Study on the stability and rheological properties of nitrogen foam under high-pressure condition

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Abstract. After a period of exploitation of carbonate fractured-vuggy reservoir, the water content of oil well keeps increasing, and some wells appear violent water flooding in a short period of time, which leads to the rapid decrease of production. The injection of particle plugging agent is one of the main measures to improve the oil recovery. Foam fluid has the characteristics of low density, high viscosity and low moisture filtration, which can effectively carry plugging particles to the target plugging layers. A stable foam system with high temperature and salinity is optimized and the rheological properties of the foam are studied in this research. The results show that the foam can maintain high viscosity and carry particles effectively even at a higher shear rate.

Keywords: Nitrogen foam; foam stability; rheological property.

1. Introduction
Fractured-vuggy carbonate reservoir has strong anisotropy and heterogeneity (Manrique et al., 2007; Roehl and Choquette, 2012). After a period of exploitation, the water content of oil well keeps rising, and some wells appear violent water flooding in a short period of time (Dai et al., 2018; Wang et al., 2016). The overall effect of oil field development is deteriorated due to the large quantity of water discharge. Therefore, water-plugging technology is the best measure for precipitation and oil increase.

At the same time, carbonate reservoirs are located in ultra-deep strata with high temperature and salinity (Long et al., 2009; Wang et al., 2017; Dehghani and Kamath, 2001). The particle plugging agent ensures long-term chemical stability under harsh reservoir conditions and is almost not affected by shear action. Foam fluid is characterized by small density, high viscosity, small damage to the reservoir and strong carrying capacity (Xiao et al., 2018; Qu et al., 2018; Chen et al., 2019), so it can effectively carry different density of plugging agent particles through longer fractures (Chen et al., 2020; Xu et al., 2020). Moreover, the rise and subsidence of plugging agent particles in the formation can effectively plug the target layers. A foaming agent solution that is resistant to high temperature and salt was optimized, the effect of temperature and pressure on foam stability and the effect of foam quality on foam rheology were studied in this paper. The results show that the foam can carry particles efficiently because of its high viscosity even at high shear rates.
2. Foam system performance evaluation

2.1. Materials and apparatus

2.1.1. Material $\text{N}_2$ (provided by Qingdao Tianyuan Company, gas purity: 99.9%), foaming agent: YF-1, ZK25130, ZK12200, ZK25100, inorganic salts: $\text{NaCl}$, $\text{CaCl}_2$, $\text{MgCl}_2$ $\cdot$ 6$\text{H}_2\text{O}$

2.1.2. Apparatus: Waring Blender, high temperature and pressure magnetic stirring blender, measuring cylinder, stopwatch, pressure gauge.

![High temperature and pressure magnetic stirring blender](image)

**Fig.1** High temperature and pressure magnetic stirring blender

2.2. Experimental Steps

2.2.1. Normal temperature and pressure evaluation. Waring Blender was used to evaluate the properties of the foaming agent under normal temperature and pressure. After 100mL foaming agent solution was stirred at a speed of 8000r/min for 3min, the measuring cylinder was used to measure the foam volume. The foam volume represented the foaming ability of the foaming agent. Then, the half-life for precipitation of 50mL liquid from the foam was recorded to characterize the foam stability.

2.2.2. High temperature and pressure evaluation. In the stability evaluation of high temperature and high pressure of foam, close the bottom valve and inject 100mL foaming agent solution into the magnetic stirring blender agitator. Nitrogen container was connected with the blender and the pressure gauge indicates the pressure. The valve was closed to keep the device airtight. After setting different temperature and pressure, stirring at 1300r/min for 3min, the volume of foam can be obtained in the visual window and the time when the volume of foam changes to half of the initial time can be recorded by the stopwatch. The gas cylinder can supplement extra $\text{N}_2$ to make the blender reach to specific pressures.
2.3. Results and analysis

2.3.1. Foaming agent system optimization. Fig.2 shows the foam volume and half-life of surfactant solution at different foaming agent concentrations. As shown in Fig.2, the foam volume and half-life generally increase first with the increase of surfactant concentration, and then remain stable. Since the surfactant reaches a critical micelle concentration (Chen et al., 2019), beyond which the foam improvement effect is not obvious, the preferred concentrations of YF-1, ZK25130 and ZK25100 are 0.7%, 0.6% and 0.5%, respectively. Fig.3 shows the foam stability of the foaming agent solution with optimal concentration under different salinity. It can be obtained that YF-1, ZK25130 and ZK25100 have strong salt tolerance. Considering the performance and economic factors of foaming agent, YF-1 solution with a concentration of 0.7% was selected as the surfactant system in subsequent experiments.

![Fig.2 Concentration optimization. (a) Foam volume (b) Half-life](image1)

![Fig.3 The effect of salinity. (a) Foaming volume (b) Half-life](image2)
2.3.2. The effect of temperature and pressure

![Fig.4](image_url)

Fig.4 Foam volume in visual window. (a) Solution injection (b) During blending (c) After blending

![Fig.5](image_url)

Fig.5 The effect of temperature and pressure. (a) Foam volume (b) Half-life

The evolution of foam can be observed from the visual window of the blender. Fig.4 (a) and (b) respectively represent the surfactant solution after injection from the upper inlet and foam evolution after stirring. Fig.5 shows the foam volume and half-life of surfactant solution at different temperatures and pressures. With the increase of temperature, the foaming volume and the half-life of the foam show a rapid trend of decline, however, the stability of the foam increases with the increase of pressure. From Fig.3, the foam generated by YF-1 surfactant solution with 0.7% concentration and nitrogen has strong stability under high temperature and pressure.

3. Foam rheology investigation

3.1. Experimental apparatus

Fig.6 is the flow chart of the pipe flow testing system. The gas flowmeter and the ISCO double plunger pump control the injection volume ratio of nitrogen and foaming agent solution respectively. Thus, foam of various quality can be produced in the foam generator and foam flows with various shear rates in the tube by changing the velocity at the same volume ratio. The both sides of the pipe with the length and diameter of 4.8m and 1mm are connected with differential pressure sensor to calculate the effective viscosity and rheological parameters of the foam.
3.2. Analysis of results
Experts at home and abroad regard the foam fluid system as a power law fluid, and the constitutive equation is shown below:

\[ \tau = K \dot{\gamma}^n \]

Where \( \tau \), \( K \), \( \dot{\gamma} \) and \( n \) are shear stress, Pa, consistency coefficient, Pa·s\(^n\), shear rate, s\(^{-1}\) and rheological index.

\[ \dot{\gamma} = \frac{8u_m}{D} \]

\[ \tau = \frac{D\Delta p}{4L} \]

Where \( u_m \), \( D \), \( \Delta p \) and \( L \) is average velocity of velocity, m/s, diameter, m, differential pressure, Pa, and length, m of pipe. On the double logarithmic axis, the x and y coordinate refer to \( \lg \dot{\gamma} \) and \( \lg \tau \), and curve slope is \( n \).

According to the calculation, Fig. 7 and Fig.8 show the variation curve of viscosity and shear stress of foam with shear rate under different foam qualities. As can be seen from Fig. 7, the viscosity of the foam decreases with the increase of foam quality, and the foam maintains a high viscosity when the foam mass is 66.7% and 75%. Moreover, with the increase of shear rate, the viscosity of foam decreases gradually. Since foam can be regarded as power law fluid, Table1 shows the rheological index of foam under different foam qualities. The rheological index decreases with the increase of foam quality, and the consistency coefficient increases first and then decreases slightly when the foam quality reaches 83.3%.
4. Conclusion
(1) With the increase of temperature, the stability of foam decreases gradually. However, foam stability increases with the increase of pressure. Under the condition of high temperature and high pressure, an optimized surfactant can ensure the stability of the foam.

(2) The viscosity of the foam decreases with the increase of foam quality. However, with the increase of shear rate, the effective viscosity of foam decreases gradually. Even if the foam mass is 90% and the shear rate is $630\text{s}^{-1}$, the foam viscosity is more than 30 times that of water. Therefore, foam can effectively carry the particle plugging agent to block the target layer.

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