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Effect of Temperature on Foaming Ability and Foam Stability of Typical Surfactants Used for Foaming Agent

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Abstract Foam has extensive applications in a wide range of industrial fields. Some surfactants are used as foaming agents in the preparation of foam. The performance of the foaming agent directly affects the application of the foam. In this paper, experiments were designed and conducted to reveal the influence of temperature on foaming performance of 10 typical anionic, cationic, nonionic, and amphiprotic surfactants. They were exposed to different temperature conditions to measure the foaming capacity (FC), foaming expansion (FE), and foam's half-life. FC and FE represent foaming ability (FA), and half-life represents foam stability (FS). The results show that the FC increased at elevated foaming temperature, while FS decreased with rising temperature. Anionic surfactants are less affected by temperature and have better FA and longer FS. It seems that 20–30 °C is an ideal foaming temperature. This study lays an important foundation for the efficient preparation and utilization of foam in industrial fields.

Keywords Foaming agent · Surfactant · Foaming ability · Foam stability · Temperature

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Introduction

Foam is widely used in industrial applications. Taking the coal mining industry as an example, foam is successfully used to control mine fires and coal dust [1–4]. For instance, coal dust suppression by foam has particular advantages over conventional methods, including larger contact area with dust particles and more rapid wetting properties [5, 6]. In particular, foam has a marked effect in suppressing respirable dust [7]. Specialized foaming surfactants are the essential materials in water-soluble foaming agents, reducing the surface tension of the water solution and thus allowing a large number of bubbles to be generated when air is introduced [8].

In general, the foaming performance of a surfactant is measured in terms of its foaming ability (FA) when exposed to various circumstances [9, 10]. Foam stability (FS) refers to the durability or lifetime of the foam, which is a function of the liquid membrane properties. It has been reported that the viscosity of the liquid membrane directly affects the FS, i.e., higher viscosity results in longer-lasting and more stable foam [11]. Brownian motion, critical micelle concentration (CMC), viscosity, etc. are greatly influenced by the temperature [12]. For example, the viscosity of the liquid membrane initially increases then drops with increasing liquid phase temperature [13]. Thus, the foaming temperature is an important factor influencing FA and FS. In addition, the sensitivity of different kinds of surfactants to temperature varies greatly [14], and obviously for different reasons; but the question as to the extent to which temperature influences foaming performance remains unanswered. This problem was addressed in the present study by subjecting 10 typical surfactants to a range of temperature environments to observe the effect of temperature change on the foaming performance.

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Experimental Procedures

Materials

Taking into account the economic and representational requirements, 10 foaming agents (surfactants) were selected for testing on the basis of their ionic type: anionic, cationic, amphiprotic, and nonionic (Table 1). Details including source and purity of the used experimental samples are listed in Table 2.

Instruments and Methods

The main instrument used was a FoamScan® system (Teclis Instruments, France; Fig. 1). FoamScan® measures FA and FS by generating foam then optically measuring aspects of its stability, drainage rate, and bubble size distribution. Figure 2 illustrates the measurement system, complete with analytical software for automatic control of experimental conditions.

In the present study, foam expansion (FE) and foam capacity (FC) were chosen as the standard indices to represent the FA. The half-life of the foam is here defined as a measure of its stability.

FE is the ratio of the total volume of foam after foam generation is complete to the liquid volume within the bubbles and is given by

$$FE = \frac{Vf_{foam}}{Vi_{liq} - Vf_{liq}}, \qquad (1)$$

where Vf_{foam} (mL) is the total foam volume after the foaming process; Vi_{liq} (mL) is the liquid volume at the initial state; and Vf_{liq} (mL) is the volume of liquid remaining at the end of foaming.

FC is the ratio of the total volume of foam after foam generation is complete to the gas volume, and is given by

$$FC = \frac{Vf_{foam}}{Vf_{gas}}, \qquad (2)$$

Table 1 Foaming agents of different kinds

Anionic type	Cationic type	Nonionic type	Amphiprotic type
Foaming agent			
AOS	1631	FMEE	CAD-40
SDBS	1231	AEO9	LHSB
K$_{12}$	–	–	–
LS-30	–	–	–

AOS sodium alpha-olefin sulfonate, *1631* cetyl trimethyl ammonium chloride, *CAD-40* disodium cocoamphodiacetate, *SDBS* sodium dodecyl benzene sulfonate, *1231* dodecyl trimethyl ammonium chloride, *LS-30* sodium lauroyl sarcosinate, *LHSB* lauramido propyl hydroxyl sultaine, *K$_{12}$* sodium lauryl sulfate, *AEO9* fatty alcohol polyoxyethylene ether

where Vf_{foam} (mL) is the total foam volume after the foaming process, and Vf_{gas} (mL) is the volume of gas used to generate that volume of foam.

On the basis of previous studies [3–7], the concentration of the surfactants was maintained at 0.5% and gas flow was 450 mL/min. In view of the field temperature environment for the application of foam technology, the FE, FC, and foam half-life were recorded when water temperature increased from 15 to 65 °C at 5 °C intervals.

Results and Discussions

Effect of Foaming Temperature on FA

Figure 3 shows that FC increases with increasing temperature, varying from 1.19 to 2.20 within the temperature range 15–65 °C. Overall, the generated foam volume increased with rise in temperature. Since the gas volume was maintained at a constant value, FC increased; however, different types of surfactants were affected differently by temperature change.

Anionic surfactants are often used as foaming agents. Since SDBS, AOS, and K$_{12}$ are the most commonly used agents in coal mines, these were chosen for the experiments. Because K$_{12}$ was in the form of relatively insoluble solid particles, its concentration was reduced to 0.1%. The FC behavior of the three agents followed a similar pattern from 15 to 55 °C, with a peak at 45 °C; K$_{12}$ peaked again at 60 °C; AOS continued to increase, reaching 2.11 at 65 °C; and SDBS remained basically stable (see Fig. 3a). The overall increase in the FC of these anionic surfactants with rise in temperature was thought to have resulted from the Brownian motion, in which the kinematic velocity of the ions increased with increasing temperature and caused more frequent collisions between the ions; thus the gradual increase in foam quantity was unsurprising. The cationic surfactants 1231 and 1631 were selected for the experiments. Figure 3b shows that, with some minor fluctuations, their FC increased gradually with temperature rise. It is believed that Brownian motion was also the main cause of this phenomenon.

The nonionic surfactants FMEE and AEO-9 were selected for the experiments as they are rapidly dissolved and relatively cheap. Figure 3c shows that the FC of both nonionic surfactants was similar at all temperatures, increasing with temperature rise. FMEE is an ethoxylated surfactant whose solubility decreases with rising temperature. AEO-9 is a polyethylene glycol (PEG) nonionic surfactant whose solubility varies directly with the number of moles of ethylene oxide (EO). When EO = 9, the solubility is relative low and the FC was therefore also low; however, its molecular motion increases rapidly with rise

Table 2 Source and purity of experimental samples

| Surfactants	AOS	SDBS	K_{12}	1631	1231	FMEE	LS-30	AEO9	CAD-40	LHSB
Source	Zhejiang Sinolight	Tianjin Dingshengxin	Linyi Lusen	Linyi Lusen	Linyi Lusen	Mexico Pemex	Linyi Lusen	Linyi Lusen	Linyi Lusen	Linyi Lusen
Purity (%)	92	≥90	93	40	50	70	30	99	40	35

Zhejiang Sinolight refers to Sinolight Chemicals Co., Ltd.; Tianjin Dingshengxin refers to Tianjin Dingshengxin Chemicals Co., Ltd.; Linyi Lusen refers to Linyi Lusen Chemicals Co. Ltd.; And Mexico Pemex refers to Pemex Chemicals Ltd.
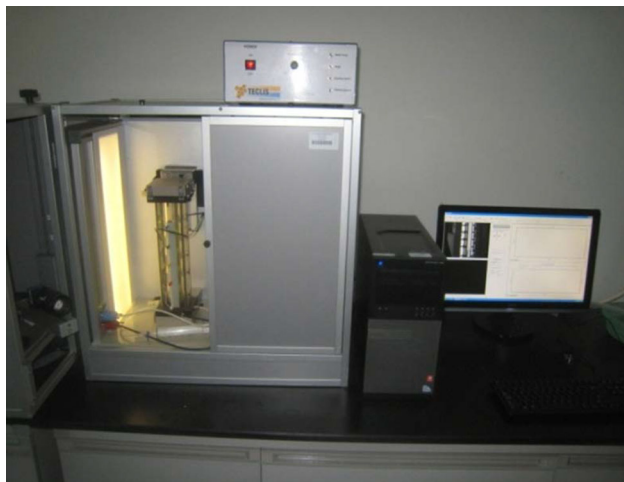

Fig. 1 Photo of FoamScan

in temperature. It has been reported [14] that the CMC and temperature of nonionic surfactants are negatively correlated; thus, surface tension is reduced more readily and more bubbles are produced. Therefore FC also increased in these experiments.

Amphiprotic surfactants act as either an acid or a base by accepting or donating a proton. The amphiprotic surfactants LHSB and CAD-40 were chosen as the test materials. Figure 3d shows a very high FC value of 2.101 for LHSB at 25 °C, followed by fluctuations between 1.60 and 1.88, but with an overall tendency to increase slightly with rising temperature. The FC of CAD-40 increased gradually from 1.43 to 1.85 with rising temperature; because of the very large fluctuation of the FC at 65 °C, this value has been omitted from Fig. 3d. This behavior is possibly connected to the pH and solubility of the material. LHSB reached its cloud point temperature at 30 °C, resulting in a very large decrease in FC, followed by FC increased slightly at higher temperatures because of a little increase of solubility. CAD-40 behavior was controlled by its pH. Whereas the pH is relatively low (6.0–8.0) for the anionic and cationic surfactants, CAD-40 has a pH as high as 9.0–10.0. Because foam is not produced readily in
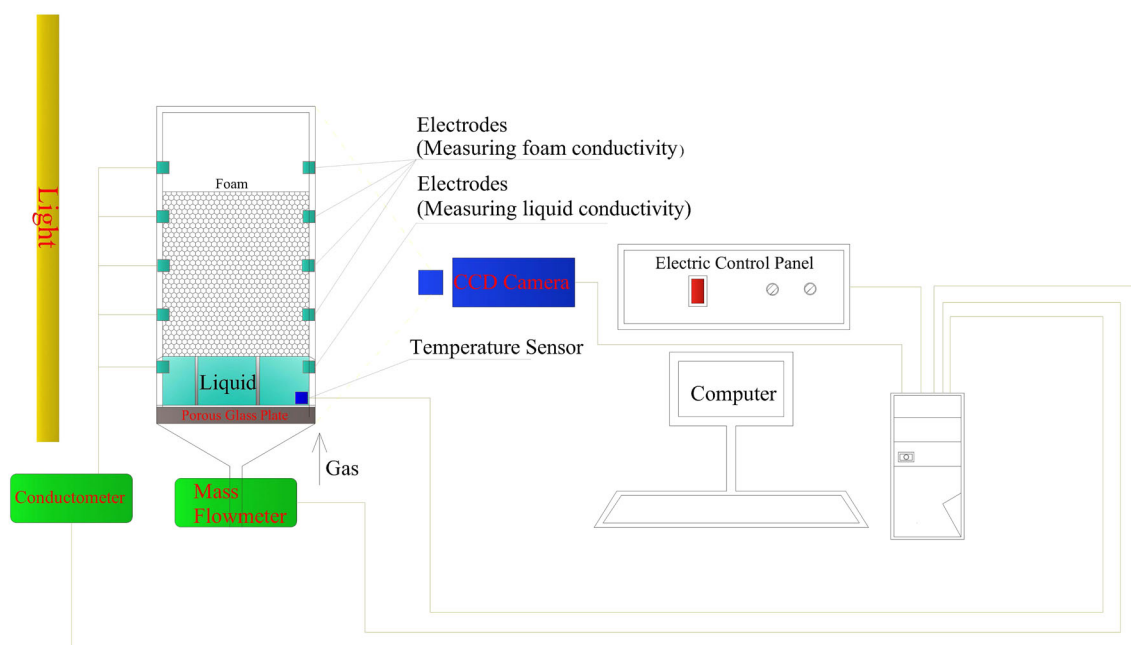
Fig. 2 Schematic of FoamScan
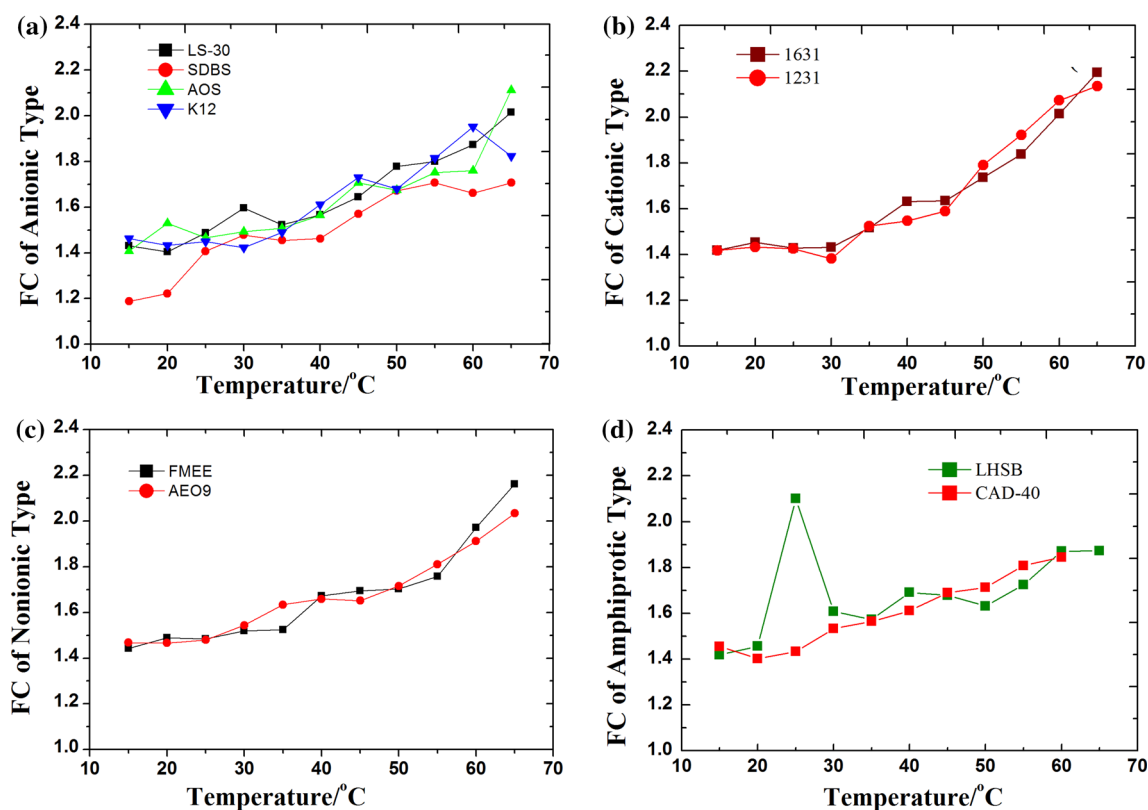
Fig. 3 Change of FC with temperature over various surfactants

alkaline solutions, the FC value for CAD-40 was the lowest for the 10 surfactants tested.

Overall, FC increased gradually with rising temperature, although some fluctuations were observed. Comparison of the four anionic surfactants showed that, except for the amphiprotic materials, the law of FC variation with temperature was similar. At low temperatures (15–35 °C) no obvious difference was observed (average FC = 1.48).

For a better understanding of the effects of temperature on FC, we conducted quantitative analysis of the effects of temperature on FA and drew fitting curves (Fig. 4), from which a mathematical formula for each foaming agent can be obtained. In Fig. 4, there is a clear linear functional relationship between FC and temperature, in which the average goodness of fit reached 0.814. For instance, the FC of SDBS could be fitted as a linear function of temperature by the expression $FC = 0.052t + 1.188$ ($R^2 = 0.903$). Among the different surfactants, the slope of LHSB is the smallest. It is probably because the cloud point of LHSB is relatively low, and the surfactant was less soluble at high temperature. For the other surfactants, Brownian motion played a dominant role which resulted in the linear increase of FC with temperature. It can be deduced from above analysis that Brownian motion accounts for the rise of FA with increasing temperature, as higher temperature caused

an increase in the kinematic velocity of ions, resulting in more frequent collisions between ions.

Foam Expansion (FE) Change Properties at Different Temperatures

The overall FE behavior is given in Fig. 5, where it is seen that the FE ranged from 3.2 to 17. While there is no apparent correlation between FE and temperature, it was noted that each kind of surfactant was influenced by temperature in a particular way.

The FE diagram for anionic surfactant shows a slight oscillation (Fig. 5a). Below 25 °C, the FE of SDBS first increased and then decreased with rise in temperature. When the temperature exceeds 55 °C, FE of SDBS increased reaching 15.39 at 65 °C, which was the highest value of all 10 surfactants. The FE of AOS also increased with rising temperature above 25 °C, but at 45 and 65 °C the values were merely 4.52 and 4.93, respectively. The FE of K_{12} fluctuated slightly with an average of 6.21, with similar behavior to SDBS.

The FE diagram of the cationic surfactants (Fig. 5b) shows similar behaviors: the FE of 1231 and 1631 reached a peak at 30 °C (8.47 and 9.45, respectively). The FE of 1631 began to decrease above 30 °C and continued to do so

Fig. 4 Quantitative relation between FC and temperature
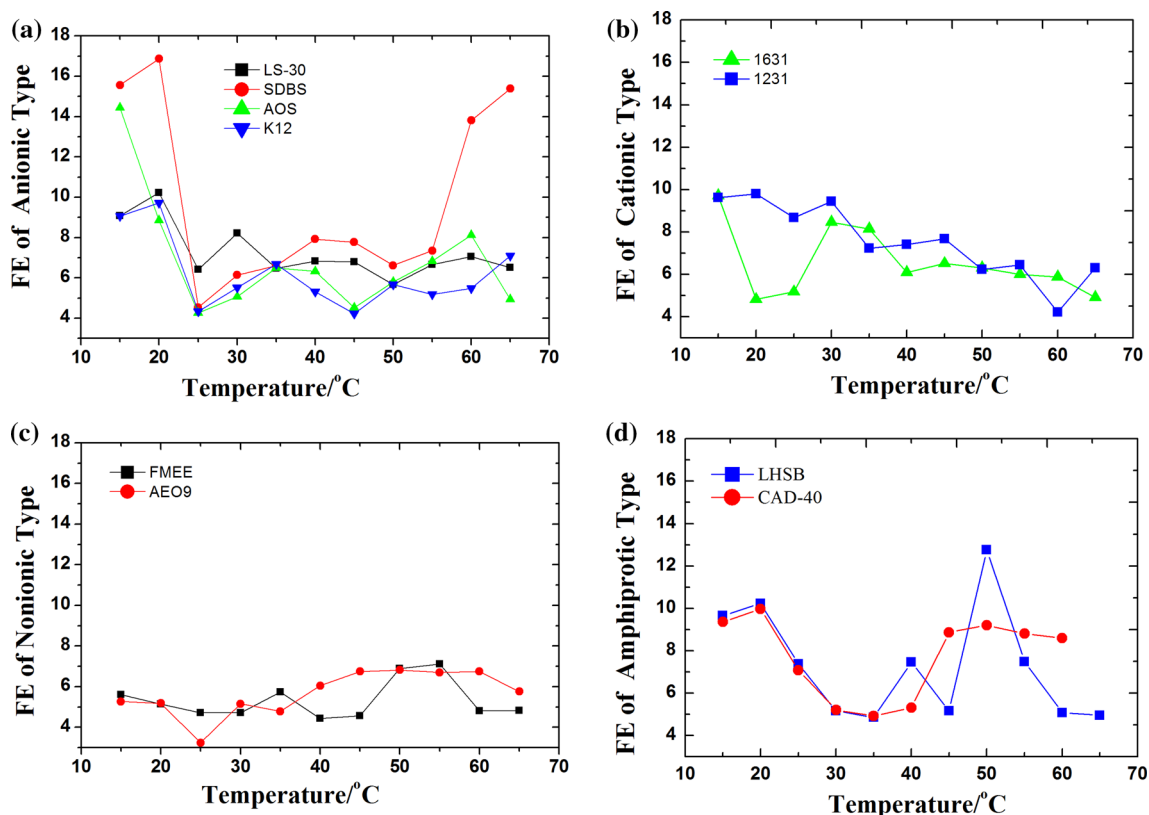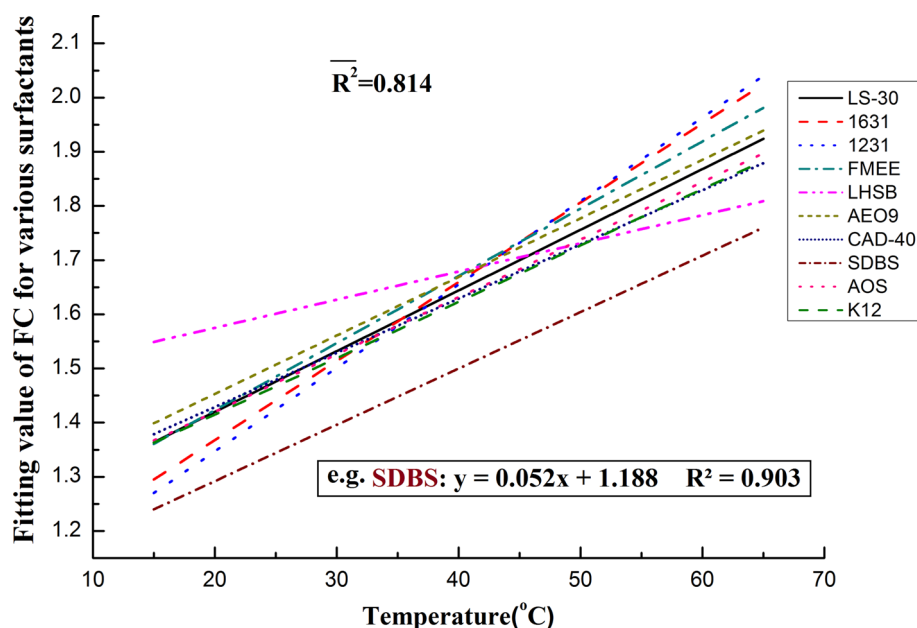
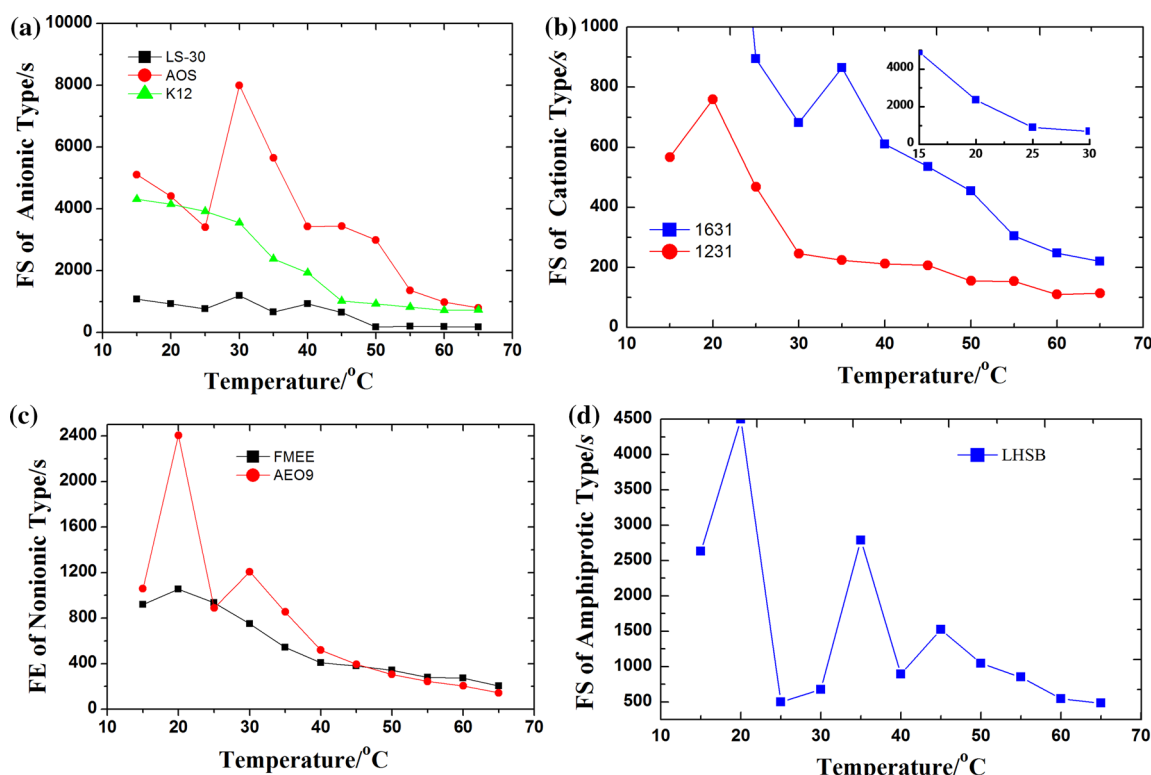**Fig. 5** Change of FE with temperature over various surfactants

with increasing temperature. Conversely, the FE value for 1231 dropped to 4.23 at 60 °C, then rose slightly at 65 °C.

The FE of the nonionic surfactants was lower, averaging 6.09. FMEE showed no obvious change in behavior, suggesting that FMEE was insensitive to temperature change.

The FE of AEO-9 also had no obvious change with the increase of temperature, roughly ranging between 5 and 7.

Seen from Fig. 5d, the FE of the amphiprotic surfactants fluctuated sharply with temperature change. The FE values of the two surfactants were very similar below 35 °C;

Fig. 6 Change of half-life with temperature over various surfactants

thereafter, they presented roughly the same trend of first increasing and then decreasing at higher temperatures.

In summary, although the FC of the anionic, cationic, and nonionic surfactants increased with rise in temperature by roughly the same amount, the FE of the nonionic surfactants was lower, averaging 6.09. This result shows that the nonionic surfactants consumed more liquid during the foaming process and were thus the least economical of the three.

From the above discussion it is seen that the FE of the anionic surfactants was greater at higher temperatures, whereas the FE of the cationic surfactants decreased with rise of temperature. Therefore, further investigation was conducted to distinguish between them.

Effect of Foaming Temperature on FS

In the previous section, it was established that the FA values of anionic and cationic surfactants were superior to the other materials, but did not show which material is best. To resolve this question, the same instrument and methodology were used to investigate the influence of temperature on FS. As the half-life of SDBS and CAD-40 was too long, these two materials were not tested further. The details are given in Fig. 6.

As shown in Fig. 6, the half-life decreased with increasing temperature. Specifically, the half-life of the anionic

surfactants differed from all of the other surfactants tested. At 30 °C the half-life of AOS was greater than 8000 s. For the convenience of data analysis, 8000 s was taken to be its value. Figure 6a shows that the half-life of AOS peaked at a value greater than 8000 s, then fell gradually. The half-life of K_{12} decreased from the initial temperature until the end of the test. In Fig. 6b it is seen that cationic surfactant behavior was similar to that of the anionic surfactants, the difference being that the FS of 1231 peaked at 20 °C. Figure 6c shows that the half-life of the nonionic surfactants decreased in a fluctuating way with the changing temperature. The behavior of AEO-9 and FMEE was similar to that of 1231 and 1231. Figure 6d shows three peaks in the half-life of LHSB, the first one at 20 °C (4500 s), the second one at 35 °C (2789 s), and the third one at 45 °C (1525 s), followed by a gradual decrease.

For a better understanding of the effects of temperature on FS, we conducted quantitative analysis of the effects of temperature on FS and drew the fitting curves of FS (Fig. 7), from which the fitting formula for each foaming agent can be obtained. As illustrated in Fig. 7, there was an obvious exponential relationship between FS and temperature, in which the average goodness of fit reached 0.797. For example, the FC of K_{12} had a good exponential fitting curve with the function of $FS = 6511e^{-0.21t}$ ($R^2 = 0.938$).

Clearly, foam stability (FS) benefits from a rise in temperature over a certain temperature range, but higher

Fig. 7 Quantitative relation between FS and temperature
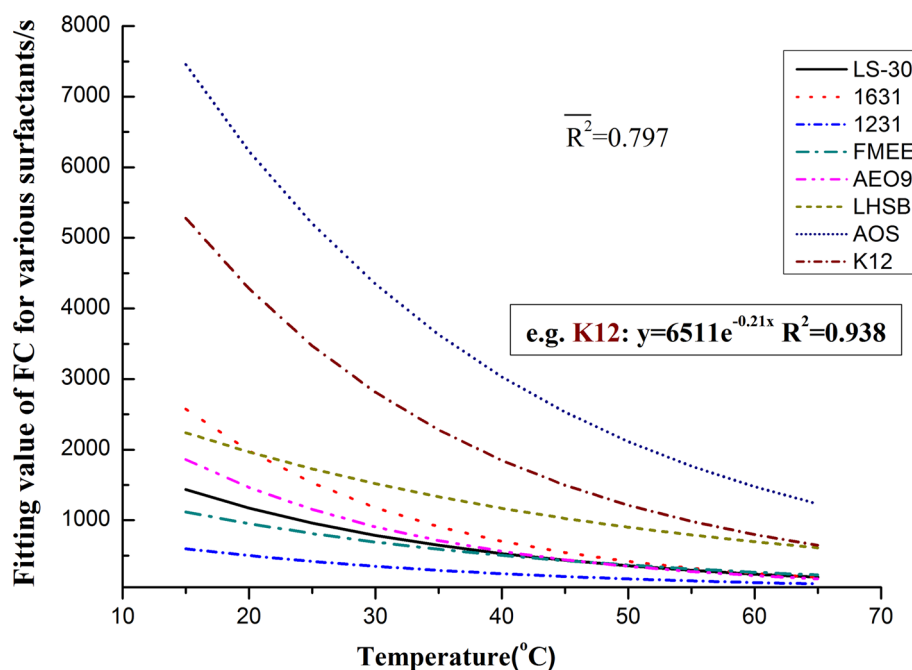
temperature would reduce the FS in turn. In other words, the half-life was negatively correlated with foaming temperature. At lower temperatures (around 20–30 °C), all four kinds of surfactants obtained their maximum half-life, possibly owing to their lower gas diffusion rate at these temperatures. At higher temperatures, however, the main factor affecting FS may be the lower surface viscosity at higher temperatures, resulting in more rapid liquid drainage and therefore lower FS.

The results of the previous section show that the FA of anionic and cationic surfactants was superior to that of the other types. The FS of anionic surfactants had the longest life at an average of 2912 s, far longer than that of other types (cationic type: 696 s; nonionic type: 646 s; LHSB: 1494 s). Thus, anionic surfactants appear to be the most suitable of the foaming agents tested, in terms both of their FA and FS.

Conclusions

In this paper, the effect of temperature on the foaming ability and foam stability of typical surfactants used as foaming agents was investigated. The following conclusions were drawn:

1. Increased FC of surfactants with rise in temperature is due to Brownian motion in the liquid, in which the kinematic velocity of the ions increases with rising temperature and causes more frequent collision between the ions. By contrast, FS and FC were found to be negatively correlated. Foaming ability (FA) increased with rising temperature. Of the materials tested, the FA of the anionic and cationic surfactants was superior to that of the other materials, and both demonstrated higher FC and FE.

2. The half-life of all surfactants decreased with rise in temperature. At lower temperatures, the FS may be influenced by the gas diffusion rate, which peaked at 20–30 °C. At higher temperatures, surface viscosity is believed to be the main influence, causing increasingly rapid liquid drainage. Thus, FS was relatively high at lower temperatures, and decreased with rising temperature.

3. The behavior of the surfactants varied in different temperature conditions; for example, foaming ability was greatest at higher temperatures, but the foam was stable for longer periods of time at lower temperatures.

    (a) Anionic surfactants were found to be the best of the foaming agents tested, in terms of both their foaming ability and foam stability.

    (b) Cationic surfactants showed better foaming ability but produced a less stable foam.

    (c) Nonionic surfactants demonstrated greater foam capacity, but their foam expansion was found to be the lowest of all the surfactants tested; thus, they are the least economical because of their requirement for more water to produce foam.

    (d) Amphiprotic surfactants were found to be unsuitable as the main constituents of foaming agents.

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