On the Foaming Kinetics of Gas Well Deliquification Process

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A kinetic model was proposed to describe the formation behaviour of foams utilized in gas well deliquification processes. The foaming profiles themselves were determined by reading the foam volume as a function of time in the presence of various concentrations of α-olefin sulfonate (AOS), under the conditions of different temperatures. Effect of the surfactant concentration, blowing rate of nitrogen gas and system temperature on the formation of foams was discussed. The formation behaviour was fitted by the empirical equation $dV/dt = kw^{\alpha}u^{\beta}$. These parameters could be calculated from the experimental data. This kinetic model was tested successfully with the use of the Arrhenius equation, which relates in its logarithmic form of the kinetic constant (ln k) linearly to the reciprocal of the absolute temperature (1/T).

Key Words: Foam, Formation kinetics, Model, Gas well deliquification.

INTRODUCTION

Foams have several applications in oil and gas field operations[1]. In gas well liquid removal applications, the liquid-gas-surfactant mixing must be accomplished downhole and often in the presence of both water and liquid hydrocarbons. Gas becomes more important energy since the demand for natural gas as a clean hydrocarbon source has grown world-wide. As natural gas is extracted, reservoir pressures decline, resulting in, reduced gas flow rates. Gas wells normally have associated water. When velocities are low enough, liquid holdup is higher in this flow regime. The gas production will decrease. There are several ways to solve this problem, *i.e.* mechanical or chemical methods[2]. For mechanical method, artificial pump lift may be used. For chemical method, foam can be used. The foam is the easiest and most economic method to try firstly. The addition of surfactant leads to decrease of the surface tension and formation of foam that has much lower density than the bulk liquid. As demonstrated below, both of these factors facilitate the deliquification of the gas wells. The foam is effective in transporting the liquid to the surface in gas wells with very low gas rates.

Hydrocarbon condensate, brine and high temperature in down hole have negative effect on foam generation. Hence, laboratory test of actual produced fluid is needed to evaluate the effectiveness of foaming properties. However, so far it received insufficient attention particularly[3-6]. To elucidate this problem it is necessary to examine both macroscopic and microscopic aspects of foaming under the gas well deliquification process[7,8].

The objective of this work was to reveal the foaming kinetics by measuring the foam volume as a function of time unloading liquid in down hole. Effect of various factors, such as surfactant concentration, blowing rate of nitrogen gas and temperature, on the foaming behaviour was also discussed.

For the foam generation, we chose α-olefin sulfonate (AOS) at the concentrations of 0.1, 0.15, 0.2, 0.25 and 0.3 %, respectively. The foam suspensions were generated using a modified set up of US Bureau of Mines[4]. A volume of 100 mL of fluid at various hydrocarbon/water ratio was added into a thermo jacket column (77 cm × 5 cm) with medium fret. The nitrogen was used as gas to create the foam at a fixed flow rate of 20, 40, 60, 80 and 100 mL/min, respectively. The amount of foam volume as a function of time was measured to quantify the effectives of the foam formation. Reported values in this paper are the means of at least two replicates.

To describe the curves in Figs. 1 to 2, the following three parameters equation was proposed:

$$\frac{dV}{dt} = kw^{\alpha}u^{\beta} \tag{1}$$

where V refers to the volume of foam at time t, k refers to the rate constant, w describes the surfactant concentration and u is blowing rate of nitrogen gas. The exponents α and β display the partial order for surfactant concentration and blowing rate during this foaming process, respectively. These

parameters could be estimated by fitting the following experimental data.

Determination of α value: Fig. 1 shows the foaming volume (V) as a function of α-olefin sulfonate concentrations (w) at the different blowing rate of nitrogen gas, in the simulated natural gas well. The effect of temperature on the foaming behaviour was depicted in Fig. 1A-1C, respectively. It was seen from above figures that the diverse foams tested all resulted in foaming curves of the same form which exhibits a linear-shaped profile. It may be inferred from this that basic mechanism of foaming was similar in all these cases and did not vary with solution composition, blowing rate of nitrogen gas and temperature. According to the measurement, the foaming behaviour follows partial first-order chemical reaction kinetics in view of surfactant concentration (w). Thus, it is concluded that the value of α is equal 1 for studied scope of temperature.

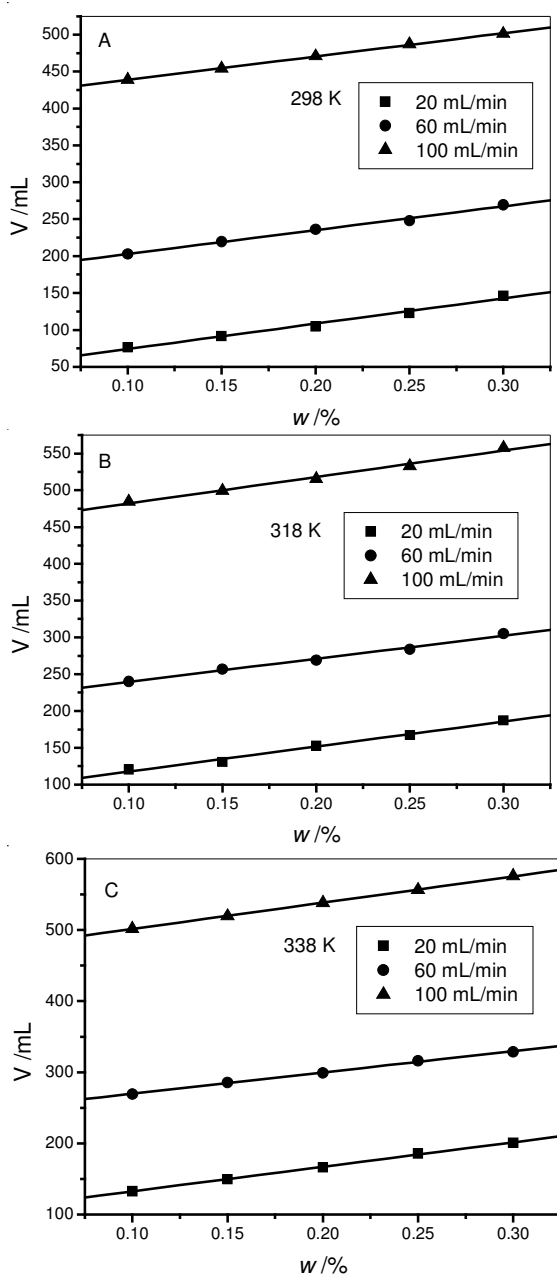**Determination of β value:** Plots of rate of conversion (dV/du) *versus* u of nitrogen gas at different temperatures obtained by differentiating the curves of relationship between and are presented in Fig. 2. From the curves of dV/du *versus* u, the shape of the conversion curve is dependent on the blowing rate of nitrogen gas and displays a linear relationship. Using linear regression, the results may be given as following equation.

$$\lg (dV/du) = I + (\beta - 1)\lg u \qquad (2)$$

The parmeter β could be estimated by eqn. 2 displayed in Table-1. It can be seen that the average values of β exhibit nearly equal at different temperature, which indicates the partial order of u is independent on the blowing rate of nitrogen gas. Here, we define the value of β as 1.62.

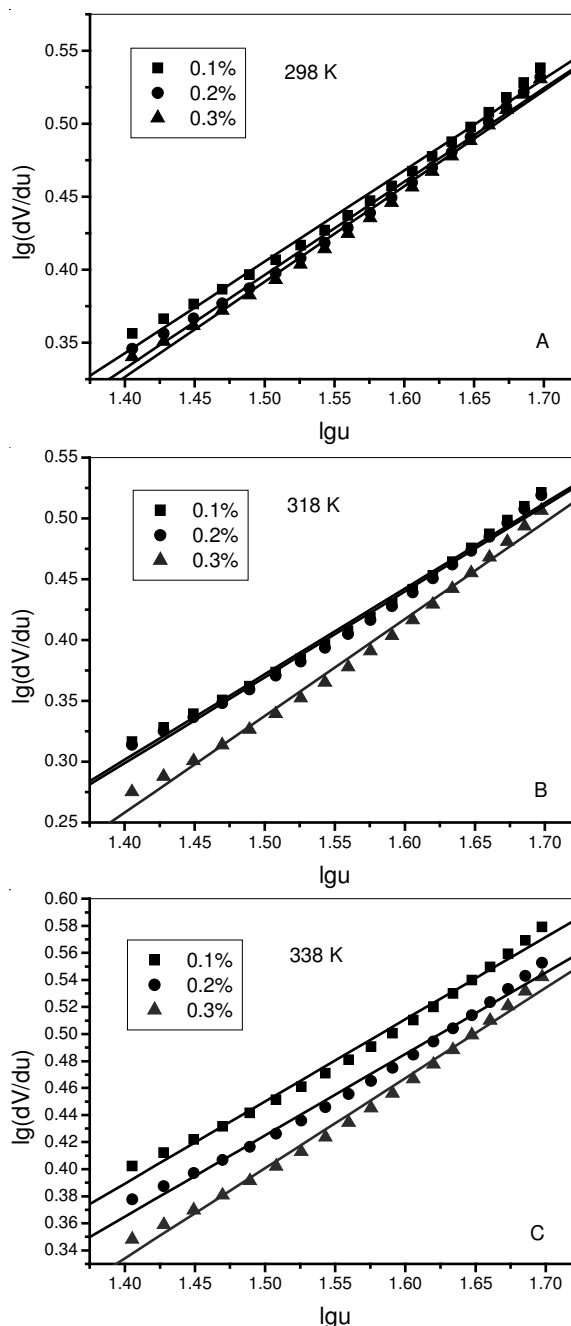Fig. 1. Comparison between predicted and experimental foaming curves for foams

Fig. 2. Comparison between predicted and experimental foaming curves for foams

TABLE-1
α VALUES AT THE VARIOUS α-OLEFIN SULFONATE CONCENTRATIONS

w (%)		0.10	0.15	0.20	0.25	0.30	Average
β	298 K	1.6538	1.6542	1.6395	1.6481	1.6255	1.64
β	318 K	1.6032	1.5951	1.6051	1.6311	1.6953	1.62
β	338 K	1.6075	1.5687	1.6017	1.6228	1.6666	1.61

TABLE-2
k VALUES AT THE VARIOUS α-OLEFIN SULFONATE CONCENTRATIONS

w (%)	0.10	0.15	0.20	0.25	0.30	Average
k	55.3	54.2	55.6	54.5	53.2	54.5
k	137.4	104.0	86.4	76.3	70.9	67.9
k	222.0	167.4	130.2	119.1	98.6	85.6

Thus, the kinetic model could be written as follow:

$$\frac{dV}{dt} = kwu^{1.62} \qquad (3)$$

On substituting the values of dV/du, w and u into the eqn. 3, the rate constant k could be calculated (Table-2).

TABLE-3
k VALUES AT THE VARIOUS TEMPERATURES

T (K)	298	308	318	328	338
1/T	0.003356	0.00324	0.00314	0.00305	0.00296
k	54.5	61.5	67.9	76.9	85.6
ln k	4.00	4.12	4.22	4.34	4.45

Effect of temperature: According to these results, eqn. 1 is regarded as a suitable kinetic model for liquid drainage events of foams. In the following, eqn. 1 is tested with the use of the Arrhenius equation, which relates in its logarithmic form the logarithm of the kinetic constant (ln k) linearly to the reciprocal of the absolute temperature (1/T):

$$\ln k = \ln A - (E_a/RT) \qquad (4)$$

where E_a (J mol^{-1}) is the activation energy and the coefficient A denotes the frequency factor, R (J K^{-1} mol^{-1}) is the gas constant and T (K) represents the absolute temperature.

The natural logarithm of the rate constant of foam formation (ln k) determined at different temperatures was plotted against the reciprocal of the absolute temperature in Kelvins (1/T) as shown in Fig. 3. Performing linear regression, a linear relationship was found between ln k and 1/T which justifies the application of eqn. 1 to the foaming behaviour of foam dispersions (R = 0.998, p < 0.0001) (Table-3).

Eqn. 1 would be an adequate mathematical model to describe the formation behaviour of foams utilized in gas well deliquification processes. Several parameters could be calcu-
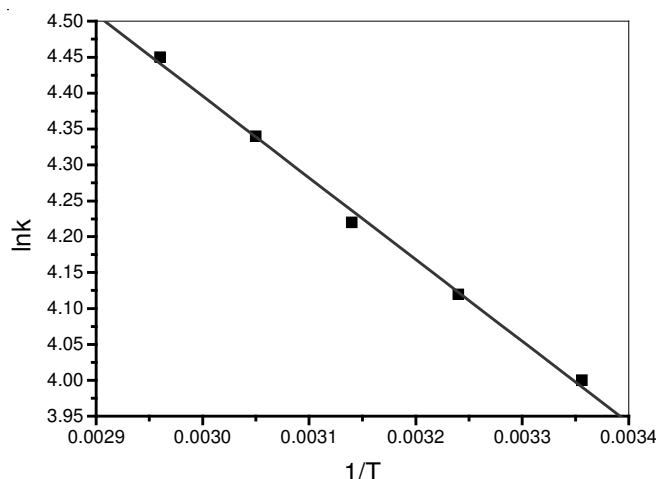

Fig. 3.   Arrhenius plot for the effect of temperature on foaming behaviour of foams

lated from the experimental data. The results of this study would provide a useful insight into the formation and stability of foams and would also helpful for the design of foam systems with specific properties in gas well deliquification technology.

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