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# Effect of foam quality on flow behavior of liquid $CO_2$-based foam fracturing fluid stabilized by hydrofluoroether

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ABSTRACT

Hydrofluoroether $C_4F_9OCH_3$, as a foaming agent in liquid $CO_2$, is used to stabilize bubble in liquid $CO_2$-based foam fracturing fluid which is waterless and no damage to oil-gas reservoir. However, characteristics of this environmental friendly $CO_2$-based foam, such as the foam morphology and its flow behaviors in pipe, are insufficiently understood. Especially, foam quality, one of important characteristic parameters in a foam fluid, has significant effects on foam structure and flow behaviors of $CO_2$-based foam. By means of the flow tests in pipes with different diameters, it was found that the $CO_2$-based foam displayed wall slip phenomenon, and Oldroyd-Jastrzebski method was used to deal with this phenomenon. Effective viscosity of this $CO_2$-based foam, as well as convective heat transfer coefficient initially increases and then decreases with the increase of foam quality. Due to dominant collision and friction among bubbles, their values reach the corresponding maximums when the foam quality is about 0.82. Meanwhile, the evolution of rheological parameters of $CO_2$-based foam with the foam quality is shown as well, and the exponential relationship between yield stress and foam quality is illustrated. Additionally, as for the flow friction characteristics, it shows that fanning friction factor increases and drag reduction rate initially increases and then decreases as the foam quality is increased.

## 1. Introduction

The contradiction between supply and demand of oil and gas is becoming increasingly prominent in China. On the basis of this situation, increasing the production of oil and gas is an important countermeasure to deal with the issue. Fracturing is one of the most widely used methods in the development of low permeability reservoir (Holt et al., 2015) which includes shale gas, tight sandstone gas and coal mine methane reservoir. The performance of the fracturing fluid is an extremely important factor that has influence on the success or failure of fracturing (Stringfellow et al., 2014; Yegin et al., 2016). As for the fracturing fluid of oil field, it is generally demanded that it has low fluid loss and friction drag, strong proppant-carrying capacity, good compatibility with the original fluid and rock of the stratum, easy flowback after fracturing operation. Usually, to reduce fracturing fluid loss and improve its carrying capacity (Pangilinan et al., 2016), crosslinking agent or thickener is added into a water-based fracturing fluid. However, these measures often lead to inevitable damage to the stratum. They generally leave residue of fracturing fluid in stratum and form filter cakes to plug the reservoir pore. On the other hand, for oil and gas reservoir of low pressure, water-based fracturing fluid will be stranded in the reservoir, which is not conducive to the flowback of fracturing fluid. Consequently, the groundwater will be polluted (Vengosh et al., 2014). Therefore, under the trends of high-efficient and non-residue of fracturing fluid, fracturing technology of no water is developed to reduce the damage of fracturing fluid to the reservoir.

Common fracturing fluid of no water includes oil-based, alcohol-based and $CO_2$-based. In comparison, the physicochemical properties of $CO_2$ make it have more advantages as a fracturing fluid, such as least damage to reservoir, exhaustive flowback, less handling expense and so on. Whereafter, in order to increase the viscosity and proppant-carrying capacity of $CO_2$ fracturing fluid, $N_2$ is added into the liquid $CO_2$ in the hope of forming foam fluid (Rogala et al., 2012). As a result, for this $CO_2$-based foam, its structure consists of a internal phase (*i.e.* $N_2$) and a external phase (*i.e.* liquid $CO_2$). Nevertheless, the forming bubbles are extremely unstable, and the internal phase $N_2$ may even turn into external phase. As a consequence, the viscosity of this fluid is even lower than that of $CO_2$. Therefore, in order to make the bubble in the liquid $CO_2$ become more stable, some researchers started to seek whether there were some foaming agents which could stabilize this $CO_2$-based foam.

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Moreover, these foaming agents must have no damage to the reservoir. At last, Gupta et al. found that hydrofluoroether could play the role of this foaming agent (Gupta et al., 2004).

This hydrofluoroether can be expressed as a general formula:

$$R_f—O—R \tag{1}$$

where, R is an alkyl group of acyclic branched or straight chain and $R_f$ is a fluorinated derivative of a cyclic or acyclic, branched or straight chain alkyl group having more than 2 carbon atoms. These compounds have no damage to the reservoir and are able to dissolve in the liquid $CO_2$. One of these compounds is $C_4F_9OCH_3$ which has been successfully used in a number of fracturing projects (Gupta, 2003). The compound ($C_4F_9OCH_3$) is nonionic foaming agent in the liquid $CO_2$. It also has low surface tension of 13.6 dynes/cm, a boiling point of 334 K and a short atmosphere half-life. These characteristics make it almost nontoxic to the ground (Gupta, 2003) and suitable for use in the liquid $CO_2$ (Gupta, 2003). Especially, for the development of shale gas in China, this system of no-water has a well application perspective since the content of clays which generally swell in water is high in some shale reservoirs of China (Luo et al., 2015a). Furthermore, $CO_2$ is able to displace $CH_4$ which adsorbs on the surface of shale due to competitive adsorption between $CO_2$ and $CH_4$ (Heller and Zoback, 2014). Meanwhile, it can implement geological sequestration of $CO_2$ as well (Tao and Clarens, 2013).

Nevertheless, the foam morphology and the detailed rheological properties of this excellent liquid $CO_2$-based foam have not been reported. As a consequence, it is difficult to guide the corresponding fracturing treatment. In practice, the general foam, known as a complex non-Newtonian fluid and a discrete system, is also a multiphase structural fluid. In this foam structure, foam quality $\Phi_g$ (*i.e.* gas fraction in foam) is one of the main parameters that have significant effects on related rheological behaviors of foam fluid. It can be expressed as:

$$\Phi_g = \frac{V_G}{V_G + V_L} = \frac{V_G}{V_F} \tag{2}$$

where, $V_G$ is gas volume (*i.e.* internal phase), $V_L$ is liquid volume (*i.e.* external phase) and $V_F$ is the total volume of foam. On the mesoscopic bubble scale, foam quality influences the local foam structure and force parameters (Jing et al., 2015, 2016), such as T1 topological event (Jing et al., 2015), bubble pressure, foam film force (Jing et al., 2016) and so on. These mesoscopic evolution with foam quality presents different macroscopical flowing behaviors, such as shear modulus (Cox and Whittick, 2006; Jaipan et al., 2013), bulk viscosity of foam (Sun et al., 2014), relation between shear stress and strain or shear rate (Sun et al., 2014), convective heat transfer behavior (Sun et al., 2011) and so on. Moreover, these macroscopical behaviors may be various due to different material compositions. For instance, with regard to the water-based foam fracturing fluid, Luo et al. (2015b) found the effective viscosity of GRF-$CO_2$ foam fluid initially increased and then decreased with foam quality. The viscosity reached the maximum value at $\Phi_g = 0.85$. Yet, Li et al. (2017) explored the rheological properties of another foam fracturing fluid and found the different evolution characteristics of viscosity with the foam quality. Therefore, it can be known that the effect of foam quality on the macroscopical flow behaviors of different foam fracturing fluids is various. With regard to this high-efficiency and environmental friendly $CO_2$-based foam, it is more necessary to explore the effect of foam quality.

To sum up, in the present work, it is mainly focused on the flow behavior of liquid $CO_2$-based foam fracturing fluid, and the influence of foam quality on flow behavior and convective heat-transfer coefficient will be explored. Therefore, this paper is organized as follows: section 2 describes the experiment system and test principle. The experimental results and analysis are displayed in section 3. In addition, the effect of foam quality on heat transfer behavior of flowing $CO_2$-based foam is shown as well.

## 2. Experiment system and test principle

As illustrated in Fig. 1, the experimental system consists of transport system of fracturing fluid, liquid $CO_2$ refrigeration system, heating system, high-pressure visual segment, rheological test and heat transfer characteristics test sections. This system is mainly used to evaluate the related flowing performance of fracturing fluid. Especially, the test section of heat transfer is designed to simulate the heating effect of fracturing fluid flowing in the stratum.

1. $CO_2$ gas cylinder; 2. high-pressure needle valve; 3. pressure gauge; 4. cooling salt water tank; 5. refrigerating machine; 6. thermocouple; 7. buffer tank of brine; 8. brine pump; 9. liquid $CO_2$ plunger pump; 10. check valve; 11. foaming agent tank; 12. High-pressure constant flow pump; 13. air compressor; 14. buffer tank of air; 15. Gas booster pump; 16. $N_2$ gas cylinder; 17. reducing valve; 18. gas mass flowmeter; 19. foam generator; 20. copper electrode; 21. current transformer; 22. voltage regulator; 23. EJA differential pressure transducer; 24. high-pressure quartz pipe; 25. heat transfer casing; 26. counterbalance valve.

In the experimental preparation of liquid $CO_2$-based foam fluid, high-pressure $CO_2$ in the gas cylinder firstly was pressurized to the experimental pressure by plunger pump after it was turned into supercooled liquid cooled by the refrigerating system. The liquid $CO_2$ was then mixed with $C_4F_9OCH_3$ which flowed from the exit of high-pressure constant flow pump. In the foam generator, the $CO_2$-based foam fluid was finally prepared by blending liquid $CO_2$ with $N_2$ which was transported by gas booster pump. The experimental temperature could be controlled by electrical heating system. Whereafter, the $CO_2$-based foam flowed through the rheological test, high-pressure visual segment, and test section of convective heat transfer in sequence. In addition, the measure of heat preservation was implemented on all the pipelines in the system, and the corresponding flux data were collected real-timely.

In the rheological test section, there are stainless steel pipes with four different inner diameters in horizontal direction: 4 mm, 6 mm, 8 mm and 12 mm. The length of stainless steel pipe of 12 mm used to be measured is designed to be 1.5 m and the others are 1 m. The EJA differential pressure transducer is furnished on each testing pipes. It can implement the measurement of pressure drop $\Delta p$ at different shear rates.

Fig. 2 shows the high-pressure quartz pipe which is used to observe foam morphology of $CO_2$-based foam fracturing fluid. It is vertically in parallel on the pipe of the experimental system, as shown in Fig. 1. The inner diameter of the high-pressure quartz pipe is 10 mm and length 185 mm. Maximum design pressure of the quartz pipe is 15.0 MPa. In the experiment, the foam fluid which was generated in the foam generator flowed into the high-pressure quartz pipe. The valves located at both ends of the quartz pipe were then closed. Meanwhile, the valve in the pipe which was in parallel with the quartz pipe was opened to ensure the security of pipeline. In addition, the pipe distance between foam generator and visual quartz pipe is close to 13 m.

Fig. 3 displays the dynamic evolution of $CO_2$-based foam in the closed high-pressure quartz pipe. It can be obviously obtained that the static stability of $CO_2$-based foam is poor. Its time of duration is only a few seconds. Nevertheless, on the basis of flowing velocity of $CO_2$-based foam in the experiments, it could be easily known that the flowing time of the $CO_2$-based foam was more than 15 s from the foam generator to this visual quartz pipe. During this period, the reason why $CO_2$-based foam could maintain the foam morphology was that bubbles constantly burst and regenerated during rapid flow in the pipe. The behavior is advantageous for the proppant transport, in comparison to pure liquid $CO_2$ fracturing fluid. Additionally, it can be seen that liquid $CO_2$-based foam fracturing fluid displays transparent situation, and single bubble approximates round sphere. As shown in Fig. 3, liquid fraction in the bottom of high pressure quartz tube increases with the foam drainage. There are a small number of bubbles in the liquid $CO_2$ and the gas finally separates from the liquid $CO_2$.

On the basis of this experimental system, shear stress and shear rate