Effect of Additives on the Foam Behavior of Aviation Coolants: Tendency, Stability, and Defoaming

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ABSTRACT: The foam tendency of aviation coolants (ACs) can be greatly influenced by additives. This study investigates the effect of additives on foam behaviors based on four commercial ACs and glycol aqueous solutions added with different additives. Experimental results show that the foam tendency of ACs can be greatly influenced by surfactants; however, inorganic salts have little effect on foam tendency. The volume of generated foam reaches up to 350 mL after ventilation for an AC with a surfactant, much larger than 40 mL of an AC with an inorganic salt. The surface tension of ACs reduces with the addition of surfactants, the lower the surface tension, the more the foam formation. Furthermore, the presence of arranged surfactants at the gas—solution interface can increase the intermolecular forces and enhance the liquid and viscosity of film elasticity, thereby enhancing the foam stability. Besides, the surfactants would weaken the gas diffusion of foams and affect the defoaming property of ACs accordingly.

1. INTRODUCTION

With the development of high frequency, integration and miniaturization of airborne electronic equipment and precision apparatus, the components of which are becoming more and more sophisticated and put forward higher requirements for the working temperature. In order to ensure the normal operation of such precision apparatus, aviation coolants (ACs) are needed to disperse the heat generated during the working of the apparatus.1,2 However, the particulate contaminants in ACs will bring about pipeline blockage, wear and tear, and even heat accumulation, resulting in precision apparatus failure to work normally.3,4 To ensure absolute flight safety, the level of particulate contamination of ACs should not exceed the upper limit of the standard (class 8 of GJB 420B), regulated by the industrial sector.5 As a matter of fact, the degree of particulate contamination is overvalued on account of the existence of excessive bubbles generated during the recirculating filtration of ACs. The bubbles are mistakenly identified as particulate contaminants by the automatic particle counter. In addition to this, there are a lot of damages caused by foams during the usage of ACs.

Some tiny solid particles can be easily absorbed by the foam and suspended in the AC because of the strong adsorption capacity of the foam during the recirculating filtration. The plug holes would be blocked by the tiny solid particles. Furthermore, the strong adsorbability of foams drives them to adsorb on the inner walls of the coolant groove, reducing the cooling effect. The dissolved foams increase the compression ratio and volume of the AC, resulting in overflowing of the AC from the container. Besides, at the operating temperature, the oxygen molecules in the bubbles would react with glycol, an essential ingredient of AC, and the service life of the AC would be shortened accordingly. Based on the above reasons, the foam behavior of ACs plays a vital role in their application, including foamability, foam stability, and defoaming. The foam behavior of ACs is affected by many factors, such as the composition of base solution,6 temperature,7 the type and quantity of additives,8 and so on. Compared with the other two factors, additives have a larger effect on foam behaviors. Unfortunately, research on such problem has rarely been reported until now.

Here, the effect of additives on foam behaviors is investigated based on four commercial ACs and glycol aqueous (GA) solutions with different volume ratios. Experimental results show that the foam behaviors of ACs with different additives vary widely. The foam tendency of ACs can be greatly influenced by surfactants; however, inorganic salts have little effect on foam tendency. The surface tension reduces with the addition of surfactants, the lower the surface tension, the more the foam formation. Furthermore, the presence of arranged surfactants at the gas—solution interface can increase the intermolecular forces and enhance the liquid and viscosity of film elasticity, thereby enhancing the foam stability. Besides, the surfactants would weaken the gas diffusion of foams and affect the defoaming property of ACs accordingly.

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2. RESULTS AND DISCUSSION

2.1. Evaluation of the Foam Tendency of No. 65 AC. It is well known that the foam tendency of ACs represents the ability to produce bubbles when aerating or stirring, which is commonly evaluated by the volume of generated foam and defoaming time.14 The more the foam formation, the longer the defoaming time and the worse the foam tendency.15–17 Figure 1 shows the foam tendency of four commercial ACs at different temperatures and GA solutions with different volume ratios. As shown in Figure 1a, the foam tendency of AC-1 is proportional to the ventilation time and inversely proportional to the testing temperature. At 25 °C, after ventilating for 5, 10, and 20 min, the volumes of generated foam are 190, 210, and 225 mL and the defoaming times are 22, 26, and 27 s, respectively. The foam volume and defoaming time are both far beyond the AC specification of 50 mL and 5 s (GJB6100-2007), indicating the inferior foam tendency of AC-1. Interestingly, the foam volume and defoaming time decrease

Figure 1. Volume of generated foam and defoaming time of (a) AC-1, (b) AC-2, (c) AC-3, and (d) AC-4 after ventilating 5, 10, and 20 min at different temperatures.

Figure 2. Foam tendency of 65% GA solution without an additive (a), with 0.2 vol % sodium molybdate (b), with 0.2 vol % n-caprylic acid (c), and with 0.2 vol % T922 defoaming agent (d).
rapidly with the increase of temperature. The foam volumes are 20 and 40 mL after ventilating for 5 and 10 min, respectively, at 88 °C, which well meet the military standard. However, the foam volume increases rapidly to 220 mL as the ventilation time increases to 20 min, even at a high temperature of 88 °C. Furthermore, as the temperature goes up, the defoaming time is shortened obviously because of the drainage effect of foam films,21 providing ideas for defoaming in the next step experiments.

Compared with AC-1, the foam volume of AC-2 and the defoaming time thereof both meet the operating requirements of the military equipment. As shown in Figure 1b, the foam volume is barely affected by the ventilation time and testing temperature with a maximum value of 25 mL, and the defoaming time is constant with a value of 2 s, indicating the desirable foam tendency of AC-2. The foam tendency of AC-3 in Figure 1c is similar to that of AC-1, and the values of foam volume and defoaming time are too high to meet the criterion at room temperature. However, the foam tendency becomes better as the temperature increases. When the temperature rises to 55 °C, the foam volume reduces to less than 40 mL, and the defoaming time also meets the criterion of 5 s. Different from the other three ACs mentioned above, the volume of generated foam and the defoaming time of the home-made AC (AC-4, Figure 1d) are too high to meet the criterion at any testing temperature. Such foam tendency of the ACs with different additives is verified by the volume of generated foam over ventilation time, as shown in Figure S1. Based on the above analysis, it can be known that the four ACs exhibit a quite different foam tendency, although they possess an identical base solution (GA solution).19−21 That is, the type and content of additives in the AC play a decisive role in its foam tendency.

2.2. Effect of Additives on Foam Tendency. To investigate the effect of additives on foam tendency, three main additives of commercial no. 65 AC, sodium molybdate (corrosion inhibitor), n-caprylic acid (preservative), and T922 defoaming agent, are selected and added to the base solution (GA solution) individually. Before this, the foam tendency of the GA solution with different volume ratios was evaluated, as shown in Figures S2−S7. The volume of generated foam and defoaming time are rarely influenced by the volume ratio of glycol to water, ventilating time, and testing temperature. The foam volume of all the samples is less than 50 mL, and the defoaming time is no larger than 5 s at different test temperatures, indicating the satisfying foam tendency of GA solutions. To highlight the difference of the samples with and without additives, the sample of 65% (glycol volume to the total volume) GA solution with inferior foam tendency (Figure 2a) was selected as the base solution.

Figure 2b shows the foam tendency of 65% GA solution with 0.2 vol % sodium molybdate, which is similar to the foam tendency of the base solution. The major difference is that the foam volume and defoaming time of the former are slightly higher than that of the latter, indicating that the sodium molybdate inorganic salt has little effect on the foam tendency of GA solution. However, the preservative n-caprylic acid, as an anionic surfactant, contributes to increased formation of micelles in the base solution,22 resulting in the formation of lots of stable bubbles. As shown in Figure 2c, the volume of generated foam reaches up to 350 mL after ventilating for 5 min, and the foam volume is not affected by the ventilation time. However, because of the vigorous movement of the liquid molecules at high temperature,23,24 the foam volume decreases from 350 to 265 mL as the temperature rises to 88 °C, which can also be confirmed by the defoaming time at different temperatures. As the temperature increases from 25 to 35 °C, the defoaming time increases slightly. If the temperature increases continually to 88 °C, the opposite tendency is observed. The main components of the T922 defoaming agent are simethicone and inorganic sulfonate, which can effectively lower the surface tension and inhibit the formation of foam. Figure 2d shows the foam tendency of 65% GA solution with 0.2 vol % T922. The foam volume of the base solution with T922 is similar to that of the base solution but decreases gradually with the extension of ventilation time, indicating that the foam tendency of GA solution is changed slightly with the addition of T922.

Based on these data, we speculate that the foam tendency of GA solution can be changed with the addition of surfactant; however, the inorganic salt has little effect on its foam tendency.25 In the process of ventilating, the surfactants arrange at the gas−water interface in a manner where hydrophilic ends come in contact with liquid and hydrophobic ends come in contact with gas (Figure 3),26−28 increasing the formation of foam and foam stability. On the one hand, with the addition of surfactants, the surface tension of GA solution is decreased, the lower the surface tension, the easier the foam formation.29 On the other hand, the presence of adsorbed surfactants at the surface interface can increase the intermolecular forces and enhance the liquid and viscosity of film elasticity, thereby enhancing the foam stability. However, the thickness of the liquid film is reduced gradually with the increase in temperature because of the vigorous movement of liquid molecules, decreasing the foam stability. Furthermore, the weakened association interaction and increased collision probability between the surfactant molecules at high temperature can also suppress the production of foam and lower the stability thereof.

2.3. Evaluation of the Surface Tension and Air Release Value of No. 65 AC. Surface tension is a contractive tendency of the surface of a liquid that allows it to resist an external force.30 Generally, the smaller the surface tension, the easier the foam formation and the better the foam stability.29,31 This is mainly because less work should be done during the
formation of bubbles in the solution with smaller surface tension.\textsuperscript{32,33} Moreover, the relationship between the surface tension and excess pressure ($\Delta P = P_i - P_o$, in which $P_i$ is the pressure inside the bubble and $P_o$ is the pressure outside the bubble) in a single bubble is known as law of Laplace, as shown in Figure 4a.\textsuperscript{34} The excess pressure is proportional to the surface tension. The smaller the excess pressure, the slower the liquid foams drainage and the better the foam stability. Hence, reducing the surface tension is conducive to improving the foam stability.\textsuperscript{35,36} Figure 4b shows the surface tension of four commercial no. 65 ACs and GA solutions. By comparison, water possesses a maximum surface tension of 72.8 mN/m among GA solutions. The surface tension of GA solution reduces linearly with the glycol volume fraction.\textsuperscript{37} The surface tension values of AC-2 and AC-3 are 53.1 and 53.2 mN/m, respectively, which are similar to that of 65% GA solution, indicating that the additives added in AC-2 and AC-3 have little effect on the surface tension. However, the surface tension of AC-1 (36.5 mN/m) and AC-4 (39.4 mN/m) is far below that of 65% GA solution (54.1 mN/m), revealing that the surfactants are added as additive, which can lower the solution surface tension effectively and promote foam formation. Indeed, as shown in Figure 4c, the air release values of AC-1 and AC-4 are much larger than those of AC-2 and AC-3. The surfactants arranged at the gas–water interface enhance the stability of the bubble film, resulting in weakened gas diffusion. Based on the above discussion, the surfactants in this work, which were denoted as AC-1 (produced by Shenyang Teli Co. Ltd), AC-2 (produced by Sinopec Co. Ltd), AC-3 (produced by Winfrith Co. Ltd), and AC-4 (produced by Inorganic Salts Co. Ltd), can be greatly influenced by surfactants; however, inorganic salts have little effect on foam tendency. That is, the foam tendency of ACs without surfactants is better than that of ACs with surfactants. Moreover, the foam tendency of ACs can be greatly influenced by surfactants; however, inorganic salts have little effect on foam tendency. That is, the foam tendency of ACs is highly dependent on surfactants. This work lays a foundation for further investigation on foam tendency of foams in the solution, which is barely affected by temperature. At low temperature, the main factor for defoaming is gas diffusion, weakened by the surfactants arranged at the gas–water interface. Although the surfactant molecules are loosely arranged at high temperature, defoaming is mainly caused by the drainage effect of foam films. Besides, the defoaming rate and generated foam number with other sizes can also provide evidence for the effect of surfactants, as shown in Figure 5c; the generated foam number of AC with a surfactant (AC-1) is much larger than that of AC without a surfactant (AC-2). In addition, the defoaming tendency of bubbles with different sizes ($\varphi \geq 6, 14, 21$, and $38 \, \mu m$) is similar.

3. CONCLUSIONS

The effect of additives on foam behaviors is investigated by comparing the foam tendency, surface tension, and air release value of samples with and without surfactants. By comparison, the foam tendency of ACs without surfactants is better than that of ACs with surfactants. Moreover, the foam tendency of ACs can be greatly influenced by surfactants; however, inorganic salts have little effect on foam tendency. That is, the foam tendency of ACs is highly dependent on surfactants. This work lays a foundation for further investigation on foam tendency of a liquid solution.

4. EXPERIMENTAL SECTION

4.1. Materials. Four commercial no. 65 ACs with different kinds and contents of additives and GA solutions were studied in this work, which were denoted as AC-1 (produced by Shenyang Teli Co. Ltd), AC-2 (produced by Sinopec Co. Ltd), AC-3 (produced by Winfrith Co. Ltd), and AC-4 (produced by Inorganic Salts Co. Ltd),
4.2. Foam Tendency. The foam tendency of the samples was measured with a BF-24A coolant foaming tendency analyzer according to the standard test method for determining the foaming tendencies of engine coolants in glassware (SH/T 0066-2002). Briefly, the sample was artificially ventilated at a constant airflow for a certain time, and the foam volume and foam vanishing time were measured by the foam-scanning analyzer (Foamscan produced by Teclis Scientific). To investigate the effect of experimental temperature and ventilation time on foam tendency, the foam tendency of the samples were measured at 25, 35, 55, 75, and 88 °C, and the ventilation time was set as 5, 10, and 20 min.

4.3. Surface Tension. The surface tension of the samples was evaluated by a KS100 surface tension meter produced by Kruess Scientific Instruments. The AC was placed in a specimen cup with varying height to accommodate the platinum plate, which was surface-treated and fixed on the scale. Note that the liquid level was very close to the platinum plate but not touching.

4.4. Foam Number. The foam number was calculated by a YSJ automatic particle counter. The AC (145 mL) was transferred to a graduated cylinder and placed in a thermostatic water bath for 10 min. Compressed air (0.2 MPa) was ventilated into the AC for 30 min and the foam number after 0, 1, 3, 5, 10, 15, and 20 min was monitored. To investigate the effect of temperature on foam number, the temperature of thermostatic water bath was set as 55, 75, and 85 °C.

4.5. Air Release Value. The air release value of the commercial no. 65 ACs was evaluated with a BF-34 air release value meter according to the standard test method (SH/T 0308-1992). Briefly, a desired amount of AC was placed in a container and the temperature was kept at 25 °C. Compressed air (0.2 MPa) was blown into the AC for 7 min and stirred vigorously. After blowing, the defoaming time was recorded when the volume of generated foam reduced to 0.2% of the initial value.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/10.1021/acsomega.0c02238.

Notes
The authors declare no competing financial interest.

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