

# Influence of Foam Characteristics on the Aviation Coolants' Pollution Degree

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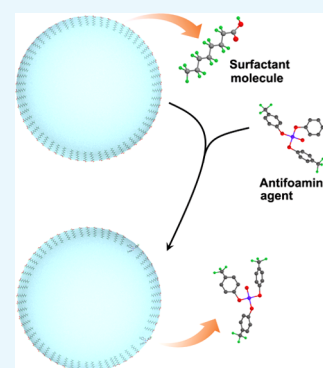


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**ABSTRACT:** The particulate contamination degree of aviation coolants (ACs) is overestimated commonly because the bubbles in ACs are erroneously recognized as particulate contaminants during the measurement process. In this work, the factors that influence the foam behavior and contamination degree of ACs are investigated. It is evidenced that the foam behavior of ACs is basically unaffected by the ratio of glycol to water of the base solution, which, however, is highly influenced by the organic additive. Also, the more the organic additive arranged at the gas–liquid interface, the lower the surface tension of glycol aqueous (GA) solution and the higher the contamination degree. Furthermore, the foam characteristics and contamination degree of ACs are highly affected by the working conditions, such as airflow, operating temperature, and gas pressure. Besides, the defoaming rate can be accelerated by adding an antifoaming agent or ultrasonic processing; however, the defoaming effect of the natural static method and pressuring positively treatment is disappointing. To further improve the defoaming effect, several efficient synergetic methods of defoaming have been proposed.



## 1. INTRODUCTION

The rapid development of airborne electronic equipment to achieve high frequency, integration, and miniaturization require the cleanliness levels of aviation coolants (ACs) to be higher and higher because excessive particulate contaminants in ACs would bring about the blockage of pipeline, wear and tear of aviation components, and even heat accumulation.<sup>1,2</sup> To ensure the stable operation of airborne equipment, the industrial sector had stated that the particulate contamination level of ACs should not exceed class 8 of GJB 420B.<sup>2</sup> The particulate contamination degree, however, is overestimated commonly because the bubbles in ACs are erroneously recognized as particulate contaminants during the measurement process. This is mainly because the number of particulate contaminants is measured by an automatic particle counter based on the physically based shading model, which is influenced by both particulate contaminants and bubbles.<sup>3</sup>

Generally, ACs are composed mainly of base solution and additives,<sup>4–6</sup> with glycol aqueous (GA) solution as the main component of the base solution due to its fast heat exchange, high stability, and low toxicity.<sup>7–9</sup> In our previous work, we found that the additives, especially organic additives, have a decisive effect on the foam behavior of ACs, including tendency and stability.<sup>2</sup> However, the influence of components of ACs on their pollution degrees has not been deeply investigated. Furthermore, the working conditions of ACs, i.e., ventilation rate, pressure, and airflow, which have an effect on

the foam behavior of ACs,<sup>10–12</sup> is usually unintentionally neglected.

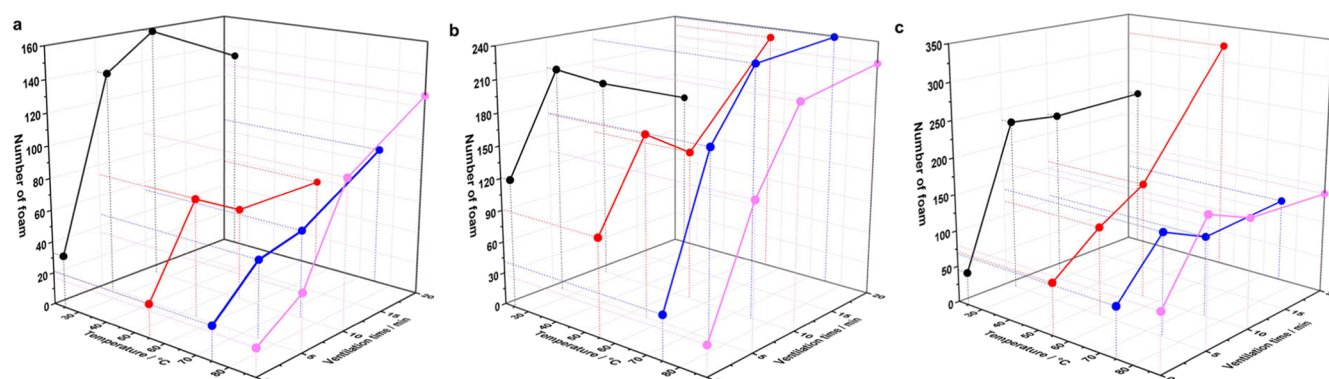
Herein, the influence of the working conditions and composition of ACs on its foam behavior and contamination degree is evaluated. Experimental results show that the foaming tendency of the GA solution is basically unaffected by the ventilation time, temperature, and the ratio of glycol to water, which, however, is highly influenced by the organic additive. Moreover, the working conditions, such as air flow, operating temperature, and gas pressure have a great influence on the foam characteristics and contamination degree of No. 65 AC. The effecting law and action mechanism of the working conditions varies greatly. As for defoaming, the stabilized membrane formed by the surfactant molecules at the gas–liquid interface can be undermined by adding an antifoaming agent, which exhibits a better defoaming effect than other methods, including natural static method and pressuring positively treatment. Based on the effect of such defoaming methods, several efficient synergetic methods have been proposed evidentially.

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**Figure 1.** Foam tendency ( $\varphi \geq 14 \mu\text{m}$ ) of (a) 35% GA solution, (b) 65% GA solution, and (c) 95% GA solution at different temperatures and ventilation time.

**Table 1.** Foam Number and Particulate Contamination Degree of 65% GA Solf with Different Additives for Comparison

surfactant	ventilation time/min	$\geq 4 \mu\text{m}$	$\geq 6 \mu\text{m}$	$\geq 14 \mu\text{m}$	$\geq 21 \mu\text{m}$	$\geq 38 \mu\text{m}$	$\geq 70 \mu\text{m}$	degree
sodium molybdate	0	13 111	3320	148	31	1	0	7
	5	13 475	3328	198	59	5	0	7
	10	13 813	3431	186	51	4	0	7
	20	14 097	3580	206	59	3	0	7
<i>n</i> -caprylic acid	0	7252	1614	151	38	7	1	7
	5	39 284	40 094	8469	2504	326	4	12
	10	62 516	56 606	11 569	4045	915	9	12
	20	65 631	58 440	12 060	4642	1253	6	12
T922 (tritoly phosphate)	0	11 259	2794	134	23	0	0	7
	5	43 327	11 369	744	158	0	0	9
	10	34 243	12 659	1703	401	7	0	9
	20	56 120	20 807	2729	596	9	0	10

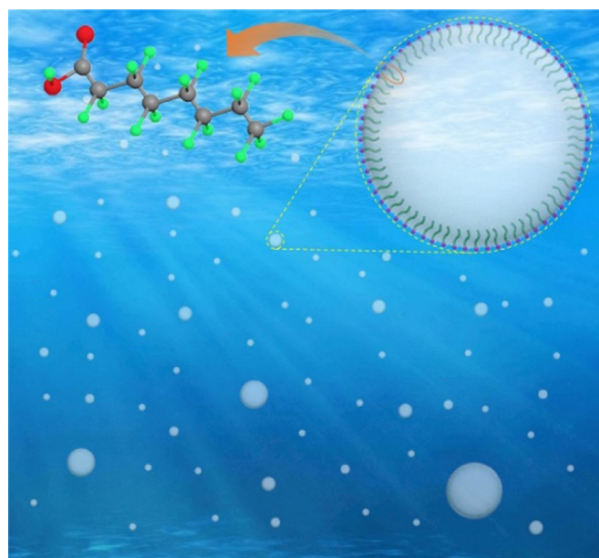
## 2. RESULTS AND DISCUSSION

**2.1. Effect of AC Components.** **2.1.1. Evaluation of the Composition of Base Solution.** Bubbles formed easily in the pure liquid when it is aerated or agitated vigorously; however, the formed bubbles dissipate quickly because the membrane between the bubbles is unstable.<sup>13</sup> To investigate the foam behavior and particulate contamination level of the base solution, which is composed mainly of water and glycol, the foaming tendency of a base solution with different contents of glycol was measured. As shown in Figure 1, the foam number ( $\varphi \geq 14 \mu\text{m}$ ) of the GA solutions with different glycol content changes inconspicuously with variations of temperature and ventilation time, with a maximum value of 322. The number of foams with a smaller size, however, is much greater than those with a higher size. For example, after ventilating 20 min at 55°C, the number of foam  $\varphi \geq 6 \mu\text{m}$  for 95% GA solution is 3712, which is much higher than that of the foam  $\varphi \geq 14 \mu\text{m}$ . This is mainly because the foam with a smaller size is easier to form in solution. Nonetheless, the foaming tendency of the GA solutions with different ratios of glycol to water is nearly identical. These results suggest that the foaming tendency of the base solution is basically unaffected by the ventilation time, temperature, and ratio of glycol to water. The number of formed foam is too few to affect the result of particle contamination degree.

**2.1.2. Evaluation on the Additive.** It is widely known that bubbles are stable in lubricating oil due to the presence of additives at the gas–liquid interface, which can reduce the surface tension effectively.<sup>14,15</sup> As for No. 65 AC, there are small amounts of corrosion inhibitor, preservative, defoamer,

and other additives apart from the GA solution to ensure other properties of the AC. To investigate the effect of additives on the foam behavior and contamination degree, experiments were carried out on 65% GA solution with three kinds of additives commonly used in AC, i.e., sodium molybdate, *n*-caprylic acid, and T922 (tritoly phosphate). The percentage addition of additives is 0.2 vol %. As shown in Table 1, the initial contamination degree of GA with sodium molybdate (GA-SM) is 7, which is basically identical to that of GA without an additive. After ventilating for 5 min, the number of foam of different sizes for GA-SM increases slightly with an unchanged contamination degree. With the prolonging of ventilating time to 10 and 20 min, the number of foam of different sizes and contamination degree is still invariable. These results suggest that sodium molybdate, as an inorganic additive, has little effect on the foam behavior and contamination degree of GA.

However, the effect of *n*-caprylic acid on foam behavior should not be overlooked. The number of foam of different sizes for GA with *n*-caprylic acid (GA-CA) increases dramatically after ventilating for 5 min, and the contamination degree reaches up to 12 from 7, which is well above the prescribed level of 8. For instance, there is a 56-fold increase in the number of foams ( $\varphi \geq 14 \mu\text{m}$ ) for GA-CA relative to the initial value. Furthermore, the number of foam in different sizes increases continually along with the ventilation time extension. This is mainly because the *n*-caprylic acid, as an organic surfactant, are easily concentrated at the gas–liquid interface regularly in a certain way (Figure 2).<sup>16–18</sup> The foamed monolayer additive at the gas–liquid interface reduces the interfacial tension of the GA solution significantly and



**Figure 2.** Schematic of the effect of *n*-caprylic acid on the foam behavior of the GA solution.

makes the bubbles thermodynamically stable. The more organic surfactant in the GA solution, the closer the surfactant molecules are arranged at the gas–liquid interface, and the more stable the bubble.<sup>19,20</sup>

As for GA with T922 (tritolyl phosphate, abbreviated as GA-TP), after ventilating for 5 min, the foam number increases rapidly with a contamination degree of 9. By comparison, the foam number and contamination degree of GA-CA are less than those of GA-TP. In addition, the growth rate of the foam number of GA-TP is also lower than that of the latter (Table 1). The contamination degree reaches a maximum value of 10 after ventilating for 20 min. Although this value is lower than the corresponding value of GA-CA, which is also well above the prescribed level of 8. It might be because the large molecular volume of tritolyl phosphate increases the intermolecular spacing between themselves at the gas–liquid interface, which reduces the stability of the foam.<sup>14,21</sup>

All in all, the foam behavior of the GA solution is highly influenced by the organic additive; however, the inorganic additive has little effect on the foam behavior and contamination degree of GA. Moreover, the concentration of organic additive at the gas–liquid interface is affected by the molecular volume and the interaction between the surfactant molecules.<sup>2,22</sup> The more organic additive arranged at the gas–liquid interface, the lower the surface tension of the GA solution, and more easily the bubbles are formed.

**2.2. Effect of Working Conditions.** **2.2.1. Air Flow.** As shown in Table 2, the number of foam in different sizes increases visibly under the agitation of air and the

**Table 2. Foam Number and Particulate Contamination Degree of No. 65 AC at Different Air Flows**

air flow/mL/min	≥6 μm	≥14 μm	≥38 μm	degree
0	4979	320	2	8
600	48 884	8668	26	11
800	57 564	9070	23	11
1000	59 376	9480	32	11
1200	61 357	10 550	166	12
1400	57 403	9986	332	12

contamination degree reaches up to 11 from 8 at a flow rate of 600 mL/min. The number of foam with small size increases slowly as the flow rate increases; however, the foam number with a large size ( $\varphi \geq 38 \mu\text{m}$ ) increases quickly after steady growth. These results suggest that the bubbles with small size are easier to be saturated in No. 65 AC than those with large size. Also, with the increase in the flow rate, the foaming ability of No. 65 AC increases rapidly and gradually flattens out.

**2.2.2. Operating Temperature.** To investigate the effect of temperature on the foam behavior of No. 65 AC, the foam number and particulate contamination degree were measured at 25, 35, 55, 75, and 88 °C, respectively. After ventilating at 25 °C, the foam number of No. 65 AC increases visibly and the contamination degree reaches up to 12 from 8 (Table 3). As

**Table 3. Effect of Operating Temperature on the Foam Number and Particulate Contamination Degree of No. 65 AC**

temperature/°C	≥6 μm	≥14 μm	≥38 μm	degree
initial	4673	258	1	8
25	44 333	6742	343	12
35	47 947	7523	162	12
55	55 783	11 971	31	12
75	46 080	8682	30	12
88	30 625	4777	30	10

the temperature rises continuously to 55 °C, the foam number increases accordingly. If the temperature rises continually to 88 °C, the opposite tendency is observed, and the contamination degree downgrades to 10. The reason for this phenomenon is that in the range of temperature, with the rise in temperature, the kinetic energy of the surfactants increases and more surfactants are assembled at the gas–liquid interface. The enhanced concentration of the surfactant at the gas–liquid interface reduces the surface tension effectively and enhances the stability of the foam accordingly.<sup>23</sup>

As the temperature rises to 75 °C or even higher, the intermolecular distance between the surfactants increases, resulting in a weakened interaction between the molecules and decreased stability of the foam.<sup>24,25</sup> Furthermore, the interaction between the hydrophilic groups decreases at high temperature, resulting in a decreased surface viscosity, accelerated drainage rate, and reduced foam stability.

**2.2.3. Gas Pressure.** Apart from airflow and operating temperature, gas pressure is another major factor that greatly affects the foam behavior.<sup>26–28</sup> As shown in Table 4, the foam number increases visibly as the gas pressure rises to 0.005 MPa and the contamination degree reaches up to 12 from 8. Moreover, the number of foam in different sizes increase continually with the gas pressure rises, until the pressure rises up to 0.02 MPa. When the gas pressure continues to mount,

**Table 4. Effect of Gas Pressure on the Foam Number and Particulate Contamination Degree of No. 65 AC**

pressure/MPa	≥6 μm	≥14 μm	≥38 μm	degree
initial	4331	323	1	8
0.005	62 367	47 384	15 194	12
0.01	91 551	73 160	21 236	12
0.015	142 696	117 687	42 604	12
0.02	151 582	122 263	41 858	12
0.025	158 278	121 910	44 196	12

Table 5. Defoaming Results ( $\varphi \geq 14 \mu\text{m}$ ) of No. 65 AC with Different Methods

method	number of foam						
antifoaming agent/ $\mu\text{L}$	initial	0.2		0.5		1	
	3202	2114		726		657	
natural static method/min	initial	5	10	30	60	120	240
	120 616	27 803	7324	342	283	211	241
ultrasonic method/min	initial	1	2	3	5	10	15
	106 462	1118	790	707	667	624	577
positive pressure method/MPa	initial	0.01		0.02		0.03	
	82 664	919		911		784	
natural static + ultrasonic method/min + min	initial	5 + 5		5 + 10		5 + 15	
	82 095	754		307		268	
natural static + positive pressure/min + MPa	initial	5 + 0.04		10 + 0.04		15 + 0.04	
	90 299	355		251		225	

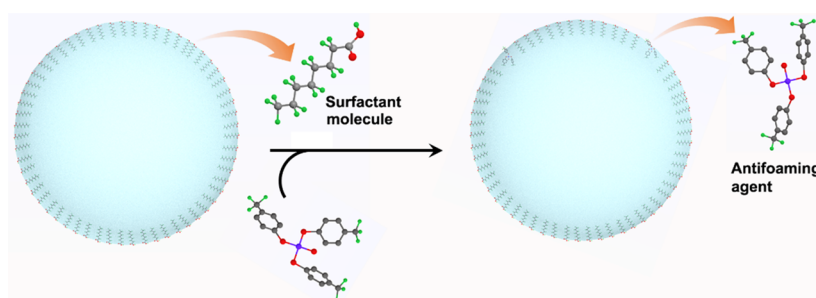


Figure 3. Schematic of the effect of antifoaming agent on defoaming.

the foam number increases at a negligible rate, indicating the foam in No. 65 AC is saturated.

**2.3. Defoaming.** To eliminate the effect of bubbles on the contamination degree of AC, several common methods of defoaming were adopted, i.e., addition of antifoaming agent, natural static method, ultrasonic method, positive pressure method, and synergetic method of natural static and ultrasonic/positive pressure treatment.<sup>29–32</sup> As shown in Table 5, with the addition of 0.2  $\mu\text{L}$  of an antifoaming agent, the foam number decreases from the maximum value of 3202–2114 and continuously decreases to 657 with its adding amount being 1  $\mu\text{L}$ . This is mainly because the antifoaming agent can replace the surfactant molecule and undermine the stabilized membrane formed by surfactant molecules at the gas–liquid interface, the mechanical balance of the stabilized membrane is destroyed accordingly and the bubble is broken (Figure 3).<sup>33–35</sup> Meanwhile, after a period of quiescence, the number of foam also decreases visibly. Also, such a decrement continued with the extension of static time. Compared with the natural static method, the defoaming rate of the ultrasonic method is much faster, indicating the energy brought by ultrasonic wave accelerates the vibration of the surfactant molecules and reduces the concentration thereof at the gas–liquid interface.

Although the drainage effect of bubbles is promoted at a positive pressure, the action time of pressure is too short to reduce the foam number effectively, resulting in an inferior defoaming effect than that of the ultrasonic method. Above all, ultrasonic treatment is an effective way to decrease the foam number compared to the other two methods. However, the number of foam in small size ( $\varphi \leq 6 \mu\text{m}$ ) is invariable after ultrasonic treatment. To further improve the defoaming effect, a synergetic method of natural static and ultrasonic treatment is adopted. As shown in Table 5, the number of foam with

different sizes decreases rapidly after static and ultrasonic treatment, and the particulate contamination degree of ACs well meets the operating requirement. A similar defoaming effect is achieved by the synergetic method of natural static and pressuring positively. As shown in Table 5, the foam number decreases from the initial value of 90 299–355 after static treatment for 5 min and pressuring with a value of 0.04 MPa.

### 3. CONCLUSIONS

The effect of additive on the foam behavior and contamination degree is investigated based on the GA solution with different additives. By comparison, the organic surfactant has a measurable effect on the contamination degree. Also, the concentration of organic additive at the gas–liquid interface is affected by the molecular volume and the interaction between the surfactant molecules, which plays a critical role in the foam behavior. Moreover, the contamination degree of No. 65 AC is also affected by the airflow, operating temperature, and pressure. In addition, the effects of several common defoaming methods are investigated. The antifoaming agent can replace the surfactant molecule and undermine the stabilized membrane formed by surfactant molecules at the gas–liquid interface, resulting in unbalanced mechanical equilibrium of the foamed membrane and desirable defoaming effect. Furthermore, compared with natural static and positive pressure methods, the defoaming rate of ultrasonic method is much faster but lower than that of the synergetic method of natural static and ultrasonic/positive pressure treatments.

### 4. EXPERIMENTAL SECTION

**4.1. Chemicals and Materials.** No. 65 AC was produced by Shenyang Teli Co. Ltd., China. Ethylene glycol, sodium molybdate, *n*-caprylic acid, and T922 defoaming agent were of analytical grade and purchased from Tianjin Chemical Reagent

Company, Aladdin Reagent Company and Hongze Zhongpeng Oil Additive Co. Ltd., China, respectively. Distilled water used in this work was home-made in the laboratory.

**4.2. Foam Number.** One hundred and forty-five milliliters of to-be-detested AC was transferred into a beaker and placed in a thermostatic water bath (25, 55, 75, and 88 °C) for 10 min. And then, at that temperature, the sample was bubbled with compressed air (0.2 MPa) at a rate of 1000 mL/min. Thirty minutes later, the foam number in the AC was detected and recorded by a YSJ automatic particle counter.

**4.3. Defoaming.** The defoaming of the air-bubbled AC was carried out by means of static placing, ultrasonic processing, raising the pressure and temperature, the addition of antifoaming agent, and synergic treatment of the above two methods. Briefly, 145 mL of AC was placed in a thermostatic water bath for 10 min and bubbled with compressed air (0.2 MPa) for 30 min sequentially. Then, the foam number in the AC was detected after static placing, ultrasonic processing, adding antifoaming agent, or pressuring, in which the ultrasonic frequency was set as 49 kHz in ultrasonic processing. As for synergetic methods, the foam number in the AC was detected after static placing and ultrasonic processing (pressuring) sequentially, in which the pressure on AC was 0.04 MPa.

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### Notes

The authors declare no competing financial interest.

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