, it is observed that in the early stage of the well washing operation, the turbulent energy of the outer orifice to the annulus position is much larger than the annulus position without the outer orifice. But in the later stage of the well washing, the turbulent energy of the above two annulus positions are basically at the same level. The airflow generated by the outer orifice will eventually form a stable upward flow field in the lower center of the rising vortex airflow. As the flow field rises to the internal swirl orifice, this portion of the airflow will flow into the rising vortex flow, creating a stable rising vortex.

**5 DISCUSSION**

Apparently, the analysis of the numerical simulation results indicate that the cyclone reverse circulation well washing device has no dead angle during cleaning and can fulfill the requirements of the well washing operation. The internal
swirling orifice acts as the core structure of the device, playing a crucial role in causing a rising vortex.

In order to improve the cleaning ability of the device, the structural parameters (helix angle $\theta$, aperture diameter $d$) of the inner swirl hole are optimized. Numerical simulations of different helix angles ($\theta = 30^\circ, 40^\circ, 50^\circ, 60^\circ$) and orifice diameters ($d = 2$ mm, 4 mm, 6 mm, 8 mm) were performed accordingly using Fluent software, as shown in Figure 7.

5.1 Discussion of cleaning effect under different orifice angles

As illustrated in the curve fitted by the numerical simulation results (Figure 8), the orifice angle has a great influence on the mass flow rate of the inlet and outlet interfaces. The mass flow rate at the inlet interface changes linearly with the orifice angle. As the angle of the orifice increases, the mass flow rate into the inlet boundary surface gradually decreases. When the inlet angle $\theta = 30^\circ$, the mass flow rate $Q$ is the highest and the device has the strongest suction capacity for the bottom debris. In such case, the reverse circulation effect is the best. The curve trend also demonstrates a sharp sudden drop as the orifice angle $\theta$ changes from $30^\circ$ to $40^\circ$ and relatively gentle decrease as the orifice angle further enlarges.

In order to reveal the influence of different orifice angles on the internal pressure of the device under the same orifice diameter, a path is established on the axis of each device model. Through analyzing the distribution of static pressure along the path, such influence relationship is understood.

It can be seen from Figure 9 that the distribution trend of static pressure on the axis of different orifice diameters $d$ is

![FIGURE 6](image6.png)  Longitudinal/transverse section turbulent kinetic energy distribution. (A) the turbulent kinetic energy distribution diagram with different longitudinal sections (B) dynamic energy distribution map with different transverse section

![FIGURE 7](image7.png)  Structural parameters of cyclone reverse circulation well washing device

![FIGURE 8](image8.png)  The curve of the mass flow $Q$ of the inlet interface with the angle $\theta$ of the orifice
basically same. Since the gas rises to the ground in the form of rising vortex airflow, the pressure at the top of the axis is low, and a good negative pressure region will be formed at the bottom of the device. The presence of such region causes the top of the bottom of the hole to be reversed. Under the same orifice diameter, the absolute value of the static pressure on the axis decreases significantly with the increase of the orifice angle. The larger the absolute value of the negative pressure, the more favorable the debris is, which possibly explains why the mass flow rate $Q$ of the overcurrent at the interface decreases as the orifice angle $\theta$ increases.

5.2 Discussion of cleaning effect under different orifice diameters

As shown in Figure 10, the mass flow rate $Q$ of the inlet interface is a function of the diameter $d$ of the orifice. We have known from Figure 9 the great influence of the diameter $d$ of the orifice on the mass flow $Q$. From the overall trend, the mass flow rate $Q$ of the four kinds of orifices changes with the diameter $d$ of the orifice, and the trend is parabolic. When the orifice diameter $d$ is about 4 mm, the mass flow rate reaches the maximum value, which proves that the strongest suction capacity of the device is at the bottom of the hole.

Since changes in the gas velocity field is small when $\theta = 40^\circ$, $50^\circ$, and $60^\circ$, the discussion herein revolves around $\theta = 30^\circ$.

The gas velocity field cloud diagram for different apertures $d$ is shown in Figure 11. When $d = 4$ mm, the gas phase velocity value at the bottom of the device is significantly larger than $d = 2$ mm, 6 mm, and 8 mm, which proves that the device has the strongest suction ability to the bottom flow. Interestingly, when $d = 2$ and 6 mm, the gas velocity field at the bottom of the hole is relatively close, which is also greater than the airflow velocity at the bottom of the hole when $d = 8$ mm.

5.3 Conclusion analysis

The gas mass flow rate $Q$ passing through the lower surface of the chip discharge passage is used as an evaluation index of the salvage capacity of the device. The variation law of
the mass flow rate in different models is fitted as depicted in Figure 12. As shown, the mass flow rate through the lower surface of the chip discharge passage decreases with the increase of the helix angle of the inner swirling orifice. When the orifice angle is constant and the diameter of the inner swirling orifice is 4 mm, the mass flow rate through the lower surface of the chip discharge passage is the largest. When the orifice angle is 30° and the orifice diameter is 4 mm, the mass flow rate of the gas reaches the maximum value. It is the most ideal combination of structural parameters of the device to yield the strongest reverse circulation capability.

The cleaning efficiency of the two devices under different cuttings conditions is shown in Figure 14. During the well washing process, the partial reverse circulation well washing device has low cleaning efficiency of the five kinds of cuttings (<80%). As the particle diameter increases, the cleaning efficiency gradually decreases. The cleaning efficiency for 60 mm cuttings is only 68.2%. However, cyclone reverse circulation well washing device has better cleaning ability. The cleaning efficiency for each particle cuttings is higher than 95%, which is also less affected by the variation of the cuttings particle size.

7 | CONCLUSION

During the well washing process, the airflow jetted from the outer orifice of the cyclone reverse circulation well washing device is responsible for collecting the debris at the outer ring gap and the outer periphery of the hole bottom, and the airflow injected by the inner swirling orifice forms a rising vortex airflow to return the debris to the ground. Under the joint action of the inner and outer orifice, the device shows no dead angle for cleaning the bottom debris, which addresses the problem of debris leftover during the use of the salvage device, eliminates the occurrence of grinding and milling.
and can effectively improve the safety operation level of the salvage operation.

By simulating the models of multiple sets of different inner swirling orifice diameters and angles, the relationship between the salvage capacity of the cyclone reverse circulation well washing device and the structural parameters of the device was clarified. As the angle of the orifice increases, the mass flow through the lower surface of the chip evacuation passage gradually decreases. When \( d = 4 \text{ mm}, \theta = 30^\circ \), the gas mass flow rate is the highest and the device has the strongest salvage ability.

The design of the cyclone reverse circulation well washing device introduces artificial tornado technology and is used together with the double-walled drill pipe to effectively solve the unsatisfactory washing effect caused by leakage. Compared with the local reverse circulation well washing device, it is found that the use of air as the well washing medium greatly reduces the well washing cost, solves the easy-to-freeze problem of the washing medium in winter, and ensures safe and effective operation of the well washing operation. The cyclone type reverse circulation well washing device is easy to clean, low in cost, and continuous in operation, which can deliver better economic benefits to oilfield development.

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