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Experimental study on the rheology of CO₂ viscoelastic surfactant foam fracturing fluid

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ABSTRACT

Foam provides a highly attractive alternative to conventional non-Newtonian fluids for various oil and gas fracturing applications because of high viscosity and low liquid loss. However, much work has been carried out under 7 MPa, a pressure much less than that of the practical fracturing value. In this paper, the rheology of CO₂ viscoelastic surfactant foam fracturing fluid was investigated under downhole condition on a large scale flow-loop experiment system. The testing results show that the foam fluid is shear thinning and its rheological properties can be described by the power-law model. Besides, the character of the fluid is different greatly from that of single phase non-Newtonian fluid because of its formation of foam and structure of external phase. It was also found that the viscosity of CO₂ viscoelastic surfactant foam fracturing fluid was proportional to the increment of foam quality and pressure, which, however, was inversely proportional to the increase of temperature and shear rate. Moreover, through analysis of the effects of different factors on the rheology characteristics, the correlations of rheological parameters, as well as the relation of frictional resistance coefficient λ versus generalized Reynolds number Re' , were obtained.

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1. Introduction

Characterized by excellent proppant carrying capacity, quick flowing back, less formation damage and fluid loss (Gidley et al., 1995), foam fracturing technology that takes foam fluid as sand carrier is especially suitable for exploiting low permeable oil/gas reservoir and plays an important role in hydraulic fracturing. As a fracturing fluid, the foam fluid's properties, especially its rheological characteristics, have a great effect on the fracturing result. So up to now, much attention was paid to it.

Mitchell et al. (1970) studied the aqueous foam in small capillary tubes and classified it as a Bingham fluid with a strong dependence on foam quality. No wall slippage effect was observed as shear stress and tube diameter increase. Furthermore, the viscosity was dependent on shear rate when foam quality was greater than 54%.

Saintpere et al. (1999) investigated the rheological properties of the aqueous foam for underbalanced drilling. Gelled foams with polyacrylamide (PAA) and xanthan were investigated at the ambient conditions using parallel-plate geometry. It was found that the apparent viscosity of foam was under the influence of foam quality, texture and the concentration of polymers in the liquid

phase. Their results confirmed that foam is a yield-pseudoplastic fluid and can be represented by a Herschel–Bulkley model.

King (1985) found foams to be pseudoplastic and several orders of magnitude more viscous than the liquid phase, with drier foams having higher apparent viscosity than wet ones. As the capillary-tube dimensions decreased (both length and diameter), the apparent viscosities measured increased.

Reidenbach et al. (1986) used a recirculating loop to perform experimental tests with gelled water foams using N₂ and CO₂ as the internal phase. The Herschel–Bulkley model was used to describe gelled foams, and aqueous foams were characterized with a classical Bingham plastic model. It is concluded that the flow behavior index of foam fluids was the same as that of the liquid phase, while the foam consistency index was a function of the liquid phase consistency index and foam quality.

Harris and Reidenbach (1989, 2000) used a recirculating flow loop to investigate the rheology of nitrogen foam at 6.9 MPa and various temperatures up to 149 °C. Hydroxypropyl guar (HPG) was used as the liquid phase. A phenomenon of yield pseudoplastic was observed on the foam, which can be described by the Herschel–Bulkley model. In addition, they assumed that the flow behavior index of foam fluid was the same as that of the liquid phase and that the consistency index was a function of liquid-phase consistency index and foam quality (percentage ratio of CO₂ over the total foamed fluid volume). Harris (Harris et al., 2000) investigated the rheological properties of mixed-gas foams and the

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effects of crosslinker concentration on flow properties of the crosslinked foams. He observed that the rheological properties of mixed foams are very similar to the rheologies of N₂ and CO₂ foams. He also found that viscosity of the crosslinked foams was generally one to two times higher than that of linear gel foams by using the Herschel–Bulkley model to define both of their rheological behaviors. In addition, empirical correlations were developed for borate-crosslinked foam viscosity.

Phillips and Couchman (Phillips et al., 1987) investigated the rheology of CO₂ foam at 6.9 MPa and high temperatures (37.8–121 °C) with a single-pass viscometer. Increasing foaming-agent concentration enabled little corresponding increase in foam stability when that is greater than a certain level, while increasing the gelling agent's concentration could do it.

As a substitute of polymer fracturing fluid, viscoelastic surfactant (VES) fracturing fluid was first put forward by engineers of Schlumberger and experts of Eni-Agip (Samuel et al., 1999). The surfactant molecules in the solution would associate with each other and form micelles at specific conditions (Mendes et al., 1997), the micelles overlap with each other and interweave into a complex network structure, which results in the viscoelastic character of VES fracturing fluid. The micelles is a balance system, the molecular weight and the structure of micelle are subjected to the variation in the conditions (Zhang et al., 1999), and the micelles are broken by dilution by formation water or by contact with hydrocarbons, but the surfactant molecules remain intact (Fu and Chang, 2005). CO₂ viscoelastic surfactant (VES-CO₂) foam fracturing fluid, which combined VES fracturing fluid and CO₂ foam fracturing technology, was first successfully used to develop low permeability and low pressure sandstone reservoir in 2006. The rheological properties and combining forms of VES-CO₂ fracturing fluid have been the hotspots in related researches. Buston et al. (2007) found that the viscosity of VES-CO₂ fracturing fluid is not a function of shear time, and comparing to the crosslinked guar system, the VES-CO₂ fluid viscosity is greatly reduced, yet the proppant transportation ability is not. Chen et al. (2005) studied the combining forms of VES fluid and supercritical CO₂, pointing out that the mixture of fracturing fluid and supercritical CO₂ will behave more like an emulsion, which is commonly referred to as a foam.

However, most of the experimental research work has been done under 7 MPa, which is much less than that of the practical fracturing. Great change of pressure can influence the fluid's property obviously, because the inner phase is gas which is easily compressed. This means the data obtained under low pressure may be not applicable to practical fracturing (Harris et al., 2000). Considering the lack of the present research on the rheology of foam under high pressure, here we studied the rheological properties of VES-CO₂ foam fracturing fluid under down-hole condition on a large scale flow-loop experiment system.

2. Experiment setup

In addition to normal solid, liquid and vapor phase, CO₂ can also exist in a supercritical phase when the temperature is above 31 °C and pressure is above 7.3 MPa. Under fracturing conditions, system pressure usually ranges between 10 MPa and 60 MPa, CO₂ is a liquid below 31 °C and in its supercritical state when the temperature is above 31 °C in this pressure range, and when CO₂ enters the supercritical state, it exhibits unique physical properties, and it has the solvating power of a liquid and a diffusivity of a gas (Chen et al., 2005). The main agent in VES fluid used as thickener in this experiment is 18 alkyl three methyl ammonium bromide, which is one of the most used surfactant at present (Zhang et al., 2011), and the molecular structure was shown in

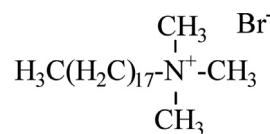


Fig. 1. Molecular structure of surfactant.

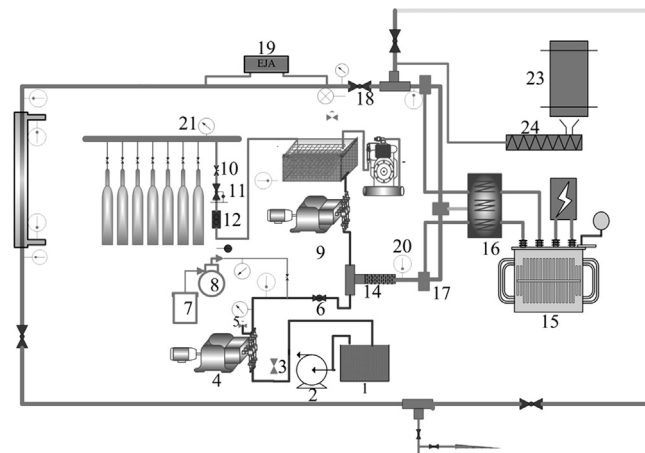


Fig. 2. The experiment system. 1. Liquid cell, 2. Rotameter, 3. Valve, 4. Plunger pump, 5. Safety valve, 6. Check valve, 7. Surfactant pool, 8. Adding pump, 9. Plunger pump, 10. Valve, 11. Check valve, 12. Buffer tank, 13. Liquefaction plant, 14. Foam generator, 15. Transformer, 16. Electrical heater, 17. Electrode, 18. Needle valve, 19. EJA differential Pressure Transmitter, 20. Thermocouple, and 21. Manometer.

Fig. 1, the concentration of main agent in VES fluid is 3.8 wt%. Sulfosalicylic acid triethanolamine ester is used as crosslinker with 1.5 wt% concentration in the VES fluid, and potassium chloride is used as activator with 0.8 wt% concentration, the zero shear viscosity of VES fluid under 100 °C is 100 mPa s, and the temperature resistant capability is above 120 °C.

The VES-CO₂ foam fracturing fluid used in this research belongs to non-Newtonian fluid. Several apparatuses are developed to test the rheological properties of non-Newtonian fluid, such as tubule rheometer, rotating cylinder viscometer, plate cone rheometer and dynamic stress rheometer. Different apparatuses are suitable for different conditions. For instance, the tubule rheometer is applicable to the condition on which the shear rate is both low and high, and it is especially useful in high shear rate. Moreover, it works effectively when pressure and temperature change. According to the principle of the tubule rheometer, a large scale flow-loop experiment system was designed, in which the rheological parameters of foam fracturing fluid can be obtained by testing flux and pressure drop when the fluid flows through tubule in constant shear rate.

Fig. 2 shows the schematic diagram of the experiment system. The flow loop could generate foam fracturing fluid at temperature above 120 °C and pressure above 60 MPa. As shown in Fig. 2, the flow loop is not a real recirculating loop. The whole system pipeline is about 20 m, the heating section is about 12 m before fluid enters the test section, and the time of residence in the loop is about 35–75 s. The equipment is composed of test sections of rheology and convective heat transfer. The pipes of both sections are 8 mm in inner diameter, 16 mm in outer diameter and 1000 mm in length. Pressure drop and temperature are monitored by EJA differential pressure transmitter and K-type thermocouples, respectively, the accuracy and resolution of each sensor are illustrated in Table 1. Before each experiment, the measuring instruments and pumps should be calibrated, and standard fluid water would be used to test the experiment system to ensure reliability.

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