HIGH TEMPERATURE RHEOLOGY
OF
CO_2 FOAM FRACTURING FLUIDS

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ABSTRACT

CO_2 foam properties were measured to 300°F in a high temperature, high pressure pipe viscometer. The effects of foamer type and concentration on high temperature CO_2 foam rheology were determined. It was found that, above a certain level, further increases in foamer concentration provide little corresponding increase in foam stability or rheology. CO_2 foam stability can be improved by the use of higher concentrations of gelling agent.

Test data indicates that higher concentrations of foamer and gellant are required to produce stable CO_2 foams, as compared to N_2 foams. It was found that rheological data generated for N_2 foams will not be sufficient to describe the same system when pumped as a CO_2 foam.

INTRODUCTION

During the past several years, CO_2 foam stimulation treatments have become increasingly common. There are many benefits associated with the use of these fluids. CO_2 foam is a low viscosity, perfect support fluid which provides more rapid and complete treatment fluid recovery in under pressured zones, and reduces formation damage by its low pH and by minimizing the quantity of aqueous fluid which enters the formation.

CO_2 offers several advantages over N_2[1]. Because CO_2 is more soluble in treating fluids that is N_2, longer shut-in times may be tolerated without excessive loss of gas energy. The higher density of CO_2 provides increased hydrostatic pressure. This may result in lower surface treating pressures, providing the advantage is not offset by higher tubular friction pressures.

In order to take full advantage of the unique properties of CO_2 foam fracturing fluids, an accurate knowledge of foam rheology at downhole conditions is necessary.[1] Data has previously been published for CO_2 foams at ambient temperature[2] and for N_2 foams at high temperature.[3] Carbon dioxide and nitrogen foams behave similarly at ambient temperature and this relationship was assumed to be true at higher temperatures.[2]
It has been shown that low pH, such as that caused by CO_2, degrades natural polymers[4] and adversely effects the performance of some foamers.[5,6] This data raised questions regarding the high temperature performance of foams prepared with carbon dioxide. Testing was designed to determine the validity of the assumption that CO_2 foams are equivalent to N_2 foams.[2]

Carbon dioxide foam rheology has now been measured at high temperature and pressure. A variety of CO_2 foam systems were tested at 1000 psi and temperatures ranging from 100°F to 250°F. Surfactant and gelling agent concentrations were varied so that optimum systems could be developed at each temperature. Nitrogen foam was tested under similar conditions for comparison. Common additives were tested to determine their effect on foam rheology.

*Currently employed by the EPA.

TESTING METHODS

Foams are tested on a single pass pipe rheometer, as shown in Figure 1. Liquid CO_2 or gaseous N_2 is mixed on-the-fly with the aqueous portion of the fluid. The mixture passes through an in-line mixer, a heat exchanger, and a rheological test section. The test section consists of three sections of different diameter pipe plumbed in parallel and connected to transducers for measurement of ΔP. Measurements are made over a range of shear rates from 50 to 1000 sec^{-1}. Following the rheological test section, the foam flows into a heated sight glass for measurement of static foam stability (half-life). Previous testing has shown that static foam stability measurements made at high temperature and pressure are a good indicator of flow behavior of foam in porous media.[7]

RESULTS AND DISCUSSION

Comparison of carbon dioxide and nitrogen foams

The pipe rheology data generated by the methods described herein shows that higher loadings of gellant and surfactant are required to produce high temperature stable CO_2 foams as compared to N_2 foams. As shown in Figure 2, the same quantities of gellant and foamer produce a less viscous, less stable CO_2 foam. Although viscosity measurements are shown to 250°F for the CO_2 foam, the foam was not stable under static conditions above 125°F. In contrast, the same system foamed with N_2 was stable to above 250°F.

The difference in stability is partially due to the low pH (∿3.2) which results from the carbonic acid produced by CO_2 saturation of the aqueous phase (Eq. 1). The carbonic acid causes acid hydrolysis of the polymer. Thus, the polymer degrades causing the viscosity of the gelled aqueous phase to decrease, thereby reducing foam stability.

$$\text{Eq.1} \qquad CO_2 + H_2O \rightleftharpoons HCO_3 + H^+ \qquad K_a = 2 \times 10^{-4}$$

Some foamers also appeared to be adversely affected by CO_2. Of the numerous foamers tested, only a very few were capable of producing a stable CO_2 foam. Less than five produced high temperature (>200°F) stable CO_2 foams. In contrast, most of the foamers tested produced high temperature stable N_2 foams.

Tests were conducted to determine if poor foamer performance in the presence of carbon dioxide could be attributed to the low pH (acidity) which results from CO_2. However, when N_2 foam was generated at high temperature using a pH 3.2 aqueous phase, several of the foamers which did not perform acceptably with CO_2, did perform in low pH N_2 foam. These results suggest a chemical interaction, such as carboxylation, between the CO_2 or carbonic acid and some of the foamers.

Rheology of high temperature stable CO_2 foams

Foam stability, like crosslinked gel stability, is critical to job success.[8] This testing has shown that the same system will almost always be much more temperature stable in N_2 than in CO_2. High temperature stable CO_2 foam systems can be obtained using CO_2-compatible foamers and higher gellant loadings.

Rheology data for stable CO_2 foams over a range of temperatures is summarized in Figure 3. Minimum quantities of gellant and foamer are required to support a stable foam at a given temperature. At higher temperatures, more gellant and foamer are required. Above a certain concentration, additional foamer does not provide increased stability. This confirms data previously presented in the literature.[7,9] Figure 3 shows the minimum quantity of gellant required to produce a stable foam at each temperature. If less than the specified amount of gellant is used, an unstable foam may result. Therefore, extrapolation of data is not recommended.

Several of the common fracturing fluid additives and solvents have been shown to behave as anti-foams. All fracturing fluid additives should be tested to determine their effect on foam stability and rheology before they are included in a foamed fluid.

CONCLUSIONS

As with crosslinked fracturing fluid, the goal of a foamed fracturing fluid is to carry proppant into the formation and support it in the fracture until pumping ceases and the formation closes. This can only be accomplished with foams which are stable under low shear and static conditions. Unstable foams tend to phase separate very quickly under conditions of low shear, such as those in the fracture.[3] When phase separation (foam disintegration) occurs, viscosity drops and proppant fall rate increases. This can cause screen-outs and result in less than desirable proppant distribution profiles in the fracture.

The data generated in these tests has already proven very useful in foam fracturing job design. It provides readily available rheology data for use in frac design computer programs. More importantly, it provides much needed information regarding foam stability at temperature. In the past, foam frac screen-outs have been attributed to too little foamer or fluid loss additive.[10,11] The data shows that a particular combination of the correct type and quantity of foamer and a minimum gellant concentration are required to produce a stable foam at temperature.

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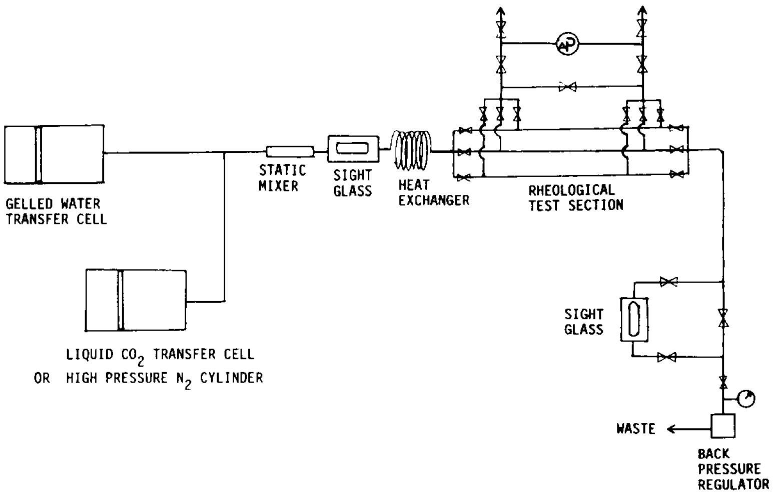

Figure 1—Pipe rheometer

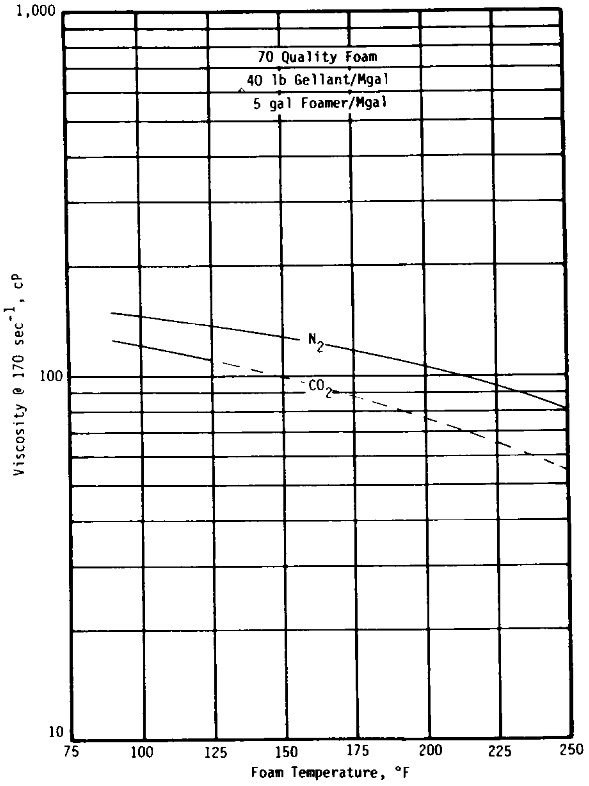

Figure 2—Effect of gaseous phase on viscosity and stability of foam

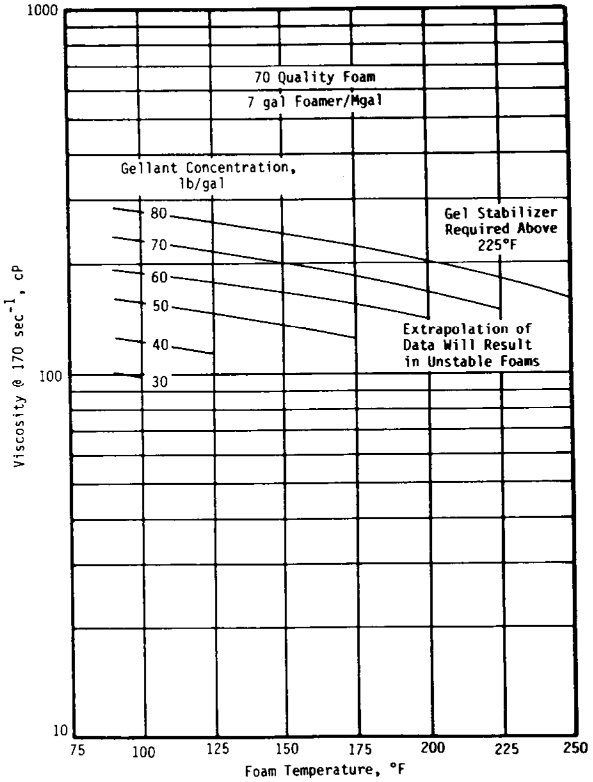

Figure 3—Effect of gellant concentration on viscosity of CO_2 foam