

Article

Research on the Process Parameters and Mechanism of Long-Slit Sealing Failure Plugging of Blowout Preventer Based on CFD-DEM

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Abstract

In the process of oil and gas drilling, the blowout preventer (BOP) serves as the last line of defense before wellhead loss of control, and its sealing reliability is of critical importance. However, under the erosion of high-pressure sand-containing fluids, the sealing components of the BOP are prone to failure, resulting in long-slit-type leakage ports, which seriously threaten well control safety. In response to the current lack of theoretical guidance for emergency plugging process parameters, this paper adopts the coupled computational fluid dynamics and discrete element method (CFD-DEM) to establish a numerical model for the plugging of long-slit-type gaps with particles under blowout conditions. The migration and bridging plugging behaviors of three typical shaped particles, namely spherical, cylindrical, and square, under different sizes, concentrations, and pump injection rates are systematically studied. The results indicate that particle transport within the wellbore can be divided into an initial transport stage dominated by jet diffusion and a plugging-structure formation stage dominated by bridging and particle accumulation. When the particle size exceeds the slit width, cylindrical particles exhibit comparatively better plugging performance under the conditions considered in this study. For a long-slit leakage channel with a width of 5 mm, the combination of cylindrical particles with an equivalent diameter of 6 mm, a particle volume concentration of 20%, and a pumping rate of 2.4 m³/min demonstrated relatively favorable overall plugging performance. The particle concentration mainly affects the bridging time, and the bridging time tends to stabilize when the concentration reaches 20%. The higher the pump injection rate, the earlier the particles reach the gap opening, but it has little impact on the final plugging effect. This study provides a scientific basis for the optimization of emergency plugging process parameters after BOP sealing failure, filling the gap in the research on the plugging mechanism of equipment leakage under blowout conditions.



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Keywords: long-slit leakage; particle plugging; CFD-DEM coupling; process parameter optimization

1. Introduction

In oil and gas drilling and production operations, well-control safety is directly related to the safety of personnel, environmental protection, and property security [1]. As the final barrier against loss of well control, the sealing reliability of the blowout preventer (BOP) stack defines the operational safety boundary of drilling activities [2]. With the continuous expansion of oil and gas exploration toward unconventional reservoirs, difficult-to-produce reserves, and ultra-deep wells, well-control risks have become increasingly significant [3].

However, under extreme blowout conditions, the erosive effect of high-velocity sand-laden fluid inside the well on the sealing elements can cause severe damage and lead to the formation of long-slit leakage channels. Once such leakage occurs, the risk of catastrophic incidents such as loss of well control, fire, and explosion will escalate sharply if timely and effective remedial measures are not taken [4]. As shown in Figure 1, during drilling operations, CNPC recorded 48 annular well blowout incidents, of which 26 were attributed to blowout preventer (BOP) failures [5,6]. Therefore, developing an emergency process capable of rapidly and effectively plugging the failed sealing sections of the BOP stack under blowout conditions is of significant practical value in engineering.



Figure 1. Blowout scene.

Reference [7] indicates that the morphology and dimensions of leakage channels generated by BOP sealing failures constitute the primary basis for selecting plugging materials and designing plugging process parameters. Based on field observations and measurements, BOP sealing failures can generally be classified into three representative types: square-hole leakage, long-slit leakage, and small-hole leakage. Among these, failures of the ram top seals and blade seals occur with relatively high frequency, and the long-slit leakage channels formed thereby account for approximately 50% of failure cases; the slit width typically ranges from 1 to 10 mm, while the length can reach tens of millimeters. As shown in Figure 2, once such a failure occurs, the BOP will be rapidly and completely washed out by high-pressure fluid erosion, leading to the total loss of wellhead sealing integrity. Therefore, research on plugging long-slit channels possesses outstanding urgency and representativeness.

At present, only a limited number of studies have proposed the use of hemp-fiber-based temporary plugging technology for wellhead sealing applications [8]. However, this approach is not suitable for the complex conditions encountered during blowout events. For emergency response following BOP seal leakage, field technicians have attempted to connect a plugging manifold to the side of the kill manifold and pump plugging materials to the leakage port, thereby temporarily restoring wellhead sealing and creating stabilized pressure conditions for subsequent well killing operations [9]. As shown in Figure 3, the feasibility of this process has been preliminarily verified through the emergency rescue practice at a BZ well and the experimental study on emergency plugging of ultra-high-pressure, high-flow-rate BOP sealing failures conducted by Jing and Zou et al. [10]. However, key process parameters—such as pumping rate, particle concentration, particle shape, and particle size—still largely rely on the empirical judgment of emergency response personnel, lacking systematic theoretical guidance and a scientific basis for parameter optimization. This deficiency severely constrains the reliability and universality of the process under emergency conditions.



Figure 2. Ram seal failure location.

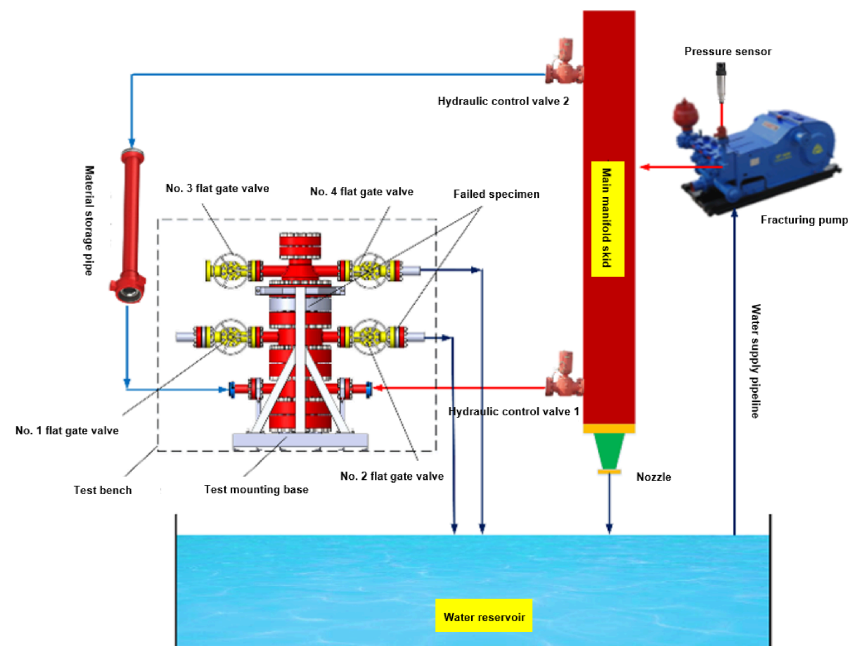


Figure 3. Plugging process flow.

Although particle plugging technology has been extensively investigated in the context of formation lost circulation control, its research background differs fundamentally from leakage scenarios involving wellhead equipment. Considerable efforts have been devoted to the plugging of subsurface fractures: Jie Ren et al. [11] developed a highly elastic honeycomb porous plugging material that can remain well suspended in low-density drilling fluids. Shaofei Lei et al. [12] developed a novel temperature-responsive adhesive plugging material composed of bridging and adhesive loss-circulation materials (LCMs). Wang et al. [13] employed the discrete element method to study the effects of particle shape, size, and concentration on the location and timing of fracture plugging; Feng et al. [14] used a CFD-DEM coupling approach to reveal the patterns of particle migration and plugging zone distribution in rough fractures; Li et al. [15] further analyzed the influence of Young's

modulus, particle size distribution, and friction coefficient on fracture bridging capacity; Lin Chong et al. [16] adopted a CFD-DEM coupling method to simulate particle plugging in propagating fractures and examined the effects of positive pressure differential, particle concentration, and particle shape on plugging mechanisms; and Zhu Baiyu et al. [17] applied CFD-DEM numerical simulation to analyze the impact of vugs on particle bridging mechanisms in fracture-vuggy reservoirs. These studies have laid an important foundation for understanding particle plugging behavior in confined spaces. However, their research objects are exclusively downhole formation fractures, rather than the long-slit leakage ports of wellhead equipment under blowout conditions. The latter involves a significantly higher pressure differential (up to 70 MPa), a more complex flow field structure, and a unique transport path in which particles enter through a lateral bypass pipe. Consequently, existing findings cannot directly guide the design of the plugging process for such scenarios.

Based on the above analysis, this study focuses on the emergency plugging of long-slit leakage ports in blowout preventers (BOPs) under blowout conditions, aiming to elucidate the particle bridging and plugging mechanisms within long-slit channels. A numerical model for particle plugging in long-slit channels is established under realistic high-pressure and high-flow-rate blowout boundary conditions using a coupled computational fluid dynamics and discrete element method (CFD-DEM). By systematically investigating the transport and bridging processes of particles with three typical shapes—spherical, cylindrical, and cubic—the effects of particle size, concentration, and pumping rate on plugging efficiency and dynamic behavior are quantitatively analyzed, the differences in plugging mechanisms among different particle shapes are revealed, and an optimal combination of particle characteristics and process parameters for long-slit channel plugging is identified. The findings are intended to provide a theoretical basis for the design and parameter optimization of emergency plugging processes for BOP sealing failures, thereby filling the research gap concerning the plugging mechanisms of long-slit equipment leakages under blowout conditions.

2. Numerical Model and Methods

2.1. Governing Equations

2.1.1. Governing Equations for the Fluid Phase

In the CFD-DEM coupled computation, the fluid is treated as a continuous phase, and its flow is governed by the Navier–Stokes equations. The governing equations are expressed as follows [18]:

Continuity equation:

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \nabla \cdot (\alpha_f \rho_f u) = 0 \quad (1)$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}(\alpha_f \rho_f u) + \nabla \cdot (\alpha_f \rho_f u u) = -\alpha_f \nabla p + \nabla \cdot (\alpha_f \tau_f) + \alpha_f \rho_f g + F_{p \rightarrow f} \quad (2)$$

where α_f is the liquid density, kg/m³, ρ_f is the liquid volume fraction, %, u is the liquid velocity, m/s, p is the pressure, pa, g is the gravitational acceleration, m/s², $F_{p \rightarrow f}$ is the fluid–particle interaction force, and τ_f is the viscous stress tensor of the liquid phase.

2.1.2. Governing Equations for the Particle Phase

During the pumping and plugging process, particles typically exhibit both translational and rotational motion, which is governed by the surrounding fluid and neighboring particles. In the CFD-DEM coupling framework, the discrete element method (DEM) in the Lagrangian coordinate system is employed to solve for the particle phase. The particle

velocities and positions are obtained by calculating the external forces acting on the particles. Since particle motion obeys Newton's second law, the governing equations can be divided into translational and rotational equations [19].

$$m_p \frac{dv_p}{dt} = F_c + F_{f \rightarrow p} + m_p g \quad (3)$$

$$J_p \frac{dw_p}{dt} = M_c + M_{f \rightarrow p} \quad (4)$$

where m_p is the particle mass, kg, v_p is the particle linear velocity, m/s, F_c is the contact force between particles, N, $F_{f \rightarrow p}$ is the additional fluid–particle interaction force, including the pressure gradient force and the fluid drag force, J_p is the particle moment of inertia kg·m², w_p is the particle angular velocity, rad/s, M_c is the contact torque between particles, N·m, and $M_{f \rightarrow p}$ is the torque exerted on the particle by the fluid velocity gradient, N·m.

2.2. Interaction Forces

2.2.1. Fluid–Particle Interaction Forces

In solid–liquid two-phase flow, particles are subjected to various fluid forces, including the drag force, lift force, pressure gradient force, added mass force, Saffman force, Basset force, and Magnus force [20]. In this study, forces with relatively minor contributions are neglected, and only the drag force, lift force, and pressure gradient force are considered. Accordingly, the fluid–particle interaction forces are expressed as follows [21]:

$$F_{f \rightarrow p} = F_D + F_{\nabla P} + F_L \quad (5)$$

$$F_{\nabla P} = -V_p \nabla P \quad (6)$$

$$F_L = C_L \rho_f V_p u^{rel} \times (\nabla \times u) \quad (7)$$

$$F_D = \frac{1}{2} C_D \rho_f A' |u - v_p| (u - v_p) \quad (8)$$

where F_D is the drag force, N, $F_{\nabla P}$ is the pressure gradient force, N, F_L is the lift force, N, C_L is the lift coefficient, u^{rel} is the relative velocity between the particle and the fluid, and C_D is the drag coefficient.

2.2.2. Particle–Particle Interaction Forces

Due to the continuous collisions between particles and the pipe wall, the particle trajectories exhibit significant uncertainty. To faithfully reproduce this complex motion behavior, the Hertz–Mindlin no-slip contact model is employed in this study to accurately calculate the particle–particle and particle–wall contact forces. This model effectively simulates particle collision behavior through the combined action of springs, dampers, and sliders [22].

Normal force model:

$$F_n = \hat{K}_H s_n^{\frac{3}{2}} + \hat{C}_H s_n^{\frac{1}{4}} \dot{s}_n \quad (9)$$

Tangential force model:

$$F_\tau = -\mu F_n (1 - \varsigma^{\frac{3}{2}}) \frac{s_\tau}{|s_\tau|} + \eta_\tau \sqrt{\frac{6\mu m^* F_n}{s_{\tau, \max}}} \varsigma^{\frac{1}{4}} \dot{s}_\tau \quad (10)$$

where F_n is the normal contact force, $\hat{K}_H$ is the stiffness coefficient, s_n is the normal overlap, $\dot{s}_n$ is the time derivative of the normal overlap, $\hat{C}_H$ is the damping coefficient, μ is the friction coefficient, $s_{\tau, \max}$ is the maximum relative tangential displacement at which

particle sliding begins, $\dot{s}_\tau$ is the tangential component of the relative velocity at the contact point, and m^* is the equivalent particle mass.

2.3. Model Construction

As shown in Figure 4, referring to the large-scale BOP plugging test system established a fluid domain geometric model for the numerical particle plugging model was developed based on the actual structural dimensions of its full-scale conveying pipeline, test chamber, and failed specimen. As shown in Figure 5, this geometric model primarily consists of two parts: a pump-injection pipeline section and a simulated wellbore section. The pump-injection pipeline is divided into three segments: the first segment is the material storage pipe section, with a diameter of 130 mm and a length of 2500 mm; the second segment is the reducer section, with a length of 459 mm, a large-end diameter of 130 mm, and a small-end diameter of 78 mm; the third segment is the flexible elbow section, with a diameter of 78 mm, a bend radius of 156 mm, and an outlet end length of 399 mm. The simulated wellbore section has a diameter of 350 mm, and the bypass pipe has a diameter of 78 mm.

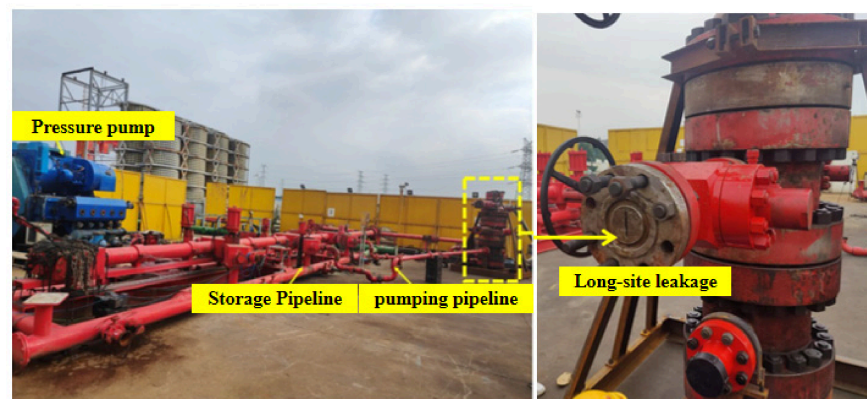


Figure 4. Field experiment.

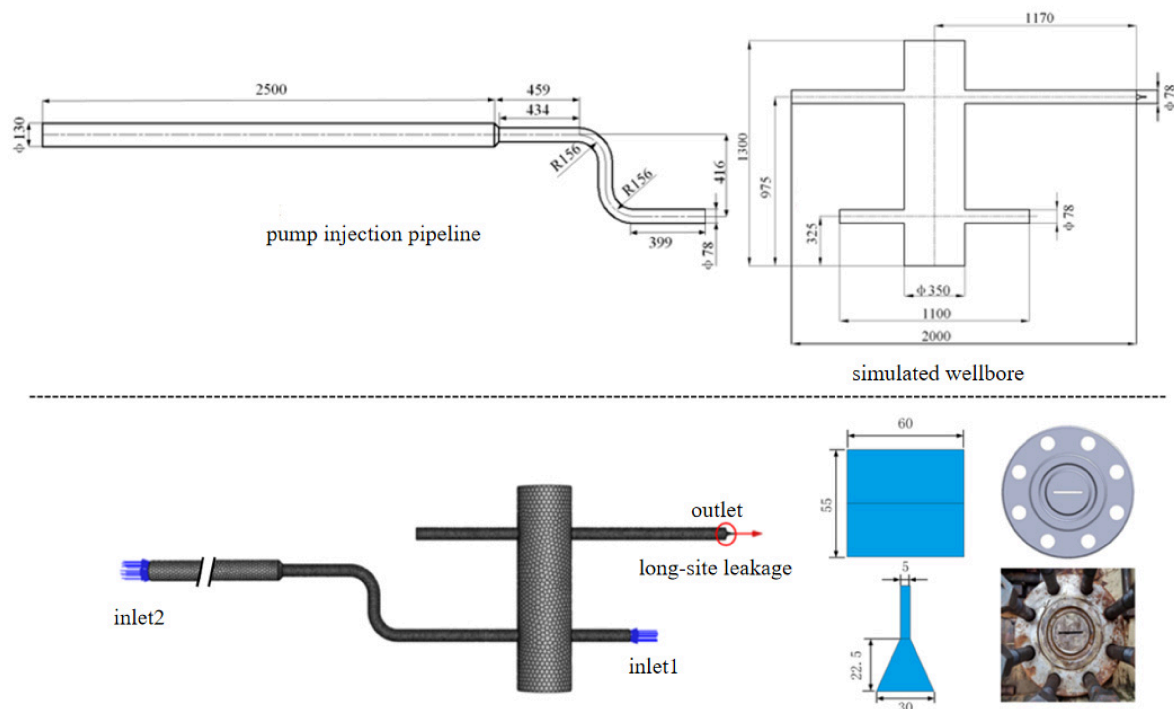


Figure 5. Geometric model.

2.4. Boundary Conditions and Parameter Settings

The present study adopted polyether ether ketone (PEEK), which was used as the plugging material in the previous emergency plugging experiments. To ensure consistency between the numerical simulations and the physical experiments, the same material properties were employed. From an engineering perspective, spherical, cylindrical, and cubic particles can respectively represent commonly used granular plugging materials, cut cylindrical particles, and angular crushed particles encountered in field applications. Therefore, the simulation results possess a certain degree of engineering relevance.

In the model, Inlet1 serves as the simulated blowout inlet. To replicate the maximum wellhead pressure of 70 MPa after shut-in, this inlet is set as a pressure inlet with a specified pressure of 70 MPa. Inlet2 represents the inlet for pumping plugging materials, where the fracturing pump operates at a constant flow rate. Since the maximum flow rate of the fracturing pump at 70 MPa is $2.4 \text{ m}^3/\text{min}$, this inlet is configured as a velocity inlet with a maximum velocity of 3 m/s. The slit outlet is connected to the atmosphere and is therefore set as a pressure outlet with a pressure of 0 MPa. The boundary condition settings under the test conditions are shown in Figure 4.

2.5. Model Validation

To effectively validate the accuracy of the model, reference is made to the earlier full-scale physical experiment on long-slit leakage in a BOP under ultra-high pressure and high flow rate conducted by Jing and Zou. The pressure curves obtained from the blank test (without plugging material) and the plugging simulation test of the long-slit channel are presented in Figures 6a and 6b, respectively. During the system pressure test at a flow rate of $1.69 \text{ m}^3/\text{min}$, the chamber pressure of the test apparatus in the blank test could only reach approximately 5.5 MPa. In contrast, during the plugging simulation test for the long-slit channel, the pressure rapidly increased to 70 MPa once the fracturing pump was started and was maintained for 10 min. These experimental results demonstrate that the plugging material can be transported by the fluid to the long-slit opening, effectively plugging the channel, and withstand a pressure of 70 MPa after plugging.

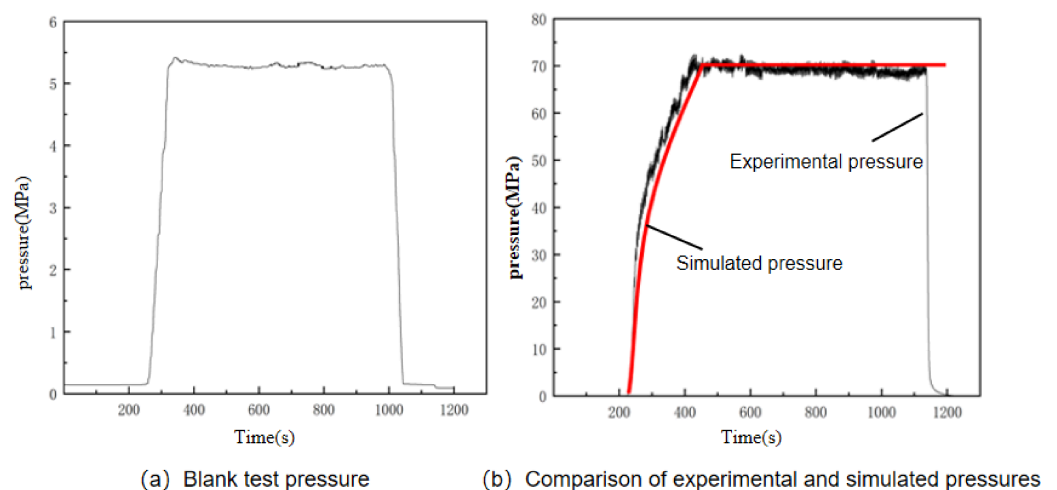


Figure 6. Experiment vs. simulation.

Under the same operating conditions as those used in the physical experiments, the numerical plugging model developed in this study successfully achieved a stable plugging pressure of 70 MPa, with a maximum relative error of 3.2% compared with the experimental results. This error was calculated based on the stabilized pressure stage after completion of the plugging process. The primary purpose of the validation was to assess the accuracy

of the model in predicting the system pressure response after a stable plugging structure had been formed. Owing to current experimental limitations, real-time measurements of particle bridging structures and particle distributions inside the long slit are not yet available. Therefore, the particle transport and bridging evolution processes were mainly investigated through numerical simulations.

3. Results and Discussion

3.1. Analysis of Particle Transport Process

Based on the earlier findings of Jing and Chen [23] on the flow behavior of plugging particles in the pump-injection pipeline, this study analyzes the transport process of plugging material particles in the simulated wellbore under long-slit test conditions within the parameter range that allows particles to flow through the pump-injection pipeline smoothly (see Table 1). Under the long-slit test conditions, the transport process of plugging material particles in the simulated wellbore can be divided into an initial transport stage dominated by jet diffusion and a plugging structure formation stage dominated by bridging and accumulation.

Table 1. Simulation parameters.

Object	Parameter	Value	Unit
Fluid	Density	998.2	$\text{kg}\cdot\text{m}^{-3}$
	Viscosity	1	$\text{mPa}\cdot\text{s}$
	Pressure inlet	70	MPa
	Velocity inlet	1.2, 1.6, 2.0, 2.4	$\text{m}^3\cdot\text{min}^{-1}$
	Pressure outlet	0	MPa
Particle	Shape	Spherical, cylindrical, cubic	-
	Equivalent diameter	6, 7, 8	mm
	Density	1300	$\text{kg}\cdot\text{m}^{-3}$
	Young's modulus	3.8	Gpa
	Wall Young's modulus	21.4	Gpa
	Particle–particle restitution coefficient	0.775	-
	Particle–particle friction coefficient	0.3	-
	Particle–wall friction coefficient	0.4	-

As shown in Figure 7, in the initial transport stage dominated by jet diffusion, when the high-velocity jet carrying plugging particles is injected into the simulated wellbore from the pump-injection pipeline, the jet rapidly diffuses and its momentum attenuates due to the sudden expansion of the flow cross-section. During this stage, particles are primarily driven by the fluid drag force, and their trajectories are highly dependent on the local streamline distribution. However, the simulated blowout inlet continuously supplies a significantly larger main flow rate, and the strong shearing action of the main flow near the outlet forces the pump-injected particles to deviate from their original linear trajectory, rapidly diverting and dispersing them toward the bottom region of the wellbore. Consequently, particle transport is dominated by momentum exchange, and the spatial distribution exhibits strong non-uniformity. At this stage, a large number of particles have not yet entered the effective plugging zone and begin to disperse near the inlet of the pump-injection pipeline.

As shown in Figure 8, after particles enter the wellbore, the impingement of the simulated blowout jet and the pump-injection jet creates a large-scale vortex structure at the bottom of the wellbore. The majority of particles are entrained into this bottom vortex. Since the mechanical properties of all particles are identical, whether an individual particle can escape from the vortex and enter the bypass pipe depends on its initial entry position

and stochastic collisions with the wall. Consequently, the trajectory of a single particle exhibits a certain degree of randomness. However, the collective transport behavior of a large number of particles remains relatively stable. Therefore, comparisons among different operating conditions primarily reflect the characteristics of particle-group behavior rather than the random motion of individual particles. Once inside, the high flow velocity within the bypass pipe rapidly transports the particles toward the slit opening.

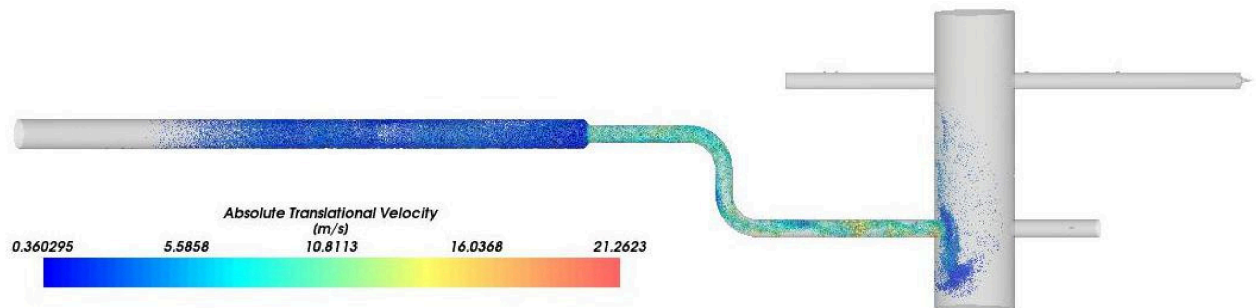


Figure 7. Particle pumping-in stage.

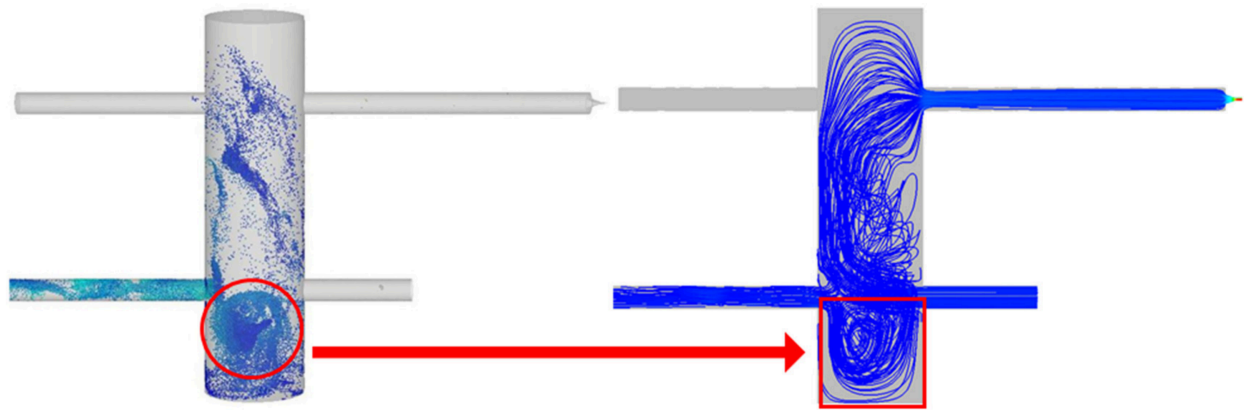


Figure 8. Particle accumulation at the bottom of the apparatus.

As shown in Figure 9, during the plugging structure formation stage dominated by bridging and accumulation, when particles are released from the vortex zone and transported by the high-velocity fluid in the bypass pipe to the slit opening, the bridging stage begins. Depending on the relationship between particle size and slit width, two typical dynamic behaviors emerge: as shown in Figure 9a, a single particle cannot bridge independently, requiring multiple particles to cooperatively form a force chain structure at the slit opening. This process is accompanied by frequent cycles of bridging, destabilization, and reconstruction; as shown in Figure 9b, a single particle can be directly trapped at the slit opening, forming an instantaneous bridge. Because its size exceeds the slit width, the fluid drag force cannot dislodge it, and the bridging structure exhibits greater stability.

Ultimately, as shown in Figure 10, once the slit is effectively plugged, the flow velocity within the bypass pipe drops sharply. Subsequent particles no longer participate in bridging but instead settle or accumulate under the influence of gravity and the residual vortex, forming a secondary stable structure that further consolidates the plugging effect.

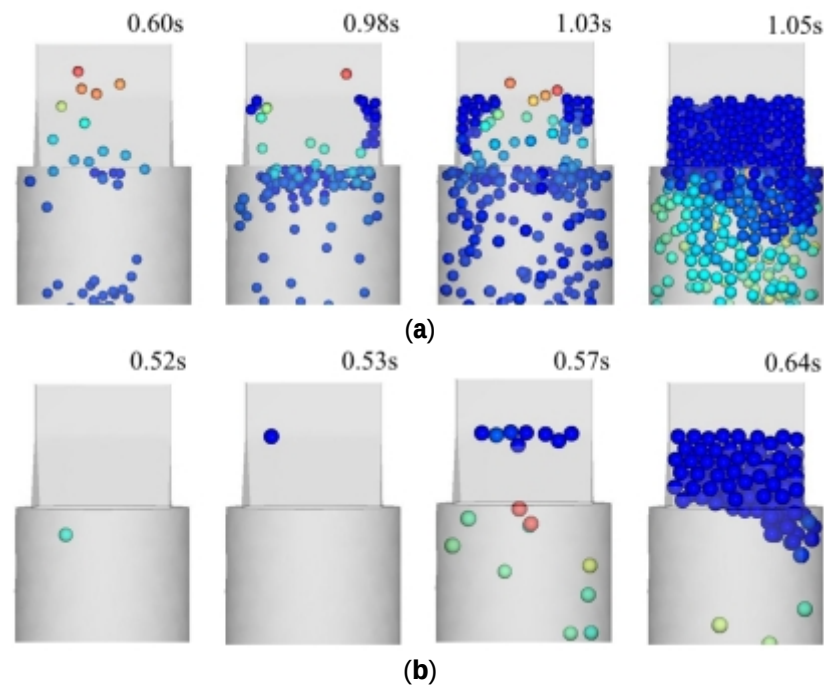


Figure 9. (a) Process of plugging and filling the slit with small spherical particles (5 mm). (b) Process of plugging and filling the slit with large spherical particles (7 mm).

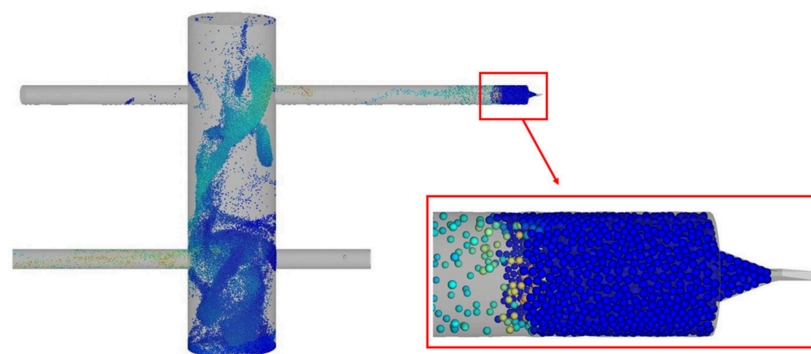


Figure 10. Particle accumulation.

In summary, under the long-slit test conditions, after entering the simulated wellbore, the plugging bridging particles undergo four distinct stages—particle injection, particle dispersion, particle bridging, and particle accumulation—and are ultimately transported by the fluid to the leakage port, successfully plugging the long slit. This demonstrates the feasibility of the plugging process for sealing long-slit channels.

3.2. Effects of Particle Shape and Size on Plugging Performance

Previous investigations revealed that at a particle volume concentration of 15% and particle sizes below 15 mm, spherical, cylindrical, and cubic particles could all be smoothly pumped into the chamber of the test apparatus. Accordingly, particles with a volume concentration of 15% and sizes below 15 mm were selected to study the plugging effectiveness of different shapes and sizes on the long-slit channel at a pumping rate of $2.4 \text{ m}^3/\text{min}$. The leakage rate curves for spherical, cylindrical, and cubic particles with equivalent diameters of 5 mm, 6 mm, and 7 mm are presented in Figure 11a–c.

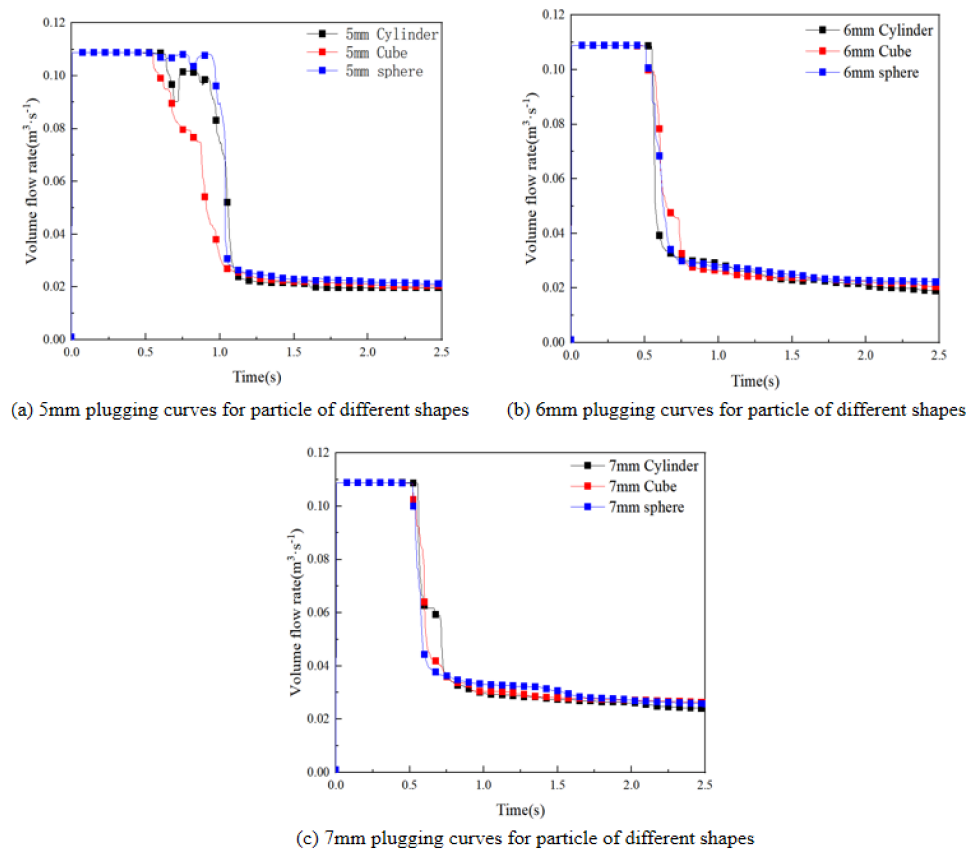


Figure 11. Leakage rate curves during particle plugging.

When the particle equivalent diameter was 5 mm, during the early stage of bridging, all three particle shapes exhibited particle expulsion from the slit because relatively few particles had diffused to the slit opening, and the particle distribution was relatively sparse. As time progressed, more particles were transported to the slit opening, and a stable bridging structure was formed at the slit opening through mutual compaction among multiple particles, leading to a rapid decline in the flow rate. During the bridging process, owing to their smooth and rounded surfaces, the cylindrical and spherical particles tended to form bridging structures less readily, resulting in substantial flow rate fluctuations. In contrast, the cubic particles, characterized by sharp edges, were capable of forming multiple support points against the slit walls, and their diagonal dimension exceeded the slit width. Consequently, cubic particles formed bridging structures more easily, as illustrated in Figure 12.

When the particle equivalent diameter exceeded 5 mm, the sizes of all three particle shapes were larger than the slit width; consequently, no particle expulsion was observed during the bridging process, and all shapes rapidly formed a stable bridging structure, leading to a prompt reduction in the flow rate through the slit. In terms of plugging effectiveness, the cylindrical particles slightly outperformed both the cubic and spherical particles.

In summary, when the cylindrical particle size exceeds the slit width, cylindrical particles, like cubic and spherical particles, can achieve rapid bridging; however, their plugging effectiveness is marginally better. Considering both bridging efficiency and plugging effectiveness, cylindrical particles are recommended for plugging a 5 mm wide long slit.

The influence of cylindrical particle size on plugging effectiveness is shown in Figure 13. A smaller equivalent diameter of the cylindrical particles results in smaller interstitial voids within the packed slit, thereby yielding better plugging effectiveness.

However, when the particle equivalent diameter equals 5 mm, bridging is difficult to form and requires a longer bridging time. When the equivalent diameter exceeds 6 mm, the mass of individual particles increases, leading to a reduction in the number of particles in the wellbore. After a small number of particles plug the slit and reduce the flow rate, the fluid velocity in the wellbore decreases, which in turn reduces the fluid's particle-carrying capacity and consequently prolongs the bridging time. At an equivalent diameter of 6 mm, the fluid can transport a sufficient number of particles to the slit to achieve rapid plugging. Therefore, for plugging a long slit of 5 mm width, cylindrical particles with an equivalent diameter of 6 mm should be adopted whenever possible.

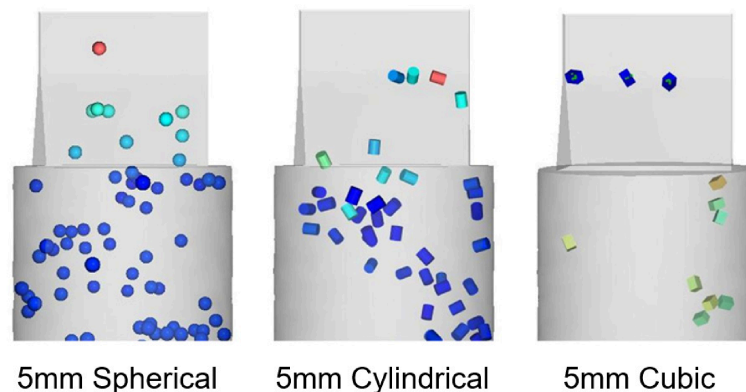


Figure 12. Comparison of bridging behavior for 5 mm particles.

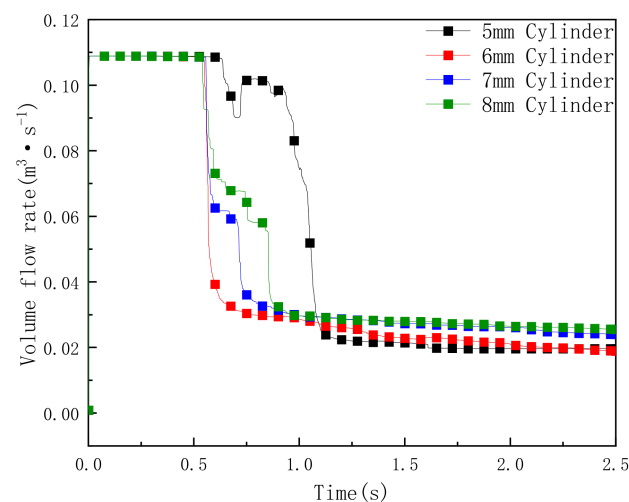


Figure 13. Leakage rate curves for cylindrical particles of different sizes.

In summary, for a long-slit channel with a width of 5 mm, cylindrical particles outperform spherical and cubic particles in plugging performance, and cylindrical particles with an equivalent diameter of 6 mm should be preferentially employed.

3.3. Effect of Particle Concentration on Plugging Effectiveness

Using cylindrical particles with an equivalent diameter of 6 mm at a pumping rate of $2.4 \text{ m}^3/\text{min}$, the effect of particle concentration on the plugging effectiveness for the long-slit channel was investigated. As shown in Figure 14, with increasing particle concentration, particle bridging was initiated earlier and the bridging time was correspondingly shortened. When the particle concentration reached 20%, the bridging time tended to stabilize.

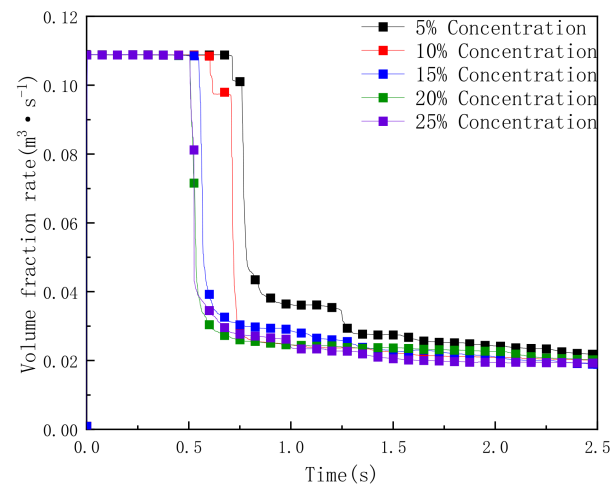


Figure 14. Leakage rate curves for different concentrations.

A comparison of the particle flow states within the wellbore at different concentrations is presented in Figure 15. When the particle concentration was below 20%, fewer particles entered the simulated wellbore within the same time period, and a vortex persisted at the bottom of the wellbore, causing the majority of particles to accumulate there while only a small number diffused to the upper region of the wellbore. Only as time elapsed did a sufficient number of particles gradually diffuse upward, resulting in a prolonged transport time to the slit opening. In contrast, when the concentration exceeded 20%, in addition to the portion of particles entrained into the vortex, a sufficient quantity of particles could rapidly diffuse to the upper wellbore region and plug the slit. Since the plugging effectiveness is primarily determined by the number of particles packed into the slit, and a sufficient number of particles can eventually fill the slit opening even at lower concentrations over time, the particle concentration exerts a relatively minor influence on the final plugging effectiveness.

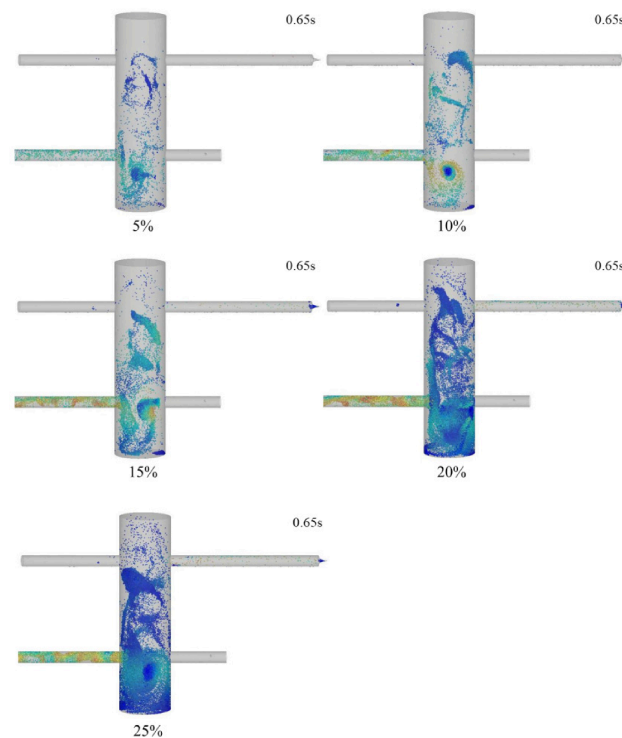


Figure 15. Particle flow states at different concentrations.

In summary, particle concentration primarily affects the particle bridging time. As the particle concentration increases, the bridging time decreases. When the particle concentration reaches 20%, the bridging time tends to stabilize.

3.4. Effect of Pumping Rate on Plugging Effectiveness

Using cylindrical particles with an equivalent diameter of 6 mm at a particle concentration of 20%, the effect of pumping rate on plugging effectiveness was investigated. As shown in Figure 16, with the increase in pumping rate, particle bridging was initiated earlier, and the time required for the leakage rate at the slit opening to stabilize became correspondingly shorter. Figure 17 illustrates the particle flow state in the simulated wellbore at the onset of bridging. A higher pumping rate resulted in higher particle velocities, allowing more particles to enter the simulated wellbore within the same time period and yielding a denser particle distribution in the upper region of the wellbore. Consequently, the time for particles to reach the slit opening was shortened, enabling faster plugging of the slit.

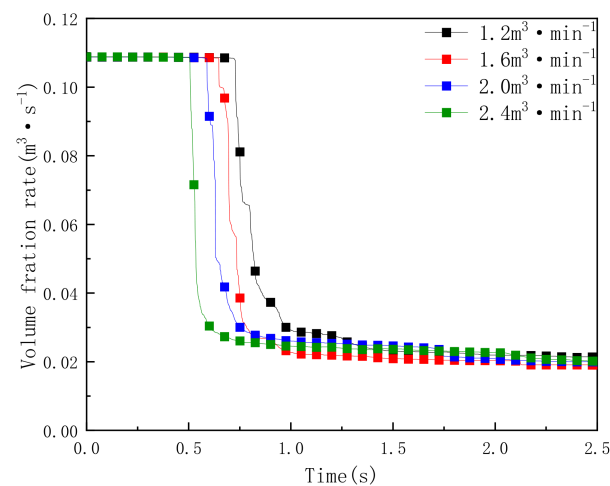


Figure 16. Plugging loss rates under different displacement rates.

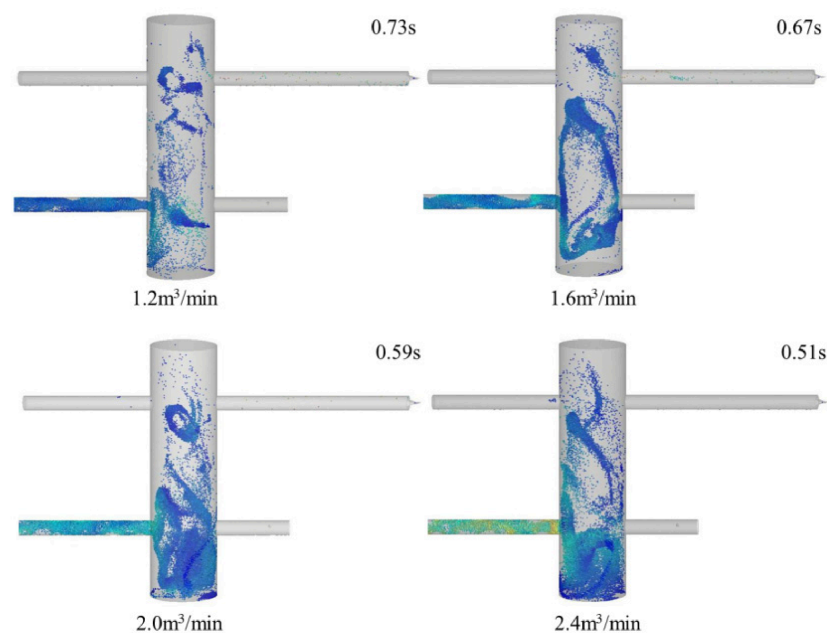


Figure 17. Particle flow states at different pumping rates.

Under the long-slit test conditions, no stabilization of the bridging time was observed. This is primarily because the long slit is located at the side of the bypass pipe, and the majority of particles are distributed inside the simulated wellbore. At the onset of bridging, relatively few particles have migrated to the slit opening of the bypass pipe, resulting in a sparse particle distribution and an insufficient number of particles to plug the slit. As can be seen from Figure 15, the pumping rate exerts a very limited effect on the plugging effectiveness of cylindrical particles for the 5 mm wide long slit. This is because the plugging effectiveness is mainly governed by the particle size. Even at a lower pumping rate, where the particle velocity is relatively low, the particles are not expelled from the slit by the fluid since their size exceeds the slit width. Over time, a sufficient number of particles will eventually accumulate at the slit opening. Furthermore, for a given particle size, both the number of particles packed into the slit and the interstitial void spaces remain essentially the same, rendering the final plugging effectiveness almost unchanged across different pumping rates.

In summary, the pumping rate primarily affects the time required for particles to reach the slit opening. A higher pumping rate leads to earlier bridging and a shorter bridging time, while the pumping rate has virtually no influence on the final plugging effectiveness. Therefore, when plugging long-slit channels, a high pumping rate should be adopted whenever possible to facilitate rapid plugging; a maximum pumping rate of $2.4 \text{ m}^3/\text{min}$ is recommended.

4. Conclusions

Based on the CFD-DEM coupling method, this study established a numerical model of particle plugging for long-slit leakage ports of blowout preventers (BOPs) under blowout conditions. The effects of particle shape, size, concentration, and pumping rate on the plugging process and effectiveness were systematically analyzed, and the following main conclusions are drawn:

(1) Under long-slit conditions, the particle transport and plugging process in the wellbore can be divided into two stages: an initial transport stage dominated by jet diffusion and a plugging structure formation stage dominated by bridging and accumulation. After entering the wellbore, particles are readily captured by the bottom vortex, and only a portion of them can migrate through the bypass pipe to the slit opening to participate in plugging.

(2) Particle shape and size significantly affect bridging behavior. When the particle size is smaller than the slit width, cubic particles, with their angular features, easily develop multiple support points and exhibit better bridging stability than spherical and cylindrical particles. When the particle size exceeds the slit width, all three particle shapes can bridge rapidly, with cylindrical particles showing marginally better plugging effectiveness than the other shapes.

(3) Both particle concentration and pumping rate mainly influence the bridging time but have only a minor effect on the final plugging effectiveness (leakage rate). A higher concentration or higher pumping rate leads to earlier initiation of bridging and a shorter bridging time. When the volumetric concentration reaches 20%, the bridging time tends to stabilize.

(4) For a long-slit leakage channel with a width of 5 mm, the combination of cylindrical particles with an equivalent diameter of 6 mm, a particle volume concentration of 20%, and a pumping rate of $2.4 \text{ m}^3/\text{min}$ exhibited relatively favorable overall plugging performance under the conditions considered in this study.

This study provides an effective emergency plugging solution for long-slit sealing failure leakage in BOPs, filling the research gap in the plugging mechanisms and process

parameters for wellhead equipment leakage under blowout conditions, and holds significant engineering application value. However, this study was conducted based on a long-slit leakage channel with a width of 5 mm, using water as the fluid medium and PEEK particles as the plugging material. Therefore, the obtained results are primarily applicable to the conditions investigated herein. In actual blowout scenarios, factors such as leakage geometry, fluid properties, particle materials, and multi-scale particle-size distributions may significantly influence particle transport, bridging, and plugging behavior. Future studies should consider a wider range of leakage dimensions, alternative plugging materials, and additional physical experiments to further improve the engineering applicability of the proposed model.

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