



Free drainage and bubble size for aqueous foams stabilized by sodium dodecyl benzene sulphonate

Junchao Wang^{a,b}, Zhipeng Li^{a,b}, Guixia Fan^c, Cuiling Ye^a, Guosheng Li^{a,*}, Yijun Cao^{b,*}

^aSchool of Chemical Engineering and Technology, China University of Mining and Technology, Xuzhou 221116, Jiangsu, China, Tel. +86-0516-8359-1116, email: wjccumt@163.com (J. Wang), Tel. +86-0516-8359-1116, email: lizpcumt@126.com (Z. Li), Tel. +86-0516-8359-1116, email: 4408@cumt.edu.cn (C. Ye), Tel. +86-0516-8359-1116, Fax +86-0516-8359-1116, email: lgscumt@163.com (G. Li)

^bChinese National Engineering Research Center of Coal Preparation and Purification, China University of Mining and Technology, Xuzhou 221116, Jiangsu, China, Tel. +86-0516-8359-1116, Fax +86-0516-8359-1116, email: caoyj@cumt.edu.cn (Y. Cao)

^cSchool of Chemical Engineering and Energy, Zhengzhou University, Zhengzhou 450001, Henan, China, Tel. +86-0516-8359-1116, email: zdhgfgx@zzu.edu.cn (G. Fan)

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ABSTRACT

Foams are widely used in industrial applications such as water treatment, mineral flotation, oil recovery, etc, therefore, it is of great significance to further investigate the foam properties. This paper systematically studied the influences of gas flow rate, surfactant concentration and temperature on the properties of aqueous foams stabilized by sodium dodecyl benzene sulphonate (SDBS) in terms of foamability, foam stability, free drainage and bubble size. The results showed that at the same surfactant concentration as an increase in gas flow rate the foamability of SDBS solution continued to increase while the foam stability was nearly gas flow rate independent. When the optimal gas flow rate was chosen, at $c < cmc$ both foamability and foam stability increased with increasing surfactant concentration, where as at $c \geq cmc$ they kept a plateau. Besides, in the range of our studied temperature, at low temperatures the foamability slightly increased with the rise of temperature, while the foam stability was less affected by temperature. At high temperatures, the foamability was almost temperature-independent, while foam stability decreased with increasing temperature, and in this system 25°C was an ideal foaming temperature. These findings provide guidelines for the efficient preparation and utilization of foam in industrial applications.

Keywords: Gas flow rate; Surfactant concentration; Temperature; Free drainage; Foam stability

1. Introduction

Foam is a dispersion of gas bubbles in a continuous liquid medium where bubbles are separated by thin films that can be relatively thick (wet foams) or thin (dry foams), which are usually stabilized by surfactants [1,2]. Due to their special properties such as lightness and large surface area, foams are widely used in industrial applications including mineral flotation [3,4], oil recovery [5–7], personal-care products, wastewater treatment [8,9], etc. Although foams

are thermodynamically unstable and take place self-destructive processes due to free drainage, bubble coalescence and Ostwald ripening, they can maintain dynamic stability under certain experimental conditions and reagent systems. Therefore, it is of significance to study the influences of foaming conditions and surfactants used to generate foams on foam performance.

Recent years, numerous studies concerning foam properties have investigated the influences of surfactant type and/or surfactant concentration [10–15], gas composition [16] and temperature [17] on foam properties. For example, Harvey et al. [18] studied the effects of different types (i.e.

*Corresponding author.

Dowfroth-250, Dowfroth-400 and SDS) and different concentrations of surfactants (always below the cmc) on foam lifetime and on initial bubble size. They found that foam stability was controlled not only by the liquid drainage process but also by the bubble coalescence. Carey et al. [19] examined the influence of surfactant concentration on foam properties using three different foaming methods. Besides, Hilgendedt et al. [20] conducted free-drainage experiments with slow- and fast-coarsening gases, and found that strong coarsening leads to shorter drainage time and independent of the initial liquid content in the foam. Vera and Durian [21] measured the increased bubble size due to coarsening for drier foams and suggested that coarsening play a significant role in free drainage. Apart from the experimental research, there is much progress in theoretical research. It is widely accepted that drainage is one of the most important foam destabilization mechanisms referring to the flow of liquid relative to bubbles driven by gravity and capillary forces [22,23], and several models have been proposed to model the drainage process [24,25]. Typically, bubble radius is considered as an input parameter for these models [1]. An alternative approach is to simultaneously model drainage and coalescence processes, but direct modeling of the coalescence process is greatly complex because it not only alters the topology of the two coalescing bubbles but also changes the topology of all adjacent bubbles [26]. In addition, the number of bubbles in the real foam is too large for a detailed treatment. These all make the theoretical research of foam properties difficult. Although foam properties have been investigated experimentally, numerically and theoretically, systematic studies are rare. Therefore, the aim of this study is to systematically investigate the influences of gas flow rate, surfactant concentration and temperature on SDBS foam properties. All experiments were performed using a commercially available instrument, FOAMSCAN, which could determine simultaneously foamability, foam stability, liquid fraction (liquid content of foam) and bubble size distribution. This means that it allows us to intensively study the foam stability mechanism because the foam destabilization is mainly controlled by foam drainage, bubble coalescence and Ostwald ripening.

2. Materials and methods

2.1. Materials

The anionic surfactant sodium dodecyl benzene sulfonate (SDBS) (the cmc of SDBS is 1.20 mM [27]) was purchased from Sinopharm Chemical Reagent Co., Ltd (in China) (purity > 98%). The surfactant solutions were prepared with the ultra-pure water which was obtained by purification with a Milli-Q system, and equilibrated for at least 2 h before use. All measurements were conducted at room temperature: $25 \pm 1^\circ\text{C}$.

2.2. Foam properties measurements

To study the foam properties of SDBS solutions systematically, a commercially available instrument, FOAMSCAN (TECLIS, France, <http://www.teclis.fr>), was used to produce foams and measure their properties. The characteris-

tic feature of this instrument is that it allows us to measure simultaneously foamability (the ability of a surfactant solution to generate foam), foam stability (the lifetime of foam), as well as the liquid fraction (liquid content of foam). In addition, it also can analyze the bubble size with the new cell size analysis (CSA) function, which, in turn, allows for a visualization of the destabilizing processes. Readers interested in FOAMSCAN are recommended to refer to [28,29]. Briefly, foam is produced in a round glass column (inner diameter 35 mm, length of the column 298 mm) by sparging N_2 through a surfactant solution (60 mL) via a porous glass disc (pore size 40–100 μm and thickness 3 mm). The gas flow rate is set and adjusted to different rates varying from 30 to 125 mL/min to find out the optimum experimental conditions. Once the preset foam volume is reached, the gas input will stop automatically at once.

A gas flow rate of 50 mL/min turned out to be a good choice and was thus used for most of the measurements. It is noteworthy that although the maximum foam volume was set to 80 mL, the foam volume was always produced between 80–85 mL due to the mechanical limitation of this device (there is a delayed effect between the gas stop and determination of foam volume). For the sake of the accuracy of the experimental results, each measurement was repeated at least three times (looking at Fig. 1 which just shows two separate measurements for reproducibility). Fig. 1 presents the data obtained with the FOAMSCAN at a gas flow rate of 50 mL/min and surfactant concentration of 1.0 cmc. It could be seen that the foam volume (top) and liquid fraction (bottom) were time-dependent. Note that $t = 0$ s is defined as the time when the generation of foam begins.

2.3. Bubble size distribution

Bubble sizes were determined with the new cell size analysis (CSA) software of FOAMSCAN, and the average bubble size was characterized using the Sauter mean radius

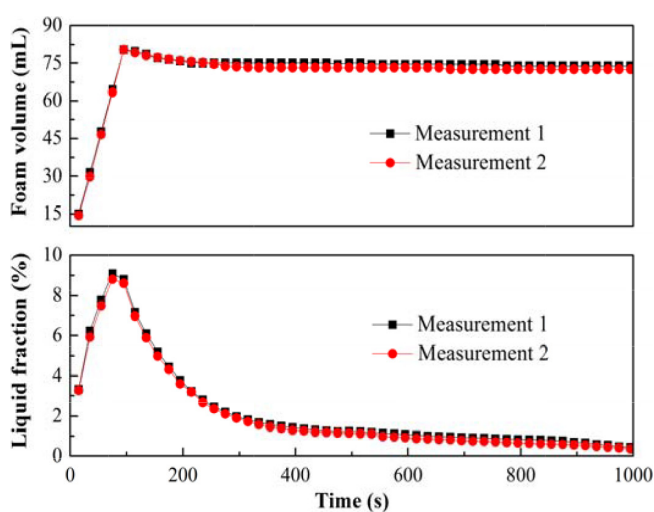


Fig. 1. FOAMSCAN results for two separate experimental measurements. Evolution of foam volume (top) and liquid fraction (bottom) as a function of time for foams stabilized by SDBS at 1.0 cmc and a gas flow rate of 50 mL/min. Note that $t = 0$ s is the time at which the foam generation begins.

$r_{32} = \langle r^3 \rangle / \langle r^2 \rangle$. The bubble images were recorded at the wall of the glass column, around the position at the second electrode, using the CSA-camera during foam generation and destruction. Note that all experiments were repeated at least two times, over 500 bubbles were analyzed in each measurement.

3. Results and discussion

This paper systematically studied the influences of gas flow rate, surfactant concentration and temperature on SDBS foam properties. When it comes to foam properties of surfactants, their characterization usually involves the investigation of both foamability and foam stability. Due to SDBS having the relatively strong foamability, at an optimal gas flow rate of 50 mL/min and all studied surfactant concentrations the foam column was always filled with foam, which meant that the difference in foamability under different experimental conditions could not be observed, so we preset a maximum foam volume (80 mL) and the foamability was evaluated as the foaming time taken to reach the preset foam volume. Foam stability was monitored by the evolution of foam volume and liquid fraction as a function time. Besides, the variation in bubble size during foam destruction also was analyzed to reveal the influence of bubble coalescence and Ostwald ripening on foam stability. In the following the results for different gas flow rates (section 3.1), various surfactant concentrations (section 3.2) and different temperatures (section 3.3) on foam properties will be presented and discussed with regard to foamability and foam stability. And the relationship between free drainage, bubble coalescence and foam stability will also be discussed.

3.1. Influence of gas flow rate

Gas flow rate has an important effect on the performance of foam, especially in terms of foamability. Fig. 2

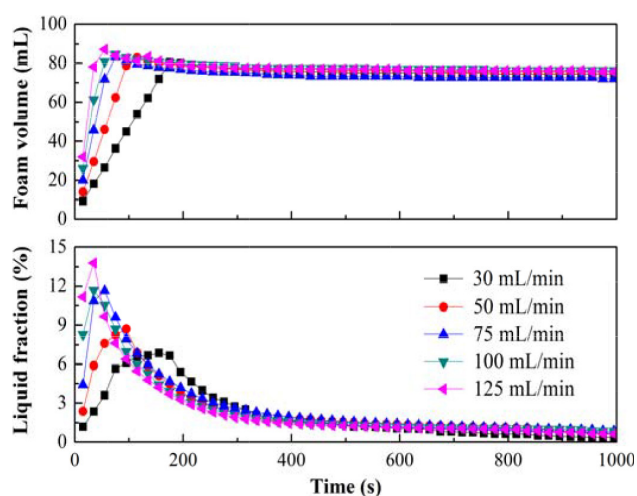


Fig. 2. (Top) Evolution of foam volume and (bottom) liquid fraction as a function of time for foams generated at a SDBS concentration of 1.0 cmc, temperature of 25°C and various gas flow rates.

shows the evolution of foam volume, liquid fraction as a function of time for foams generated at a SDBS concentration of 1.0 cmc and various gas flow rates (30, 50, 75, 100 and 125 mL/min) for a fixed foam volume of 80 mL. Note that $t = 0$ s is the time when the foam generation begins, and the front parts of profiles of foam volume and liquid fraction represent the foaming process while the latter parts of those profiles reflect the foam decay process.

The foam volume profiles (top) showed that the foaming time decreased with increasing gas flow rate, which meant that the foamability increased with the increase of gas flow rate. And at low gas flow rates the foaming time decreased dramatically with the increase of gas flow rate, which indicated that these foams were unstable and collapsed partially during the foam generation, and the foaming process was the longer the more pronounced the foam destruction [19]. However, at high gas flow rates the foaming time only showed a slight decrease with increasing gas flow rate, which meant that at these conditions the foamability was nearly gas flow rate independent. Note that too high flow rates will cause strong shear forces on the foam, which can result in the collapse of foam during the foaming. Therefore, an intermediate gas flow rate may be a good choice to separate foamability from foam stability. In the following sections (section 3.2 and section 3.3), we used a gas flow rate of 50 mL/min to investigate the properties of foams produced under different concentrations and various temperatures.

To gain further insight into the foam properties the liquid fraction (liquid content of foam) at different gas flow rates was measured. Liquid fraction profiles (bottom) showed that the maximum liquid fraction increased with the increase of gas flow rate. After the termination of foam generation, the decay of foam immediately began. Here the decrease of liquid fraction represented the foam drainage process, and the drainage rate was defined as the slope of the latter part of liquid fraction profile. We can see that the higher the gas flow rate the larger the drainage rate. This is because that the higher the gas flow rate the more the liquid carried in the foam. Correspondingly, a higher liquid fraction leads to a larger drainage rate for the same foaming solution and similar experimental conditions. Comparing the results shown in Fig. 2 with those presented in Fig. 3 we can find the relationship between free drainage, bubble coalescence and foam stability. For example, at the gas flow rates of 75 and 100 mL/min, respectively, almost the same maximum liquid fraction values were gained which resulted in the identical drainage profiles (Fig. 2 bottom). Besides, the corresponding foam volume profiles were also identical (Fig. 2 top). Furthermore, from Fig. 3 we can see that the variation of bubble size at 75 mL/min was nearly the same as that at 100 mL/min. So we can conclude that foam destabilization is dominated by foam drainage, which is in agreement with Carey and Stubenrauch [19]. Another example of the correlation between them was displayed in the results obtained at 30 mL/min and 50 mL/min. The case of foam generated at the gas flow rate of 50 mL/min had a higher liquid fraction, which resulted in a larger drainage rate compared to that produced at 30 mL/min (this could be observed in Fig. 2 bottom). In addition, when the time was longer than 600 s the bubble size at 50 mL/min was larger than that at 30 mL/min, which meant that at the later

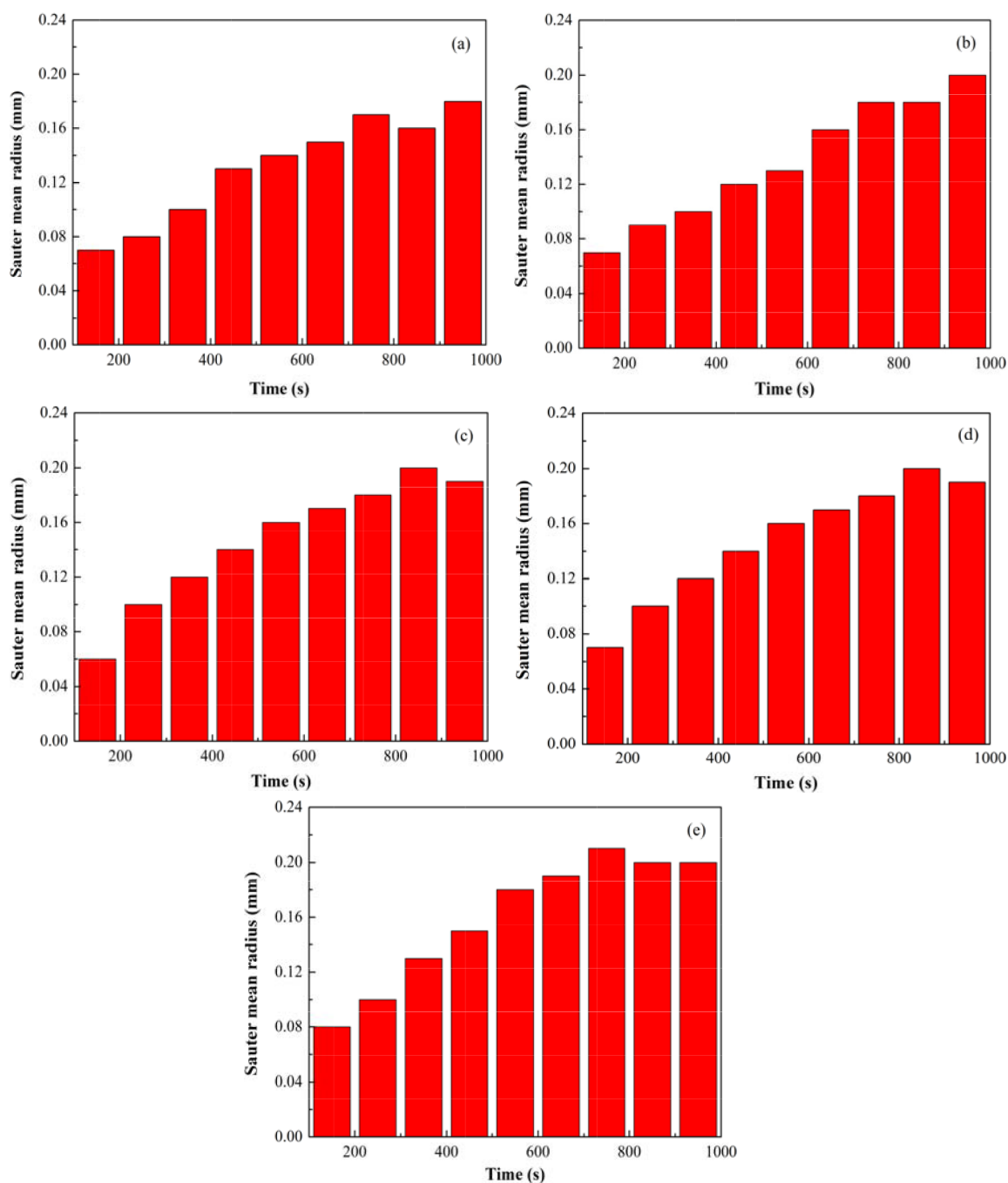


Fig. 3. Sauter mean radius as a function of time for foams generated at a SDBS concentration of 1.0 cmc, temperature of 25°C and various gas flow rates: (a) 30 mL/min, (b) 50 mL/min, (c) 75 mL/min, (d) 100 mL/min, and (e) 125 mL/min.

stage of foam decay the gas flow rate of 50 mL/min intensified bubble coalescence which promoted foam drainage, so bubble coalescence had an impact on foam stability. However, at high gas flow rates (> 75 mL/min) the variation of bubble size was rather small, this could support the argument that foam destabilization is dominated by foam drainage. In conclusion, at low gas flow rates foam drainage and bubble coalescence are responsible for the foam destabilization together while at high gas flow rates foam drainage dominates foam stability.

3.2. Influence of SDBS concentration

Surfactant concentration is a significant factor affecting the bubble size, free drainage and foam performance. So the influence of SDBS concentration on the variation of foam volume, liquid fraction, bubble size with time was studied in this section. SDBS foams were produced at a gas flow rate of 50 mL/min and various SDBS concentrations (0.5 cmc, 1.0 cmc, 1.5 cmc, 2.0 cmc). The results are presented in Figs. 4 and 5.

Fig. 4 (top) shows that the foaming time decreased with increasing SDBS concentration, which meant that the foamability increased with the increase of surfactant concentration.

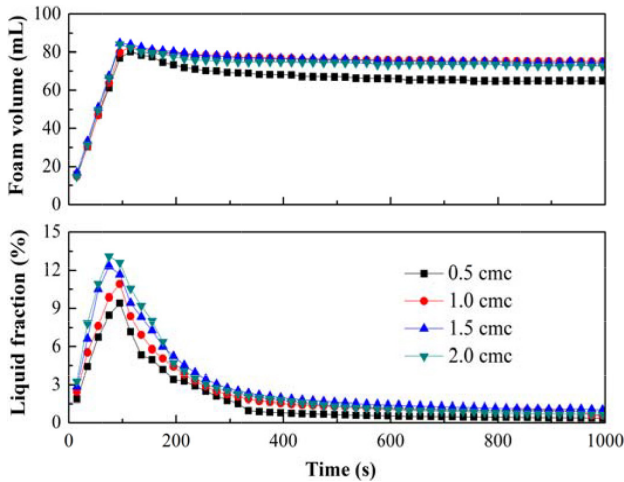


Fig. 4. (Top) Evolution of foam volume and (bottom) liquid fraction as a function of time for SDBS foams produced at a gas flow rate of 50 mL/min, temperature of 25°C and various SDBS concentrations.

It is widely accepted that foamability not only depends on the amount of surfactant adsorbed at the air-liquid interface but also on the transport rate of surfactant to the interface [30]. At the same foaming conditions, the increase of SDBS concentration indicated an increase in the amount of adsorbed surfactant molecule at the air-liquid interface, so the foamability increased. However, at concentrations $c \geq c_{mc}$ the foamability maintained the maximum value because at cmc the transport rate of the surfactant was high enough to allow for the formation of a densely packed layer in the foaming process. Therefore, the foamability of SDBS solution increased with increasing surfactant concentration at $c < c_{mc}$ and reached a plateau when the concentrations were at $c \geq c_{mc}$.

The foaming rate can also be obtained for the various SDBS concentrations, which is defined as the slope of the initial part of foam volume profile. A straight line was observed for the foaming process of all solutions which indicated a stable foaming process. After the termination of foaming, the foam decay process began which was characterized by the latter part of foam volume profile. The foam volume profiles showed that these foams produced by SDBS solutions at $c \geq c_{mc}$ had similar stability, whereas the foam of 0.5 cmc was less stable. This meant that the foam stability of SDBS solution increased with increasing SDBS concentration at $c < c_{mc}$ and reached a plateau when concentrations were at $c \geq c_{mc}$.

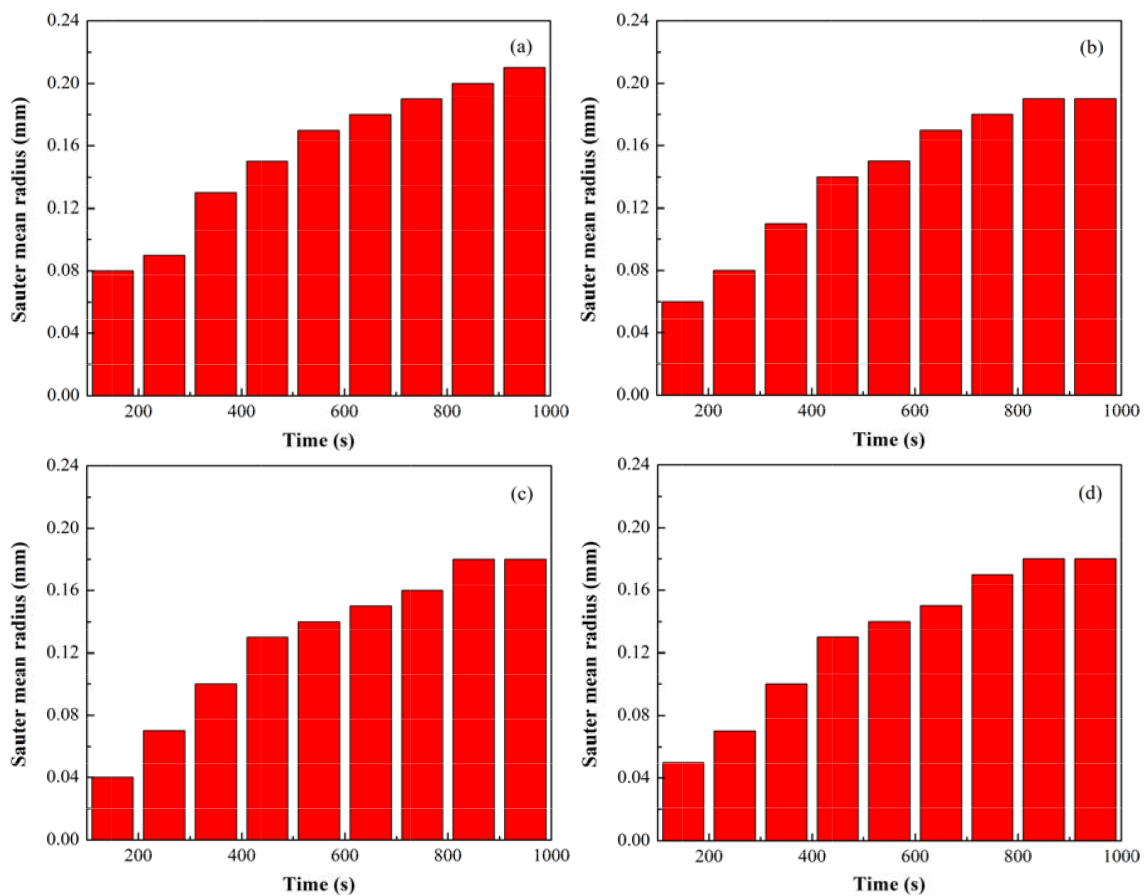


Fig. 5. Sauter mean radius as a function of time for foams generated at a gas flow rate of 50 mL/min, temperature of 25°C and various SDBS concentrations: (a) 0.5 cmc, (2) 1.0 cmc, (3) 1.5 cmc, (4) 2.0 cmc.

Apart from the evolution of foam volume, the foam destabilization can also be reflected by the variation of liquid fraction. Fig. 4 (bottom) shows the evolution of liquid fraction with time for various SDBS concentrations. These figures show that as an increase in surfactant concentration the maximum liquid fraction increased. This means that these foams become wetter and the surfactant concentration is the higher the larger the liquid fraction, which is closely related to the foaming process and can be explained from two aspects. On the one hand, increasing the surfactant concentration more surfactant molecule are transported from the bulk solution to the air-liquid interface, as a result, more fresh interfaces are formed and more liquid is carried into the foam. On the other hand, as an increase in surfactant concentration the bubble coalescence is greatly inhibited which can be supported by the variation of average bubble size shown in Fig. 5, and the foam viscosity increases, so the liquid fraction increases with the rise of surfactant concentration. It is expected to be observed that a higher liquid fraction leads to a larger drainage rate for the same gas flow rate and similar experimental conditions. The drainage rate can be obtained for the various SDBS concentrations, which is defined as the slope of the latter part of liquid fraction profile. These profiles indicated that the drainage rate increased as an increase in surfactant concentration. It is noteworthy that at $c > \text{cmc}$ the drainage rate only showed a slight increase. This is because that although the liquid fraction increases with increasing surfactant concentration, the capacity of foam carrying liquid is limited and the concentrations $c > \text{cmc}$ are very high, thus their liquid fraction shows a slight increase, and so does the drainage rate. Interestingly, the variation of bubble size for the case of 1.5 cmc was nearly the same as that for 2.0 cmc, which indicated that bubble coalescence was greatly prevented, and foam stability was dominated by foam drainage. On the other hand, at concentrations $c < \text{cmc}$ the drainage rate showed a significant increase while the bubble size exhibited a great decrease with the increase of surfactant concentration, which indicated that at these concentrations foam drainage and bubble coalescence should be responsible for the foam stability together. Note that coarsening is also expected to play a role in the variation of bubble size. However, with the increase of surfactant concentration the bubble coalescence is greatly inhibited and the foams have a narrow bubble size distribution, consequently, the coarsening is greatly decreased. Furthermore, it is a slow process with a time-scale of the order of 10 min up to several hours [31], and our experiments are not long enough to observe the bubble coarsen. In conclusion, when the concentrations $c < \text{cmc}$, the foam stability is not only dependent on foam drainage but also on bubble coalescence, whereas at $c > \text{cmc}$ the foam drainage dominates the foam stability.

2.3. Influence of temperature

After having studied the foam properties as a function of the gas flow rate and surfactant concentration under certain experimental conditions we were interested in the influence of temperature on foam properties. So we investigated the properties of aqueous foams generated at a gas flow rate of 50 mL/min, surfactant concentration of 1.0 cmc,

and various temperatures ranged from 5°C to 55°C. The results are presented in Figs. 6 and 7.

Fig. 6 (top) shows that the foaming time showed a slight decrease with increasing temperature, and reached a minimum value at 25°C, after 25°C, it kept a constant at studied temperature range. This meant that at low temperatures (5–25°C) the foamability of SDBS solution slightly increased with the rise of temperature, whereas at high temperatures (25–55°C) the foamability maintained a plateau. This trend can be seen as the outcome of the combination of two phenomena: (i) the Brownian motion, (ii) the formation of micelle. On the one hand, at low temperatures (5–25°C) as an increase in temperature the Brownian motion is enhanced, that is to say that the kinematic velocity of ions increases, which causes more frequent collisions between the ions and promotes the transport of surfactant to the air-liquid interface, consequently, the foamability increases. On the other hand, at high temperatures (25–55°C) the Brownian motion may reach the limitation, which means that at these conditions temperature has an insignificant effect on foamability. Besides, the studied concentration $c = \text{cmc}$ is rather high enough to allow for the formation of a densely packed layer in the foaming process, thus the foamability exhibits a constant. Therefore, in this system 25°C was an ideal foaming temperature, which was consistent with Wang et al. [32]. Because they suggested that 20–30°C was an ideal foaming temperature. Since the foaming solution was the same and the desired foam volume was maintained at a constant, thus the shorter the foaming time, the greater the foamability of surfactant solution. Overall, the foamability of SDBS solution increased with increasing temperature. This trend could also be found in Wang et al. [32], in which Wang et al. studied the effect of temperature (ranged from 15°C to 65°C) on foaming performance of 10 typical anionic, cationic, non-ionic, and amphiprotic surfactants.

Fig. 6 (bottom) presented that the maximum liquid fraction showed a slight increase with increasing temperature, and reached the largest value at 25°C, after 25°C, the

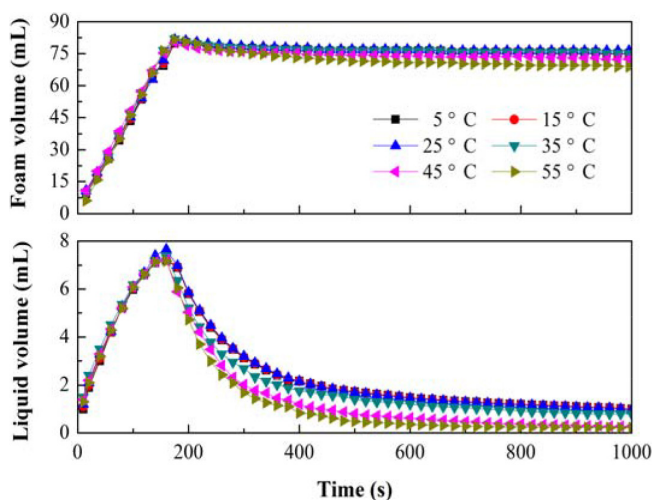


Fig. 6. (Top) Evolution of foam volume and (bottom) liquid fraction as a function of time for foams produced at a gas flow rate of 50 mL/min, SDBS concentration of 1.0 cmc and various temperatures.

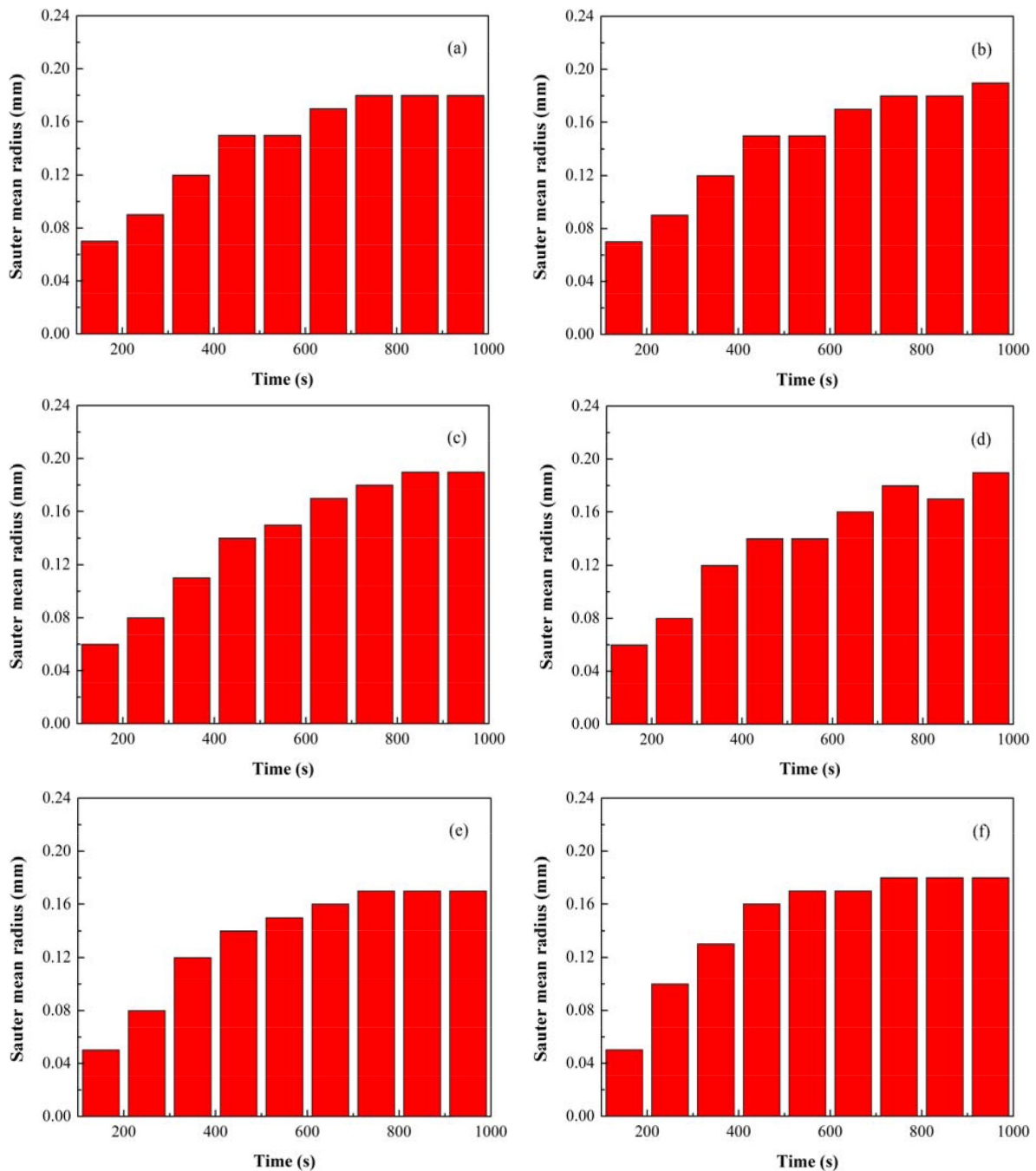


Fig. 7. Sauter mean radius as a function of time for foams generated at a gas flow rate of 50 mL/min, SDBS concentration of 1.0 cmc and various temperatures: (a) 5°C, (b) 15°C, (c) 25°C, (d) 35°C, (e) 45°C, (f) 55°C.

maximum liquid fraction showed a little decrease. This is due to that at low temperatures (5–25°C) the foamability of SDBS solution slightly increases with increasing temperature, consequently, the liquid content of foam increases, that is, the maximum liquid fraction increases. However, at high temperatures (25–55°C) the collapse of foam increases during the foam generation, so the maximum liquid fraction slightly decreases with increasing temperature.

Apart from the variation of maximum liquid fraction with temperature, comparing the results shown in Fig. 6

with those presented in Fig. 7 we can find the relationship between foam drainage, bubble coalescence and foam stability at different temperatures. Note that in Fig. 6 (top) the latter parts of foam volume profiles represented foam stability, and that of liquid fraction profiles reflected foam drainage in Fig. 6 (bottom). On the one hand, from Fig. 7 we can see that at low temperatures (5–25°C) these bubble size distributions were almost the same, and in Fig. 6 the foam volume profiles and liquid fraction profiles were also almost identical. Therefore, at low temperatures foam

stability was less affected by temperature. On the other hand, at high temperatures (25°C–55°C), from Fig. 7 it can be seen that as an increase in temperature the bubble size showed a little increase, and in Fig. 6 (bottom) the foam drainage enhanced. Besides, in Fig. 6 (top) the foam stability decreased with increasing temperature, which was expected due to the enhancement of bubble coalescence and foam drainage. Therefore, we could conclude that at high temperatures foam stability decreased with increasing temperature. Sharma et al. [33] also found that with the increase of temperature the foam stability decreased. In conclusion, at low temperatures the foamability slightly increased with the rise of temperature, while the foam stability was less affected by temperature. At high temperatures, the foamability was almost temperature-independent, while foam stability decreased.

4. Conclusions

This paper systematically studied the influences of gas flow rate, surfactant concentration and temperature on SDBS foam properties using a commercially available device, FOAMSCAN, in terms of foamability, foam stability, free drainage and bubble size. The main conclusions are as follows: (1) In the range of our studied gas flow rate the foamability of SDBS solution continues to increase with the increase of gas flow rate, while the foam stability is gas flow rate independent. And at low gas flow rates foam drainage and bubble coalescence are responsible for the foam destabilization together while at high gas flow rates foam drainage dominates foam stability. (2) At concentrations $c < \text{cmc}$ both foamability and foam stability of SDBS solution increase with increasing surfactant concentration, and reaches a plateau when the concentrations $c \geq \text{cmc}$. And at $c < \text{cmc}$, the foam stability is not only dependent on foam drainage but also on bubble coalescence, whereas at $c > \text{cmc}$ the foam drainage dominates the foam stability. (3) At low temperatures the foamability of SDBS solution slightly increases with the rise of temperature, while its foam stability is less affected by temperature. At high temperatures, its foamability is almost temperature-independent, while foam stability slightly decreases, and in this system 25°C is an ideal foaming temperature.

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