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Structure design of and experimental research on a two-stage laval foam breaker for foam fluid recycling

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Abstract

Environmental, economical and efficient antifoaming technology is the basis for achievement of foam drilling fluid recycling . The present study designed a novel two-stage laval mechanical foam breaker that primarily uses vacuum generated by Coanda effect and Laval principle to break foam. Numerical simulation results showed that the value and distribution of negative pressure of two-stage laval foam breaker were larger than that of the normal foam breaker. Experimental results showed that foam-breaking efficiency of two-stage laval foam breaker was higher than that of normal foam breaker, when gas-to-liquid ratio and liquid flow rate changed. The foam-breaking efficiency of normal foam breaker decreased rapidly with increasing foam stability, whereas the two-stage laval foam breaker remained unchanged. Foam base fluid would be recycled using two-stage laval foam breaker, which would reduce the foam drilling cost sharply and waste disposals that adverse by affect the environment.

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Introduction

Air foam drilling technology has been widely used to solve serious problems such as fractured formations and depleted or highly permeable zones in drilling oil and gas wells. However, foam fluid has long half-life and high stability, which remains stable due to long period required by the foam to dissipate back to the original liquid volume after returning to the surface (Wan *et al.,* 2010; Zhao 1999; Teichrob 1997). Containing foam thus requires a large pit to allow sufficient room for cuttings and for the foam to dissipate. The foam overflows and causes environmental pollution due to corrosion of foaming agent when the increased foam volume cannot be accommodated (Cao *et al.,* 2009). As shown in Fig.1, at drilling site of 101 well and sub-1 well in northeast of Sichuan, China, foam fills the mud pit quickly and is blown out easily with the wind, carrying various chemicals which results in environment pollution. On this account, the drilling cycle is extended by replacing foam drilling with conventional mud drilling. Foam drilling fluid can only be used once because it cannot be broken down fast enough. It consumes a large amount of water and ingredient additives, which greatly increases the foam drilling costs. For example, the TBK-2 well statistics of Iran shows that the configuration of foam fluid volume is 1799 m^3 when the hole diameter is 660 mm and total drilling footage is 378 m. The cost of ingredient additives alone reaches 0.1 million dollars (Shen 2005). Thus, high-speed foam breaking and foam base fluid recycling hinder wide application of foam drilling technology.

Physical and chemical methods can be used for foam breaking. The chemical method for foam breaking consumes large amount of antifoam agents, which tend to change the chemical and physical properties of the foam system and thus pollute the foam surfactant and reduce the reusability of the foam drilling fluid (Wang *et al.,* 2011; Wang *et al.,* 2008; Pelton 2002). The physical methods are divided into thermodynamic, ultrasonic and mechanical methods according to the function mechanism. Examples includes heat defoaming device of Shandong University (Wang *et al.,* 2012) and pulse jetting defoaming device of the China University of Petroleum (Ni *et al.,* 2012). Meanwhile, a number of mechanical foam breakers like high rotate centrifugal foam breaker (Vetoshkin 2003), foam-breaking cyclones (Guzman 2005), air jet breaker (Vetoshkin and Chagin 2002) and

Fig. 1 : Mud pit filled with foam

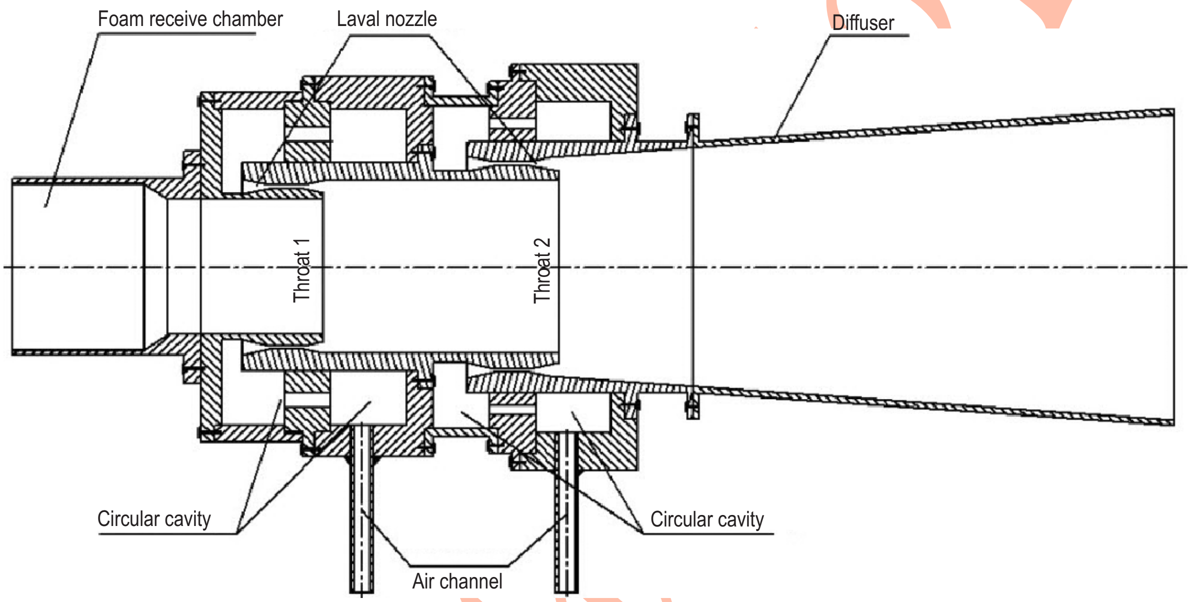

Fig. 2 : Schematic of two-stage laval foam breaker

others (Takesono *et al.,* 2003; Takesono *et al.,* 2006) have been proposed. However, most of these breakers are impractical for foam-breaking operations in high-rate gas bubbling systems of foam drilling fluid. Therefore, the structural design of foam breakers needs further improvement to increase foam-breaking efficiency, especially when foam velocity is too fast or when liquid phase viscosity is excessively high.

The annular foam breaker, which combines the effects of vacuum and shear force to break foam, achieves effective results when applied in oil field, gas well drilling and geological core drilling (Qahtan *et al.,* 2007; Cao *et al.,* 2012a,b; Cao *et al.,* 2011). On the basis of annular foam breaker, a novel two-stage laval foam breaker was designed that primarily uses a vacuum generated by Coanda effect and Laval principle to break foam. A computational fluid dynamics (CFD) code called FLUENT was employed to simulate flow phenomena inside foam breaker. An experimental platform was also established to test the performance of the proposed foam breaker. The foam-breaking efficiency of foam breakers was investigated when gas-to-liquid ratio, liquid flow rate and foam stability changed.

Materials and Methods

According to the principle of aerodynamics, a relationship between the overcurrent cross-sectional area and gas flow rate is expressed as follows (Wu 2010):

$$[M^2 - 1]\frac{dv}{V} = \frac{ds}{S} \qquad (1)$$

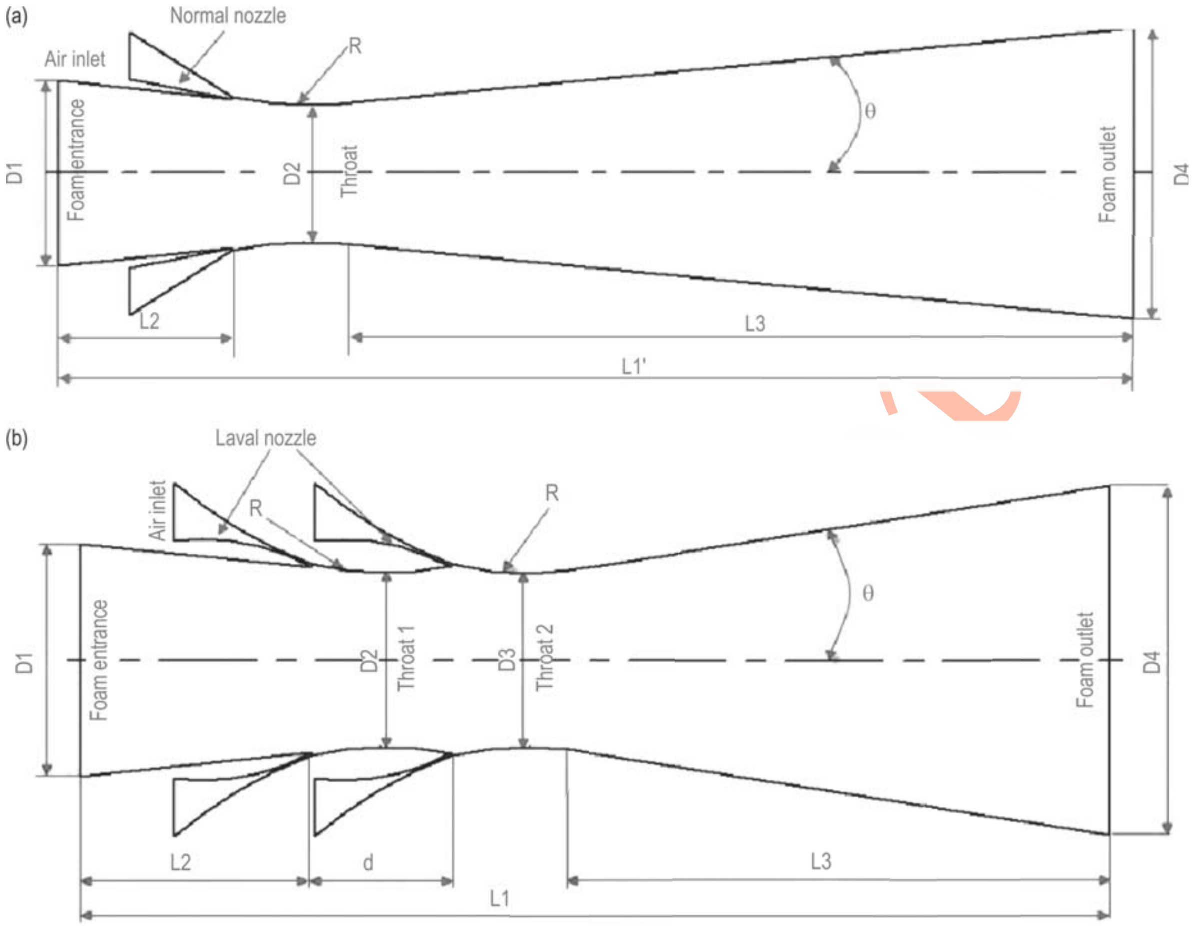

Fig. 2 : Analytical models of foam breaker: (a) Normal annular foam breaker; (b) Two-stage laval foam breaker

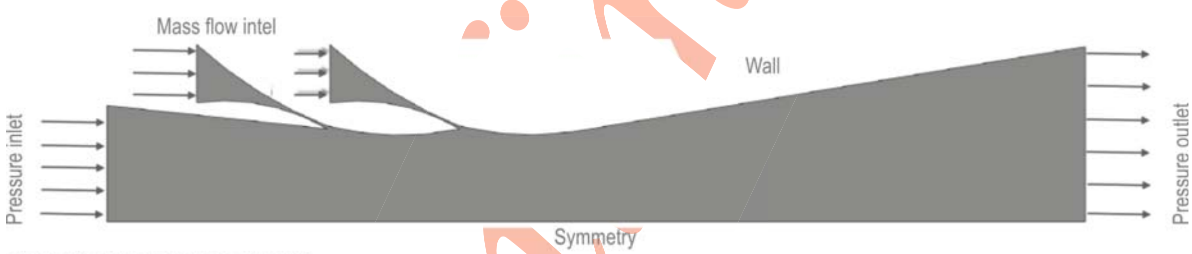

Fig. 3 : Boundary conditions of model

Where, *M* is the Mach number, *V* is the gas flow rate and *S* is the overcurrent cross-sectional area.

When airstream was subsonic ($M < 1$), the gas flow rate increased as the overcurrent cross-sectional area decreased. When airstream was supersonic ($M > 1$), the gas flow rate increased as the overcurrent cross-sectional area increased. When Mach number was equal to zero, the critical airstream was generated at minimum cross section.

The Laval-type nozzle is a convergent–divergent pipe section that has been widely used in supersonic and hypersonic wind tunnels, supersonic aircrafts, rocket nozzles and other fields. It is one of the unique structures of two-stage laval foam breaker. Airflow velocity reached sonic or supersonic levels at the throat of Laval nozzle and continued to increase as the cross-sectional area increased in the expansion section. According to preliminary theoretical and experimental study, high gas velocity equates to a great degree of vacuum and defoaming efficiency.

Theoretically, the design of Laval-type nozzle can effectively improve defoaming efficiency. On the other hand, adding second Laval nozzle behind the first one and through negative pressure of two overlapping adjacent zones to improve vacuum distribution area inside foam breaker.

The scheme of two-stage laval mechanical foam breaker is shown in Fig. 2. Compressed gas entered the circular cavity from air channel and passed through the Laval nozzle at supersonic speed. A negative pressure zone was then generated near the throat after compressed gas adhered to the convergent slot walls. When the foam drilling fluid flowed through this negative pressure region, it bursted due to pressure difference. Considering the compressible mixing effects, high-speed airflow interacted with relatively low-speed foam fluid in the jet body chamber and then mixed all along the length of the jet body and diffuser. Velocity difference between air stream and foam drilling fluid transferred the momentum from high velocity air to foam fluid, thus creating a powerful shear force that collapsed the bubbles.

Flow characteristic inside the foam breaker

Analytical model : The two-stage laval mechanical foam breaker primarily used a vacuum effect to break the foam. Therefore, the flow characteristics inside the foam breaker greatly affected the defoaming efficiency.

The analytical model of the foam breaker is shown in Fig. 2. The following structural parameters were used: D1 = 80 mm, D2 = D3 = 60 mm, D4 = 160 mm, R = 100 mm, L1´ = 500 mm, L1 = 550 mm, L2 = 70 mm, L3 = 400 mm, d = 50 mm, and θ = 8°, where, D1 and D4 are diameters of foam entrance plane and diffuser exit plane, respectively; D2 and D3 are diameters of throat plane of foam breaker; L3 is diffuser length; R is the radius of the Coanda surface; d is the annular slit distance; and θ is the diffuser angle; L1´ and L1 are foam breakers length.

Basic assumptions and boundary conditions : Fig. 3 illustrates the boundary conditions for numerical analysis. The foam breaker could be simplified into a 2D axisymmetric structured grid system with a quadrilateral mesh element to reduce computer costs and data manipulation time. The dense meshes were preset at the areas that exhibited high flow rates and high-pressure gradients to obtain accurate results. For an axisymmetric turbulent compressible flow, the governing equations of continuity, momentum and energy were solved simultaneously with constraint (i.e., the ideal gas law). The standard k-ε model was selected to model the turbulent viscosity with a coupled-implicit solver. The near wall treatment was used as standard wall function, which gave reasonably accurate results for the wall bounded with high Reynolds number flow. The mass flow inlet and pressure inlet are applied to the boundaries of the air channel and the foam channel, respectively. The initial mass flow rate was 0.10 kg s^{-1} for both air inlets of the two-stage laval foam breaker and 0.20 kg s^{-1} for the air inlet of the normal foam breaker. Given that the foam burst process is complicated and difficult to simulate, the pressure inlet boundary was set to atmospheric conditions to simplify the calculation. The boundary condition at the exit plane of the annular foam breaker was chosen as the pressure outlet condition with atmospheric pressure. In the present study, all walls were considered to be adiabatic with no slip.

Results and Discussion

Fig. 4 and 5 are the velocity and pressure contours, respectively, inside foam breakers. As indicated by velocity contours, high-speed gas adhered to arc surface because of the Coanda effect and reached maximum velocity near the throat. Both foam breakers generated a negative pressure near the throat. The value and range of throat 2 were larger than those of throat 1, as shown in the pressure contours of two-stage laval foam breaker.

Fig. 6 shows comparison of velocity and pressure distribution curves along the center axis of foam breaker. Fig. 6(a) shows that the normal foam breaker had only one velocity wave at 210 m^{-1}, whereas the two-stage laval foam breaker had two velocity waves at 210 and 300 m^{-1}. Fig. 6(b) shows that the values of maximum negative pressure of two kinds of foam breakers were fixed at 23 and 45 kpa, respectively. The figure also shows an overlap between two pressure troughs inside the two-stage laval foam breaker. Therefore, the two-stage laval foam breaker can generate a large negative pressure and feature a larger distribution region of negative pressure as compared with the normal foam breaker. Based on the results of numerical simulation, performance of the two-stage laval foam breaker was better than normal foam breaker.

Comparative experiment : An experiment platform was established to verify the actual defoaming effect of two-stage laval foam breaker and normal foam breaker under different working conditions (Fig. 7). The two-stage laval foam breaker was designed and processed (Fig.8) according to early design of annular-type foam breaker while considering the overall size, weight and site relocation and installation requirements.

Sodium dodecyl sulfate (SDS) was used as a surfactant generate foam with concentration ranging from 0.3 wt.% to 0.5 wt.% in distilled water. The aqueous polymer solution anion polyacrylamide (0.02 wt.% to 0.07 wt.%) was used as a foam stabilizer. The airflow rate used to drive foam breaker was 0.6 m^3 min^{-1} and operation pressure was approximately 0.8 MPa. The foam-breaking efficiency of two-stage annular foam breaker was calculated using Eq 2:

$$\eta = \frac{Vb - (Va - la)}{V_b} \times 100\% \quad (2)$$

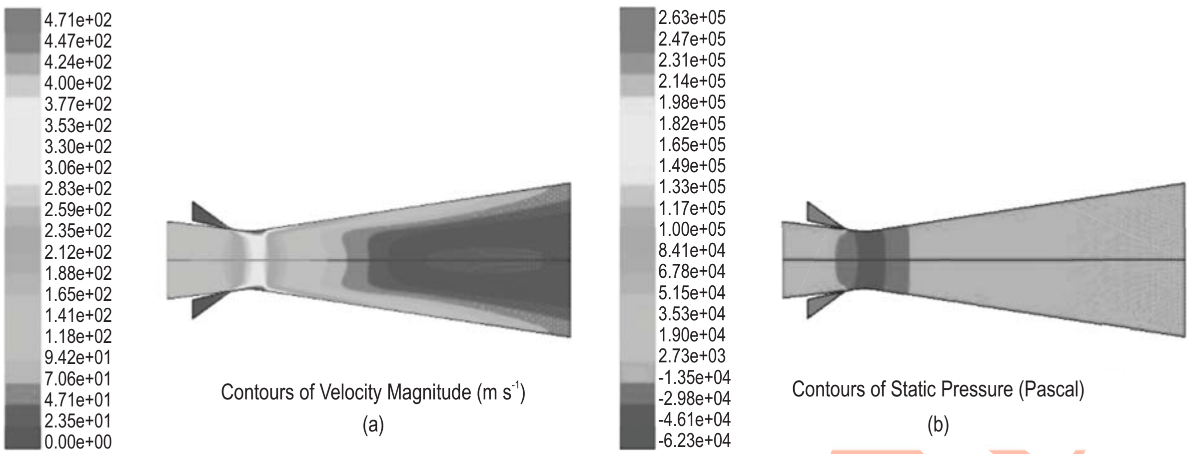

Fig. 4 : The flow characteristic inside the normal foam breaker: (a) Contours of velocity (m^{-1}); (b) Contours of static pressure (pa)

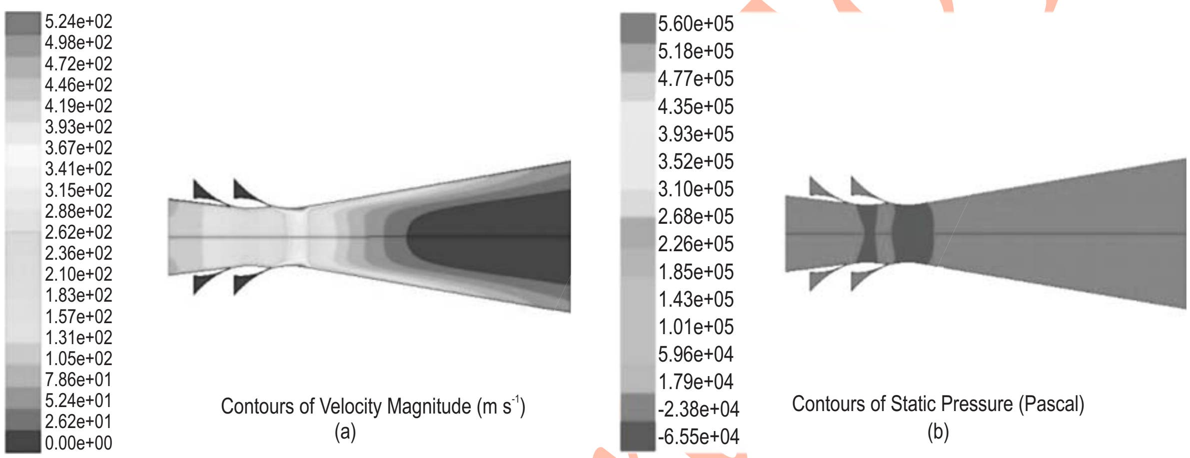

Fig. 5 : Flow characteristic inside two-stage laval foam breaker: (a) Contours of velocity (m^{-1}); (b) Contours of static pressure (pa)

Where, η is the foam-breaking efficiency; V_b is the foam volume produced before foam breaking; V_a is the mixed fluid volume after foam breaking and l_a is the net liquid volume in V_a. If no foam breaking occurs, then $l_a = 0$ such that $V_a = V_b$, and $\eta = 0$. If all the bubbles burst, then $V_a = l_a$, and $\eta = 100\%$. The foam-breaking efficiency is calculated accurately by measuring the foam volume before and after defoaming.

Influence of gas-to-liquid ratio : The foam base fluid flow was kept at 1.5 l min^{-1} to regulate the flow of foam slurry pump. Fig.9 shows the foam-breaking efficiency, when the gas-to-liquid ratio varied from 50 to 200. The foam-breaking efficiencies of normal foam breaker and two-stage laval foam breaker were 81% and 86%, respectively, when gas-to-liquid ratio was 50. The foam-breaking efficiency of two kinds of foam breakers slightly increased as gas-to-liquid ratio increased. Thus, dry foam system was effectively destroyed. The foam-breaking efficiency of two-stage laval foam breaker was higher than that of normal foam breaker, under similar conditions.

Influence of foam base fluid flow : The foam base fluid flow varied from 1 l min^{-1} to 4 l min^{-1} to regulate the flow of foam slurry pump. The gas-to-liquid ratio was kept unchanged by adjusting the air volume of air compressor. Fig.10 shows the relationship between fluid flow rate and foam-breaking efficiency. As the foam base fluid flow increased, the foam-breaking efficiency of normal foam breaker decreased to 78%, whereas that of two-stage laval foam breaker remained higher than 85% due to limited negative pressure region of normal foam breaker. Certain bubbles did not have sufficient time to burst when the foam base fluid flow was too fast, thus making the normal foam breaker ineffective at times.

Influence of foam stability : Foam stability is known to be one of the important parameters that affect foam carrying capacity. Polymers are often added to increase viscosity of the aqueous phase and to enhance its stability. Therefore, three different foam systems were configured in the experiment. The composition of these foam systems is as follows:

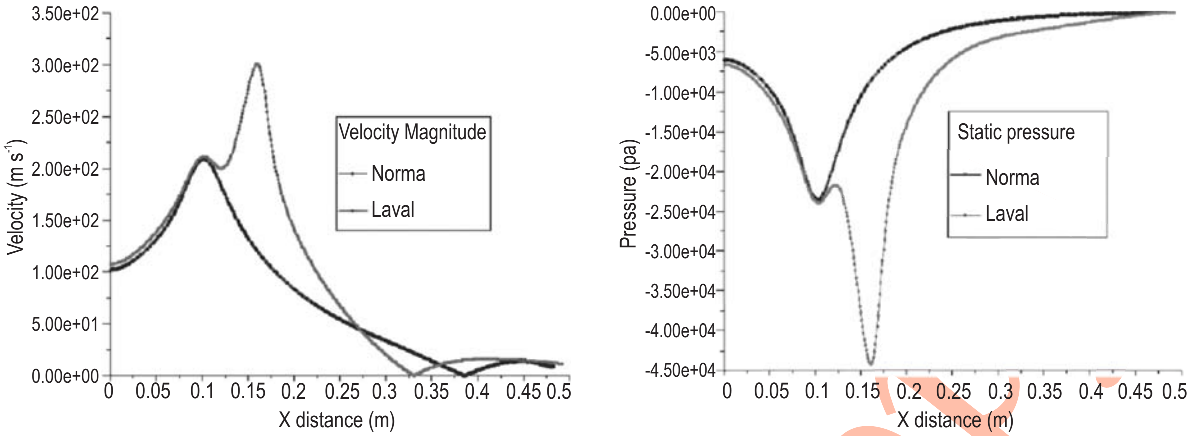

Fig. 6 : The velocity and pressure distribution curves along the center axis of the foam breaker(y=0): (a) The velocity distribution curves; (b) The pressure distribution curves

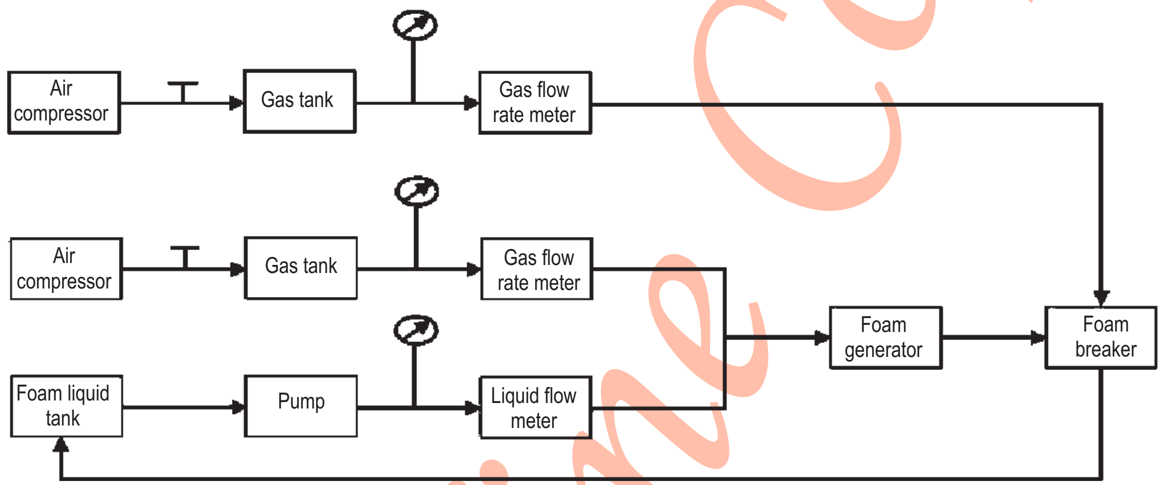

Fig. 7 : Sketch of experimental stand

Foam system No. 1: 0.5% SDS + water;

Foam system No. 2: 0.5% SDS+ 0.02% polyacrylamide + water;

Foam system No. 3: 0.5% SDS+ 0.05% polyacrylamide + water.

Half-lives of three foam systems were 10, 30, and 60 min.

The foam base fluid was kept at 1.5 l min^{-1} and the gas-to-liquid ratio at 100. The results in Fig. 11 showed that the foam-breaking efficiency decreased as the foam stability increased. The foam-breaking efficiency of two-stage laval foam breaker remained above 85% and was better than normal foam breaker.

Fig. 12 shows picture of two-stage laval foam breaker before and after foam breaking in the experiment. Fig. 12(a) shows that the foam system had a large volume and occupied a large amount of space before defoaming. When two-stage foam breaker was operated, the foam volume reduced greatly, and the fluid mixture that flowed out of the foam breaker had good fluidity, as shown in Fig. 12(b). Therefore, the foam drilling fluid could be reutilized in time, which significantly reduced foam drilling cost.

A novel two-stage laval mechanical foam breaker was designed in order to environmental antifoaming based on a normal annular foam breaker. The defoaming effect was comparatively analyzed through a numerical simulation and laboratory experiments. The following conclusions can be drawn:

The numerical simulation results showed that two-stage laval foam breaker featured greater negative pressure and larger negative pressure region compared with the normal foam breaker. The foam-breaking efficiency of two types of foam breakers increased as gas-to-liquid ratio increased, thus indicating that they are highly suitable for destroying the dry

Fig. 8 : Picture of two-stage laval foam breaker

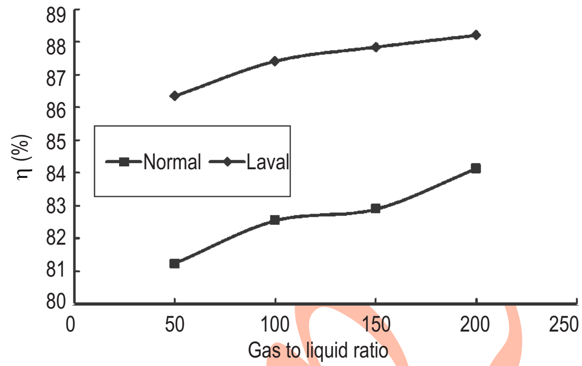

Fig. 9 : Relationship between the gas to liquid ratio and foam-breaking efficiency

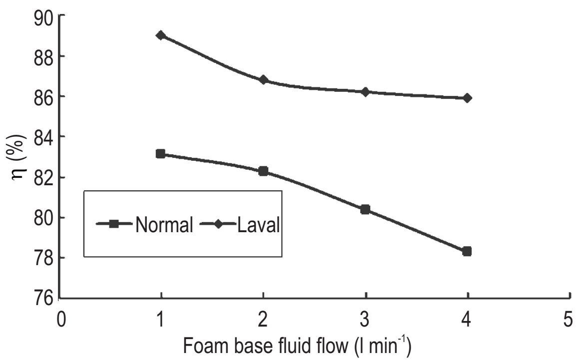

Fig. 10 : Relationship between fluid flow rate and foam - breaking efficiency

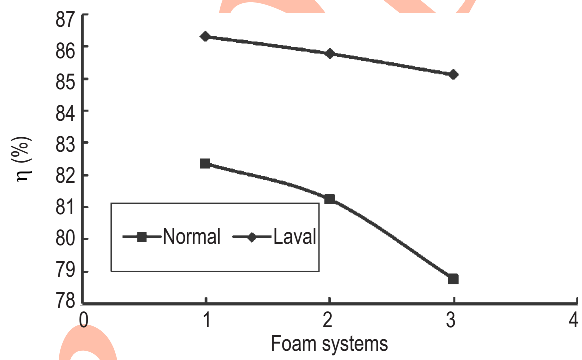

Fig. 11 : Comparison of different foam systems

(a) (b)

Fig. 12 : Experimental pictures of foam breaker before and after foam breaking: (a) State of the foam fluid before breaking; (b) State of the foam fluid after breaking

foam system. The foam-breaking efficiency of two-stage laval foam breaker was higher than normal foam breaker under similar gas-to-liquid ratio. In the experiments, the foam-breaking efficiency of normal foam breaker decreased to 78%, whereas two-stage laval foam breaker remained higher than 85% as foam base fluid flow rate increased. The foam-breaking efficiency of two-stage laval foam breaker was higher than normal foam breaker when foam stability increased. The foam solution could be recycled and reutilized by using two-stage laval foam breaker. Not only the foaming agents but also the volume of water disposed was reduced greatly which could reduce environmental pollution.

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