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REVIEW ARTICLE

Fouling corrosion in aluminum heat exchangers



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Abstract Fouling deposits on aluminum heat exchanger reduce the heat transfer efficiency and cause corrosion to the apparatus. This study focuses on the corrosive behavior of aluminum coupons covered with a layer of artificial fouling in a humid atmosphere by their weight loss, Tafel plots, electrochemical impedance spectroscopy (EIS), and scanning electron microscope (SEM) observations. The results reveal that chloride is one of the major elements found in the fouling which damages the passive film and initiates corrosion. The galvanic corrosion between the metal and the adjacent carbon particles accelerates the corrosive process. Furthermore, the black carbon favors the moisture uptake, and gives the dissolved oxygen greater chance to migrate through the fouling layer and form a continuous diffusive path. The corrosion rate decreasing over time is conformed to electrochemistry measurements and can be verified by Faraday's law. The EIS results indicate that the mechanism of corrosion can be interpreted by the pitting corrosion evolution mechanism, and that pitting was observed on the coupons by SEM after corrosive exposure.

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1. Introduction

When heat transfer surfaces become fouled, the efficiency of heat transfer will be dramatically reduced with even a

minimum of scales, causing major issues to the design and operation of the heat exchangers. New Zealand scientist, Steinhagen, investigated more than 3000 heat exchangers from thousands of different companies and found that over 90% of them had varying degrees of scaling.¹ The economic loss caused by this fouling accounted for about 0.2% of the GDP per year in developed countries.² Thackery estimated that the loss caused by fouling was nearly 500 million pounds each year.³ The inefficiency of heat exchangers in civil aircraft air conditioning (AC) systems induced by fouling may shut down the system, and jeopardize the pressure and temperature controls in the passengers' cabin.

Studies of the fouling problems beginning in the 1980s have been developing along three directions: theoretical analysis of the formation of the fouling in order to supply universal and

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accurate predictive models;^{4–6} fouling development monitoring devices;^{7–9} and the technology to control and remove the fouling.¹⁰ There is little actual published literature on the corrosive fouling found on heat exchangers. The heat exchangers on the aircrafts' AC modules are made of an aluminum alloy with inferior corrosion resistance than the other two types of commonly applied materials: the copper alloy and the stainless steel. The specific active ingredients in the fouling, chloride for example, can damage the passivated surface of the aluminum alloy, reducing the service life of the heat exchangers. The serious corrosion may even cause a leak in the pressurized air, which may de-pressurize the passengers' cabin. Some other studies on the atmospheric corrosion of aluminum alloy have certain reference value for this study.^{11–13}

In this study, the fouling was sampled from actual aircrafts' heat exchangers and analyzed for its composition. Then, the aluminum coupons covered with a coating of homogeneous artificial fouling were put into an environment chamber, which was set as close as possible to the actual service environment of the heat exchangers. The corrosive behavior were characterized by measuring the corrosion rate, comparing the effect of the corrosion on different components, and studying the mechanism of corrosion at different stages.

2. Experiment

2.1. Fouling analysis and experiment design

Samples of the fouling were collected from the heat exchangers by scratching the heat transferring surface or by centrifugally separating a sample from the cleaning solution used to remove the fouling. Each sample was then tested with an energy dispersive spectrometer (EDS) and an energy dispersive X-ray spectroscopy (EDX) respectively. The results are shown in Table 1. The results of these two tests deviate from each other on elements contents of O, S, and C because the fundamental characteristics of these two analysis methods and the corresponding samples' nature, with one being deposit sediment while the other, the liquid extract of the sediment, are different. The artificial fouling design therefore cannot be merely determined by these tests, the operation conditions of the heat exchangers must be taken into consideration additionally.

The fouling on the gas-side of aircraft heat exchangers comes from atmospheric aerosols and the engine exhaust. Atmospheric aerosols are complicated dispersions of liquid and solid particles into the atmosphere, which are mainly composed of soluble components, organic carbon, element carbon, carbon black, and inorganic aluminosilicate, among others.^{14,15} Water-soluble ions, such as SO_4^{2-} , NO_3^- , Cl^- , K^+ , Na^+ , Ca^{2+} , etc., account for a large proportion of the particles in the aerosols. The organic carbon and the black carbon mainly come from the combustion of fossil fuels in aircrafts' engines. At working temperature (100–200 °C), the fouling on the heat exchangers transforms into porous scales, which absorb humidity from the air to form a water-soaked coating over the aluminum surface in which water-soluble components travel through the solution phase to form an electrolytic cell. The Cl^- has been well accepted as one of the dominant factors of aluminum alloys' corrosion for it damages the passivation of these alloys. The black carbon favors the moisture uptake through porous covering layers down to the surface of the base

Table 1 Results of elements' contents in fouling samples.

Element	Content (wt%)	
	EDS	EDX
O	19.93	
Na	2.24	7.283
Mg	2.98	2.288
Al	42.61	11.96
Si	3.87	27.17
P	2.31	3.87
S	1.22	
K	1.28	4.385
C		24.8
Ti		1.36
Cl		0.665
Ni		0.403
Co		0.0226
Ca	1.37	2.863
Fe	20.19	12.2
Cu	1.82	0.122

metal, promoting the onset of micro-cell in the voids of the covering layers, and increases the corrosion rate due to the galvanizing effect. The other fouling components are not as important under the electrochemical corrosion mechanism of aluminum alloys. So the contents of Cl^- and carbon must be taken into account as the key variables in the study.

Based on the above analysis, this paper presents a test for corrosion caused by the artificial fouling, which is very similar to the widely applied ASTM corrodokote test,¹⁶ in order to simulate the actual corrosive factors.

2.2. Preparation of fouling and samples

NaCl , $\text{Fe}_2(\text{SO}_4)_3$, CuSO_4 , Na_3PO_4 , Na_2CO_3 , Na_2SiO_3 , $\text{Ca}(\text{NO}_3)_2$, Na_3PO_4 , Na_2CO_3 , and carbon black were added to 100 mL distilled water as per the amounts listed in Table 2, then continuously stirred for 24 h. After that, 35 g of kaolin clay was added and the mixture was stirred for another 30 min. The mixture was left standing for about 1 h until a paste formed. The paste had a gray-green to dark-green appearance.

2024 aluminum alloy (nominal composition by weight percentage: 0.50 Si, 0.50 Fe, 3.8–4.9 Cu, 0.30–1.0 Mn, 1.2–1.8 Mg, 0.10 Cr, 0.25 Zn, the balance is Al) sheets were machined into coupons of 50 mm × 5 mm × 2 mm with a 1.5 mm diameter hoisting hole near one of the short edges. Each coupon was sanded up to 1200 # abrasive paper. The fouling paste was applied on one side of the coupon using a KW-4A spinning coater. The thickness of the fouling layer was approximately 0.2 mm after drying out. The typical appearances of the testing coupons are shown in Fig. 1.

2.3. Corrosion rate measurements

The fouling covered samples were hung in a temperature-humidity test chamber, which was set at 38 °C and 80% RH. After every 24 h during the experiment, 10 samples from each group were withdrawn from the chamber for measurements.

The bare aluminum coupons were weighed (m_1) before the fouling preparation. After being exposed to the corrosive

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