INTRODUCTION

Foaming is a relatively common phenomenon that can occur in various industrial processes, such as fermentation, wastewater treatment, textiles, paper pulping, and food manufacturing.\textsuperscript{1,2} The presence of foam can result in numerous troublesome issues, including the loss of target products and substrates, reduction in the equipment working volume, and environmental pollution. Control or suppression of foam formation is an essential operational task in these production processes.\textsuperscript{3,4} Even in certain situations in which foams are required, defoaming is indispensable. For example, foams must be collapsed to remove organic pollutants and recover valuable minerals from ores during foam separation and flotation. In foam drilling, polyhedral foam is used as a drilling fluid to carry rock cuttings out of a borehole, but it must be destroyed after returning to the surface. Otherwise, an extremely large pit must be prepared because a large volume of stable foam must be discarded into temporary storage. The drilling cost is thus significantly increased because the liquid and chemical additives cannot be recycled in a timely manner. Moreover, special measures should be adopted to prevent foams from being blown by wind to avoid environmental pollution by various chemicals in the foams, as illustrated in Figure 1. In
certain cases, if the mud pit does not have sufficient capacity to accommodate the ever-increasing foams, the drilling process must be stopped or commercial defoaming agents need to be used, which further increases the drilling cost.

Various types of equipment and technologies have been employed to destabilize foams or control their formation, including chemical and mechanical methods.\(^5\) Chemical antifoaming agents are very effective and can break any foam, but they exhibit the disadvantages of toxicity and contamination, and reduce the mass transfer rate, as well as change the system properties. Therefore, mechanical foam breakers that employ mechanical or ultrasonic vibrations, centrifugal force, perforated plates or wire mesh, sprays, heat, or vacuum to break foam are becoming increasingly attractive because they do not change the chemical and physical properties of the foam system.\(^8\) For example, Garrett suggested a possible speculative model for defoaming by using an ultrasound while also involving resonance. A foam film consisting of bubbles with a critical size can be destroyed at higher incident acoustic intensities above this threshold. Thus, the defoaming efficiency becomes maximal if the size of the bubbles is within the critical range for the resonant frequency. Increasing the intensity at this frequency will produce progressively more effective defoaming.\(^9\) Takesono et al studied the performance of a stirred-tank fermentor designed with a six-sectioned disk as the foam breaker impeller. The results indicated that foam can be collapsed by the shear force generated by the shaft rotation of the foam breaker impeller.\(^10\) In the work of Kang et al, a foam breaker with synthetic sponge cylinders was developed. A synthetic sponge has a higher water-absorbing capacity, which can intensify the liquid drainage of foams and accelerate bubble breakage.\(^11\)

Although various types of mechanical foam breakers have been developed in the chemical, biological, and food production industries, foam breakers are not practical for breaking drilling foam, not only because drilling foam is continuously returned from the borehole in large volumes but also because it contains numerous rock cuttings. These small solids will decrease the usable life of mechanical foam breakers or even affect their normal operation. To recycle water and chemicals from drilling foams, Weatherford designed a unique recyclable foam system that can fulfill the foaming and defoaming requirements by adjusting the pH of the environment. Namely, acid is added to reduce the pH value at the flow line, which immediately causes foam to break. Later, a caustic soda or a similar basic material is added to increase the pH value of water to a point where it will generate foam again.\(^12\) Hanking and Rappuhn designed a special separator tank in which defoaming baffles and spray bars were designed to break foam. To improve the foam-breaking effect, a dosing device was also incorporated to add chemical materials to change the pH value of the foam system.\(^13\) In the work of Guzmán, the centrifugal force and shear created by the gas-liquid cylindrical cyclone were used to separate a foam fluid into its component vapor and liquid phases. The results demonstrated that if the liquid phase viscosity is excessively high or the foam bubbles are excessively small, this type of foam breaker will be ineffective.\(^14\) Wang et al proposed a novel mechanical foam breaker based on self-oscillation. The flow field characteristics of the foam breaker were investigated with a two-phase air-water flow model, and the effects of the structural parameters and components of the foam drilling fluid, cuttings, and temperature on the defoaming percentage were studied. The working principle and feasibility of this foam breaker were verified through a numerical simulation and experimental data.\(^15\) Based on the Coandă effect, Cao et al developed an annular foam breaker that breaks foam using the combined effect of the shear force and pressure difference.\(^16\) This type of foam breaker has been successfully applied in numerous wells in China, including Dawan 101, Pulu 1, Yuanba 10, and Yuanba 233. Specifically, in a 26-inch section of the Yuanba 10 well, only approximately 400 m\(^3\) of the original foam liquid was prepared and consumed at a drilling depth of 672 m. Without the annular foam breaker, at least 2500 m\(^3\) of the foam liquid was required. However, the efficiency of this type of foam breaker is not stable. If the liquid phase viscosity is excessively high or the foaming volume is excessively large, the breaker will be ineffective.

Therefore, although various mechanical foam breakers have been proposed for collapsing polyhedral drill foams, the search for higher-performance devices continues to be the focus of a substantial amount of current research. Based on the principle of the annular foam breaker, Wang et al developed a two-stage laval foam breaker with two laval slits. The preliminary test results demonstrated that the second laval slit in the foam breaker could greatly improve its foam-breaking efficiency.

**FIGURE 1** Methods for controlling foam pollution in a drilling field. A, Spray method. B, Mud pit enclosed by canvas.
However, the effect of the distance between the two slits on the foam breaker performance was not considered in their study. Meanwhile, operation conditions, such as the air supply pressure and method, were also neglected. More importantly, the foam volume before and after breaking was used to evaluate the foam breaker performance. Errors may not be allowable because the foam volume after breaking is difficult to accurately measure, as it is mixed with the liquid generated by the foam breaking. In this study, an aerodynamic foam breaker was redesigned based on previous research methods. The computational fluid dynamics (CFD) code Fluent was employed to analyze the flow phenomena inside the foam breaker to optimize the distance between the two annular slits. The fluid density was first used to evaluate the foam breaker performance. Moreover, a series of experiments were conducted to verify its performance. The effects of the gas-liquid ratio, foam liquid viscosity, and operating conditions, such as the air supply method, on the foam-breaking efficiency were examined.

1.1 Working process of the aerodynamic foam breaker

The structural scheme of the aerodynamic foam breaker with two annular slits, which operates similarly to a jet ejector, is illustrated in Figure 2. Compressed air working as the primary or motive flow is ejected from both the first and the second annular slits at a high velocity and flows forward, following the nearby curved surfaces because of the Coandă effect, which causes the nearby pressure to decrease, leading to a negative pressure near these regions. When the foam fluid is returned from wells with high or ambient pressure flow into the foam breaker, bubbles will burst owing to the pressure sharply changes. In addition, after entering the foam breaker, the foam fluid begins to mix with the first primary flow near the first annular slit. Then, they continue to mix and flow forward along the inner wall of the throat. Due to the large velocity difference between the first primary flow and the foam fluid, a shear layer develops between the air stream and the foam fluid, which leads to strong shear force that collapses the bubbles. After the completion of mixing in the throat section, the fluid and flow reach the region near the second annular slit, where they are further mixed with the second primary airflow. Momentum transfer consequently occurs between the second primary airflow and these mixing fluids. Thus, the residual foam is broken in this process. Then, the mixed fluid is decelerated and ejected out of the foam breaker from its diffuser.

Relative to the normal annular foam breaker, the addition of the second annular slit not only increases the negative pressure distribution region but also improves the momentum transfer process between the primary airflow and the foam fluid. Therefore, in theory, the performance of the two-stage annular foam breaker should be better than that of the normal annular foam breaker.

2 MATERIALS AND METHODS

2.1 Numerical simulation

Based on our previous work, the main structural parameters of the aerodynamic foam breaker were designed as follows.\(^\text{17,18}\),

\[
L_1 = 120 \text{ mm}; \quad L_2 = 80 \text{ mm}; \quad L_3 = 300 \text{ mm}; \quad D_1 = D_2 = 50 \text{ mm}; \quad R_1 = R_2 = 100 \text{ mm}; \quad \alpha = 6^\circ. \]

Here, \(D_1\) and \(L_2\) are the inner diameter and length of the throat pipe, respectively; \(D_2\), \(L_3\), and \(\alpha\) are the minimum diameter, length, and angle of the diffuser, respectively; \(R_1\) and \(R_2\) are the arc radius of the first and second annular slit, respectively; and \(L_1\) is the length of the throat pipe, which is the distance between the two annular slits.

Obviously, the distance \((L_1)\) between the two annular slits has an important effect on the performance of the aerodynamic foam breaker. The initial value of \(L_1\) was 50 mm, and its final value was determined by the CFD simulation test.

A geometric model of the aerodynamic foam breaker was constructed using the Autodesk Inventor software. Then, it was
imported into the Hypermesh software for meshing, from which it was then incorporated into the Fluent code to conduct a numerical analysis. The governing equations under consideration were the 3D compressible, steady-state forms of the Reynolds-averaged Navier-Stokes (RANS) equations. In Cartesian coordinates, the governing equations are given as follows:

Continuity:
\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

Momentum:
\[
\nabla \cdot (\rho u \mathbf{V}) = \nabla \cdot (\mu \nabla u) - \frac{\partial p}{\partial x} + \left[ -\frac{\partial (\rho u'^2)}{\partial x} - \frac{\partial (\rho u'v')}{\partial y} - \frac{\partial (\rho u'w')}{\partial z} \right] + S_u
\]  

\[
\nabla \cdot (\rho v \mathbf{V}) = \nabla \cdot (\mu \nabla v) - \frac{\partial p}{\partial y} + \left[ -\frac{\partial (\rho v'^2)}{\partial x} - \frac{\partial (\rho u'v')}{\partial y} - \frac{\partial (\rho v'w')}{\partial z} \right] + S_v
\]  

\[
\nabla \cdot (\rho w \mathbf{V}) = \nabla \cdot (\mu \nabla w) - \frac{\partial p}{\partial z} + \left[ -\frac{\partial (\rho w'^2)}{\partial x} - \frac{\partial (\rho u'w')}{\partial y} - \frac{\partial (\rho w'^2)}{\partial z} \right] + S_w
\]

where \( V \) is the velocity vector; \( u, v, \) and \( w \) are the average velocity components and \( u', v', \) and \( w' \) are the varying velocity components; \( S_u, S_v, \) and \( S_w \) are the source terms; and \( \mu \) is the dynamic viscosity.

Energy:
\[
\frac{\partial (\rho uT)}{\partial x} + \frac{\partial (\rho vT)}{\partial y} + \frac{\partial (\rho wT)}{\partial z} = \frac{\partial}{\partial x} \left( \frac{k}{c_p} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{k}{c_p} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{k}{c_p} \frac{\partial T}{\partial z} \right) + S_T
\]

where \( c_p, k, \) and \( S_T \) are the heat capacity, heat transfer coefficient, and viscosity dissipation, respectively.

The equation of the state for perfect gases is added to close the system as follows:
\[
p = \rho RT
\]

The near-wall treatment remained as the standard wall function, which provided reasonably accurate predictions for the majority of the high Reynolds number, wall-bounded flows. Pressure correction was achieved with a coupled implicit algorithm, while the realizable k-\( \epsilon \) turbulence model was used as the turbulence model. The convection term in the turbulence equation was discretized using the second-order upwind scheme, while a central difference scheme was applied for the diffusion terms. Compressed ideal gas was selected as the simulation fluid.

The boundary conditions of the foam breaker are presented in Figure 3A. To simplify the computation, only the velocity and pressure distribution inside the foam breaker

**FIGURE 3** Numerical models of the aerodynamic foam breaker. A, Geometric model. B, Computation grids
were analyzed, which means that the foam flow status and bubble bursting process were not considered in the simulation. Therefore, the pressure inlet boundary condition at atmospheric pressure was selected for the foam suction chamber inlet. The mass flow inlet boundary conditions were applied to the air supply inlets, and the initial mass flow rate was approximately 0.02 kg/s, which is the nominal capacity of the air compressor at our laboratory. Moreover, a pressure outlet boundary condition was used at the diffuser outlet, and the pressure was also set to atmospheric pressure.

Owing to the geometrical structure of the foam breaker, it was difficult to employ a highly uniform structured mesh grid. To obtain relatively accurate results, a mixture of structured and unstructured body-fitted meshes was used, as illustrated in Figure 3B. A high-density grid was created in the area with a high flow rate and high pressure gradient, particularly in critical zones, such as the Coandă surfaces of the foam breaker.

2.2 | EXPERIMENTAL

2.2.1 | Foam material

Sodium dodecyl benzene sulfonate (SDBS: C_{18}H_{29}NaO_3S; relative molecular weight: 348.48; produced by Tianjin Dingsheng Chemical Co., Ltd., China) and sodium dodecyl sulfonate (SDS: C_{12}H_{25}-OSO_3Na; relative molecular weight: 288.8; produced by Xi Long Scientific Co., Ltd., China) were the foaming agents commonly used in foam drilling. Xanthan gum ((C_{35}H_{49}O_{29})_n; relative molecular weight: 241.1; produced by Shandong Zhongyuan Chemical Pharmaceutical Co., Ltd., China) and polyacrylamide (PAM: anionic; [-CH_2CH(CONH_2)-]_X; relative molecular weight: 12 million; produced by Tianjin Zhiyuan Chemical Reagent Co., Ltd., China) were selected as the foam stabilizers in this study. Based on the foam volume and half-life period, a suitable foam formulation system was selected.

Foam system no. 1: 0.5% SDS + water; half-life period: 7 min.; the plastic viscosity: 1.05 mPa-s.

Foam system no. 2: 0.5% SDS + 0.05% xanthan gum + water; half-life period: 30 min.; plastic viscosity: 1.7 mPa-s.

Foam system no. 3: 0.5% SDS + 0.09% xanthan gum + water; half-life period: 86 min.; plastic viscosity: 3.15 mPa-s.

2.2.2 | Testing stand for foam breaking

A schematic of the testing stand is presented in Figure 4. An air compressor station with a working capacity of up to 3 m³/min was used to supply compressed air to the testing system. Within the system, the flow rate of air used to generate the foam drilling fluid was approximately 1 m³/min. Other airflows were used to operate the aerodynamic foam breaker. The basic liquid was supplied by a vortex pump from the liquid tank to the foam generator. The maximum flow rate of the pump was approximately 50 L/min, which was controlled by adjusting the converter to change the motor rotation speed. Several vortex shedding flow meters of the LK-VFF-50 type were employed to measure the mass flow rate of the air entering from the air station. The range and precision of this flow meter were 0.1 to 100 g/s and 1.5% FS, respectively. Triplicate tests were performed to reduce possible experimental errors.

2.3 | Evaluating indicators of aerodynamic foam breaker performance

The foam breaker performance is generally measured by the defoamed ratio. The defoamed ratio can be calculated by Equation (7):

$$\eta = \frac{V_0 - (V_1 - l_1)}{V_0} \times 100\%$$

(7)

where $\eta$ is the foam-breaking efficiency, $V_0$ is the foam volume prior to foam breaking, $V_1$ is the mixed fluid volume after foam breaking, and $l_1$ is the liquid volume generated by foam breaking.
If none of the bubbles in the foam fluid can be broken, $l_1 = 0$ and $V_1 = V_0$, $\eta = 0$, while if all the bubbles burst, $V_1 = l_1$ and $\eta = 100\%$. Hence, the mechanical foam breaker efficiency can be accurately computed by Equation (7).

In a previous study, $l_1$ was ignored in the calculation of the foam-breaking efficiency. This value is very difficult to measure because the liquid is mixed with residual foam.\textsuperscript{16,17} Because the gas-liquid ratio $\alpha$ and density $\rho$ are easy to control and measure, $\alpha$ and $\rho$ were used to calculate the $l_1$ value in this study.

The liquid volume generated owing to foam breaking can be calculated by the following equation:

$$l_1 = [V_0 - (V_1 - l_1)] \frac{1}{1 + \alpha} \tag{8}$$

specifically:

$$l_1 = \frac{V_0 - V_1}{\alpha} \tag{9}$$

where $\alpha$ is the gas-liquid ratio of the foam system at the stand pressure and temperature. If all of the gases and liquids are involved in generating the foam, $\alpha$ can be defined as follows:

$$\alpha = \frac{V_g}{V_l} = \frac{V_0 - V_f}{V_f} \tag{10}$$

where $V_g$ and $V_l$ are the gas and liquid volumes used to generate the foam, respectively.

According to the formulae above, the foam-breaking efficiency can be rearranged as follows:

$$\eta = \frac{(V_0 - V_1)(1 + \alpha)}{V_0\alpha} \times 100\% \tag{11}$$

**FIGURE 5** Velocity and pressure distribution contours at a representative longitudinal section ($z = 0$). A, Velocity distribution. B, Pressure distribution
Using the fluid density for the calculation, the expression for the foam-breaking efficiency can be written as follows:

\[ \eta = \frac{(\rho_1 - \rho_0) (1 + \alpha)}{\rho_0 \alpha} \times 100\% \]  

where \( \rho_0 \) and \( \rho_1 \) are the foam density and mixing fluid density following foam breaking, respectively.

3 | RESULTS AND DISCUSSION

3.1 | Simulation results

3.1.1 | Flow characteristics inside the foam breaker

Figure 5 illustrates the velocity and pressure distribution contours inside the foam breaker at a representative longitudinal section (\( Z = 0 \)). As indicated in Figure 5A, following ejection from the first annular slit, the first primary flow moved downstream along the curved surface of the foam breaker. The surrounding air was sucked into the foam breaker from the suction chamber inlet and was mixed with the first primary flow near the first annular slit. Thereafter, the mixture moved forward and began to mix with the second primary flow near the second annular slit. They continued to mix and flow forward, attaching to the second arc surface and diffuser inner wall until being exhausted from the foam breaker. In these mixing and flowing processes, energy transfers occurred among the suction flow and first and second primary flows.

Figure 5B shows that negative pressure was generated close to each arc surface. Because the airspeed was faster near the second arc surface, the pressure was lowest in this region. The minimum negative pressure reached approximately 7.21 kPa.

3.1.2 | Effect of distance \( L_1 \)

Figure 6 presents the velocity and pressure distribution curves along the center axis of the aerodynamic foam breaker (\( y = 0 \) and \( z = 0 \)). The air velocity rapidly increased from the suction chamber inlet to the region near the second arc surface and then rapidly decreased because most of the air flowed along the diffuser inner wall. However, the static pressure decreased to a minimum near the second arc surface and then began to gradually recover along the diffuser to an ambient pressure. Moreover, the magnitude of the static pressure near the second arc surface was almost the same when the value of \( L_1 \) increased from 40 to 60 mm, but it began to decrease when the value of \( L_1 \) increased further. Therefore, the \( L_1 \) value suggested in this case is 60 mm.

3.1.3 | Effect of the air supply modes

If compressed air was supplied only through the first annular slit, air would flow forward along the inner wall of the first arc surface, throat pipe, and second arc surface and then enter the diffuser. However, if compressed air was supplied only through the second annular slit, it would directly enter the diffuser after attaching to the second arc surface. Moreover, the first annular slit was near the suction chamber. Therefore, the former working condition had a stronger suction effect than the latter one. When compressed air was supplied through both annular slits at the same time, the performance of the foam breaker was far superior to the others, as illustrated in Figure 7. Notably, negative pressure was generated near each annular slit for all three operating conditions, meaning that both Coandă surfaces played an important role in the generation of negative pressure, regardless of whether air was supplied to the foam breaker through both slits. At this point, the
performance of the two-stage annular foam breaker should be superior to that of the normal foam breaker.

### 3.2 | Experimental results

The gas-liquid ratio $\alpha$ is one of the most important parameters for dealing with the air compressor output under surface conditions in stable foam drilling. An appropriate gas-liquid injection ratio is crucial for maintaining the foam quality at the desired value to ensure its holding and lifting capacities. According to field experience, foam systems generally operate at a gas-liquid ratio from 50/1 to 500/1, which yields a down-hole quality from 52% to 90%. Within this foam quality range, optimal hole cleaning can be reached. In most drilling cases, $\alpha$ should be between 60 and 300. Otherwise, if $\alpha$ is excessively high or low, the foam system may become unstable and can easily change into mist or slugs of water and gas. The gas-liquid ratio of foam also has a strong influence on the foam breaker efficiency, as illustrated in Figure 8.

In all three foam systems, the efficiency $\eta$ of the foam breaker was positively correlated with $\alpha$. When $\alpha$ increased from 60 to 180, $\eta$ improved from 72% to 82% for foam system no. 1, while $\eta$ increased from 67% and 63% to 79% and 76% for foam systems no. 2 and no. 3, respectively. The main reason for this result may be that the liquid phase of the foam decreased as $\alpha$ increased, so the foam became dry because of the decrease in foam density. The mechanical foam breaker can more easily break bubbles. As indicated in Figure 8, when $\alpha$ increased from 60 to 180, the foam density was reduced from 0.231, 0.238, and 0.272 g/cm$^3$ to 0.160, 0.165, and 0.177 g/cm$^3$ for foam systems no. 1, 2, and 3, respectively.

As discussed previously, the defoamed ratio was highest when compressed air was simultaneously supplied through the two annular slits, as opposed to being supplied only through the first slit. The foam-breaking efficiency was slightly superior to that under other conditions when air entered the foam breaker through both annular slits, as illustrated in Figure 8.

Figure 9 presents the density of the mixing fluid flowing from the foam breaker diffuser, which can directly indicate the fluid's status following foam breaking. Because of the improvement in the foam-breaking efficiency, the mixing fluid density positively correlated with the gas-liquid ratio. When air was supplied from both annular slits of the foam breaker, the mixing fluid density reached 0.87 g/cm$^3$ with $\alpha = 180$ for foam system no. 1. This result means that most of the air had been separated from the foam. However, the mixing fluid density was reduced to 0.66 g/cm$^3$ in foam system no. 3 because of the higher liquid viscosity.

The basic liquid viscosity of the foam not only affects its cuttings’ carrying capacity but also their stability and half-life. The foam half-life is the time in which half of the liquid used in a standard mixing test becomes separated from the foam. This value should be adjusted according to the stratum situation, injected gas volume, and borehole depth. According to a previous drilling in the Feng 19 well in Xinjiang, China, which was drilled with foam fluid from 3864 to 4248 m in the 215.9 mm section, the half-life period of the foam system was only approximately 70 min. This is the deepest borehole that has been drilled with foam in China to date. Considering the influences of rocks and other natural solids, foam systems no. 2 and no. 3, with half-lives of 30 and 90 min., respectively, were selected for testing in this study.

Figure 10 illustrates the changes in the foam breaker efficiency with different foam systems. Under the same conditions, the foam-breaking efficiency $\eta$ negatively correlated with the basic liquid viscosity. The difference among the three foam systems was more significant when the foam $\alpha$
value was lower. For example, when \( \alpha \) was approximately 6.0 it was only approximately 60% for foam system no. 3, while it was approximately 66% and 70% for the other two foam systems. However, this difference became smaller as \( \alpha \) increased. When \( \alpha \) increased to 180, \( \eta \) was approximately 81%, 78%, and 75% for foam systems no. 1, no. 2, and no. 3, respectively. Nonetheless, a higher viscosity of the basic foam liquid resulted in lower foam breaker efficiency.

The foam breaker performance at a higher gas-liquid ratio was predicted through a linear regression analysis of the experimental data, as illustrated in Figure 10. When \( \alpha \) increased to 300, the efficiency \( \eta \) of the foam breaker was improved.
to approximately 92.4%, 91.1%, and 90.0% for foam systems no. 1, no. 2, and no. 3, respectively.

The density of the mixing fluid that was ejected from the foam breaker clearly showed a positive correlation with the foam-breaking efficiency. When $\alpha$ increased to 300, the mixing fluid density was approximately 0.94, 0.82, and 0.71 g/cm$^3$ for foam systems no. 1, no. 2, and no. 3, respectively.

Destroying foam with a low-viscosity liquid phase appears to be a more effective approach. To obtain optimal foam-breaking results in the drilling field, the foam gas-liquid ratio should be as high as possible, while its liquid phase viscosity should be as low as possible.

The air supply pressure of the foam breaker also has a certain effect on its performance. Figure 11 presents the results of the foam breaker operating under different air supply pressures. In this test, foam system no. 3 with a gas-liquid ratio of 60 was selected because it was the most difficult to destroy. The foam-breaking efficiency was positively correlated with the air supply pressure, as was the mixing fluid density. When the air supply pressure was increased from 0 to 0.8 MPa, the foam-breaking efficiency improved from 60% to 69%, and the mixing fluid density increased from 0.59 to 0.75 g/cm$^3$ if air was supplied through both annular slits of the foam breaker simultaneously. Therefore, the air supply pressure should be optimally improved during a foam breaker application.

Varying forms of foam liquid in different stages are illustrated in Figure 12. The foam system volume was large before foam breaking and occupied a large space. When the aerodynamic foam breaker was operating, the foam volume was reduced to such an extent that the fluid mixture flowing from the foam breaker was easily pumped. Therefore, the liquid extracted from the degraded foam can be reused over time, which will significantly reduce the costs of foam drilling.

4 | CONCLUSIONS

A novel aerodynamic foam breaker with two annular slits is investigated in this study. When compressed air is ejected from the annular slits, a major negative pressure region is formed nearby. The momentum transfer process between the foam fluid and the air stream is strengthened because of the design of the second slit, which is beneficial to enhancing the performance of this aerodynamic foam breaker.
The CFD code was used to analyze the velocity and pressure distribution inside the foam breaker. The optimal distance between the two annular slits was approximately 60 mm. Regardless of the manner in which the air stream enters the foam breaker, a wider negative pressure zone was created because of the design of the second slit. Under the same conditions, the foam breaker’s performance was significantly superior to the performances of other operating conditions if compressed air was supplied through both annular slits simultaneously.

The experimental results demonstrate that both the gas-liquid ratio and the liquid viscosity of the foam system strongly influence the foam breaker’s performance. Its foam-breaking effect negatively correlates with the liquid phase viscosity, whereas in the effect has a rapidly positive correlation with the gas-liquid ratio. When the gas-liquid ratio was increased to 300, the foam breaker efficiency reached up to 90% for all three foam systems tested in this study. Therefore, to enhance the performance of this foam breaker in drilling sites, the foam gas-liquid ratio should be as high as possible and the basic liquid viscosity should be strictly controlled.

Under the same conditions, the foam breaker’s performance is significantly superior to the performances of the other operating conditions if compressed air is supplied through the two annular slits simultaneously. Accordingly, a two-stage air supply method is suggested to improve the performance of this type of foam breaker. Moreover, the air supply pressure of the foam breaker should be as high as possible to obtain optimal foam-breaking results.

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CONFLICT OF INTEREST

The authors declare no competing interests.

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