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Pollution and moisture infiltration effect assessment based on data-driven analysis for aircraft heritage protection

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Abstract. The paper deals with monitoring and analyzing the indoor environmental parameters through remote data collection to evaluate the pollution and moisture infiltration effects on aircraft heritage conservation. First, based on the meteorological and pollution data, the moisture penetration and airborne pollution infiltration into indoor spaces of a heritage site (hangar) with stored historic aircrafts are determined. The hangar under investigation is located in the Aviation museum Kbely, Prague, Czech Republic. The determination is performed by wet/dry cycles (fluctuations) evaluation and applying ISO 11844 methodology to outdoor pollution infiltration into the interior. Next, a time of wetness (ToW) is determined indoors according to ISO 9223, rather as an environmental than a surface parameter as dewing and exceeding high humidity level (approxl RH 80% at T>0 °C) are considered. The actual moisture adsorption onto polluted surfaces of aircraft artifacts is then dependent on the hygroscopic corrosion products developed. Such an adsorption prolongs actual surface ToW. In addition to ToW, even the deposition rate of indoor pollutants, particularly sulphur dioxide and chlorides, are considered and the atmosphere corrosivity is estimated by applying the ISO standardized statistical models for aluminium. The resulting iso-corrosivity figures out the aggressiveness of the hangar environment from the point of view of aircraft material susceptibility to corrosion and degradation.

1 Introduction

Generally, the cultural heritage protection is twofold: pollution infiltration mitigation and moisture penetration avoidance. Once non-invasive protection interventions are considered then a preventive protection of cultural heritage in question takes place and requires an optimization to suppress (rather mitigate) both the pollution and moisture infiltration. Assessment of the outdoor pollution infiltration is commonly conducted by ISO 11844 methodology [1], or rule of thumb [2]. The lower the air exchange rate in the heritage site the lower is the outdoor pollutant infiltration, see [3]. However, it is well-known that besides the outdoor pollution there is also indoor-generated pollution, see museum studies [4, 5]. If the air exchange rate gets below once per hour then the surface removal rate dominates in the processes that regulate the concentrations of air pollutants [3]. A transient-state mass balance describes the general pollution evolution, including the indoor-generated pollution and chemical reactions in air [6]. Since the airborne pollutants can significantly deposit on the exhibited or stored artifact surfaces then a higher humidity level can trigger a degradation or corrosion due to moisture absorption/adsorption onto polluted surfaces [7]. Unfortunately, the interventions made in favour of the pollutant removal may be contradictory to the degradation/corrosion prevention. In fact, the dry pollution deposition is to be also monitored and prevented, see for instance [8].

The pollutant concentration threshold or dosage for the artefact material degradation or corrosion depends on the aggressiveness of the environment, particularly high humidity, dust and light irradiance [9-10]. This threshold or dosage is material-dependent and in case of metals corrosion occurs. Thresholds values are reported in [9] and [10]. Besides these thresholds the so-called Time of Wetness (ToW) is to be determined [7, 11]. For the purpose of the environmental aggressiveness evaluation, ToW is rather as an environmental than a surface parameter as dewing and exceeding high humidity level (approxl RH 80% at T>0 °C) are considered [12-13]. In addition, metallic surfaces contaminated with hygroscopic salts can be wetted at humidity level lower

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than 80%. To calculate the environmental aggressiveness there are several ISO based models for metals [13]. These models provide a corrosion risk assessment, called iso-corrosivity according to ISO 9223, [14]. For corrosion detection and monitoring there are many measurement methods that are rather costly, see [15]. Popular corrosion measurement method is a metal coupon acting as a dosimeter [16].

The research in this paper has been carried out within the framework of JPICH-EU project PROCRAFT[1]. The present challenge is to propose innovative procedures and solutions for the conservation and protection of aircraft heritage. This JPI Cultural Heritage project aims at connecting the multiple actors in the operational chain from recovery to exhibition in France, Italy and Czech Republic. The research in this project focuses on aircraft heritage protection where particularly aluminium alloys are present. Among airborne pollutants, aluminium alloys are most vulnerable to chlorides, [17], and sulfides, [18]. The risk of corrosion damage to modern aircrafts was predicted by [19]. A specific issue in the aerospace industry comes from galvanic interactions at dissimilar metal couples of which the aircrafts are composed [20]. The research presented in this paper is dedicated to effective determination of pollutants and climatic parameters over time to estimate the corrosiveness of the storage site according to common standards. This determination is based on meteorological and pollution data acquisition/analysis.

2 Pollution infiltration effect assessment

The pollution infiltration evaluation is based on the knowledge of pollution deposition velocity onto the artefact surface and air exchange rate in the heritage site under investigation. This site investigated is the hangar with a collection of aircrafts fighting in WWII, located in the Aviation museum Kbely, Prague, Czech Republic. This hangar is only naturally ventilated hence the air exchange rate, n, is close to 0.5 h^{-1}. The exhibition area and hangar volume are A = 2976 m^2 and V = 7884.8 m^3, respectively. Interpolating tabular data on the deposition velocity, v_d, for aluminium alloys from [10] with respect to yearly data on RH, T (see Fig. 1) the indoor pollutant concentration results in average as follows

$$C_i = \frac{n}{n+n_s} C_o = \frac{n}{n+v_d\frac{A}{V}} C_o \qquad (1)$$

where C_o is the outdoor pollutant concentration and n_s is the surface removal rate. In Fig. 2 the measured outdoor concentration of ozone, sulphur dioxide and nitrogen dioxide are recorded in confrontation with corresponding infiltered pollutant concentration determined by (1). After that the pollution deposition rates can be evaluated as follows

$$d = v_d \cdot C_i \qquad (2)$$

resulting in $\mu g \cdot m^{-2} day^{-1}$. Deposition rates onto aluminium alloys for considered contaminants O_3, NO_2, and SO_2 are obtained with respect to tabular deposition velocities for aluminium adopted from [10]. The deposition rates resulted are then drawn in Fig. 3.

The indoor-generated pollution together with chemical reactions in air are neglected by the pollution infiltration evaluation according to (1). For corrosion prevention, $n > n_s$, particularly when C_o originates in values close to thresholds for corrosion. Based on ASHRAE, mean values of these thresholds are 10 $\mu g \cdot m^{-3}$ for all the considered contaminants (O_3, NO_2, SO_2). Of course C_i given by (1) does not determine the indoor-generated pollutants, nevertheless C_i levels provide the information on the hangar protection capability.

3 Corrosion risk estimation in the hangar environment

The corrosion risk in the hangar is estimated by applying ISO 9223 for estimating the corrosivity category with respect to the values of ToW and pollution deposition rates. Thus, besides the pollution infiltration the ToW is to be calculated according to [12]. Therein the continuous integral defines the ToW which is here adapted into a probabilistic relation with respect to hourly sampled (averaged) environmental data. Then

$$ToW = \frac{L}{a} L_T P(RH > 80\%), T > 0°C \qquad (3)$$

where $a = 8766\ h$ and L is the length of data available such that $L < a$. L_T is the data length for which $T > 0°C$. Then $P(RH > 80\%)$ is the probability $0 < P < 1$ estimate that $RH > 80\%$ which is independent of T (more details on the ToW statistical independence in [12]). For the length, $L = 3859\ h$ and $T > 0°C$ it originates $P(RH > 80\%) = 0.016$. Thus, the ToW results due to (3) in 26.32 h. To express the corrosivity category also the pollution deposition rates are to be evaluated by the product of the pollution concentration infiltered and the deposition velocity for aluminium alloys due to (2). Then averaged values of these rates for O_3, NO_2 and SO_2 result from Fig. 3 as follows: 35.39 $\mu g \cdot m^{-2} day^{-1}$, 47.23 $\mu g \cdot m^{-2} day^{-1}$ and 2.71 $\mu g \cdot m^{-2} day^{-1}$, respectively.

Due to resulted ToW and pollution deposition rate levels (T2, P0, S0) the corrosivity category based on ISO 9223 methodology results in C2.

4 Discussion of results

The assessed corrosion risk is low (C2 - indoor climates without microclimate control) and corresponds typically to storages. This is because particularly the key

[1] PROtection and Conservation of Heritage AirCRAFT (PROCRAFT) within JPICH Conservation, Protection and Use Call

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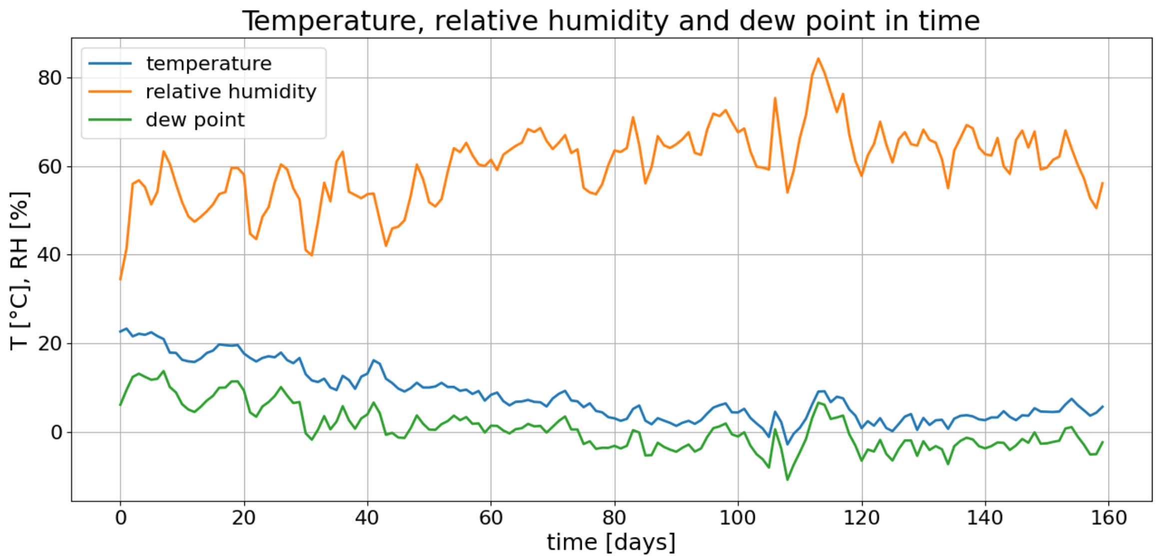

Fig. 1. *RH* and *T* measured indoors (in the hangar) and dewpoint T_{dew}

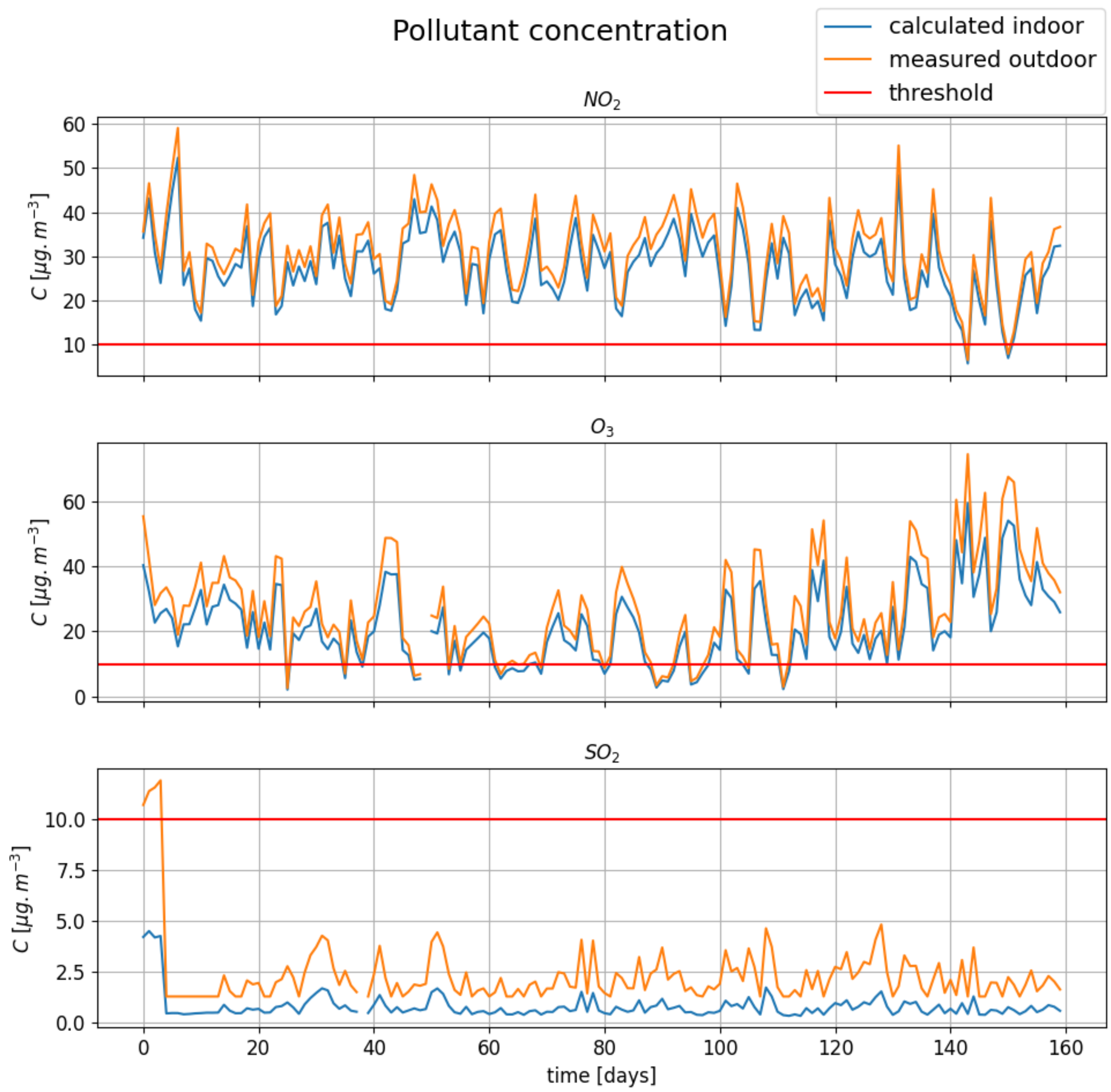

Fig. 2. Pollution infiltration for O_3, NO_2 and SO_2 compared to their thresholds

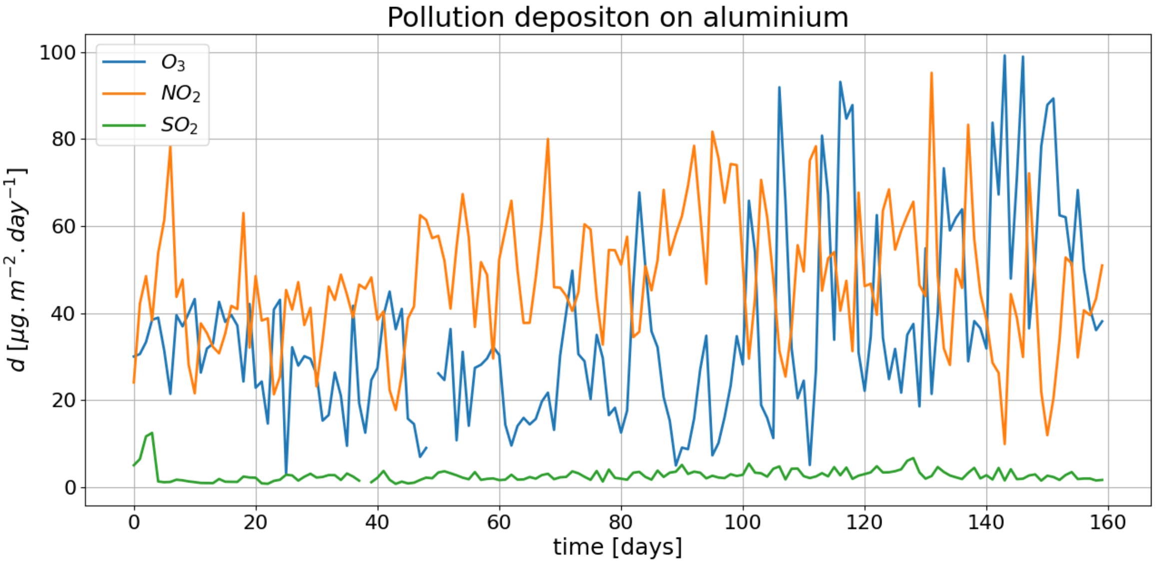

Fig. 3. Pollution deposition rates on aluminium alloy surfaces

pollution level (SO_2) from Fig. 2 is below the threshold for minimal risk of aluminium alloy deterioration and the humidity level remains below 80%, except one peak shown in Fig. 1. Additionally, no dewing occurrences in air appear within the exposure time given by the length of available data. Regarding the occurrence of chlorides, their presence in the area of the Aviation Museum Kbely is negligible, due to inland location free of industry. The other two considered pollutants are ozone and nitrogen dioxide that do not endanger the aluminium alloys. However once mutually reacted and/or NO_2 reacted in humid air, nitrous and nitric acids are generated. With respect to these indoor reactions, the indoor level of NO_2 can overcome that level outdoors but this is not known for this research study, yet. Due to the air humidity not exceeding high level, the aluminium alloys are not significantly vulnerable to chemical reactions in air, as a rule. Simultaneously, due to lower humidity level, dry deposition on aluminium alloy surfaces takes place at rates presented in Fig. 3. The impact of SO_2 on the dry deposition is minimal also for the risk of aluminium alloy deterioration. To suppress considerably the pollution deposition as a whole, the air exchange rate applied has to be sufficiently greater than the surface removal rate, in general. Then natural ventilation must be supplemented by forced ventilation for enhancing the ventilation performance. Finally, not highly humid air does not contribute to moisture adsorption into hygroscopic corrosion products, particularly when airborne salts (chlorides) are missing in the hangar environment.

5 Conclusions

The corrosion risk assessment in the hangar is evaluated by means of the ISO 9223 methodology. The estimated atmosphere corrosivity provides a virtual measurement of corrosion risk in the hangar environment from which all the data are originated. This information gives preliminary results on the environmental corrosivity, especially when the atmospheric corrosion measurement data on the exposed artifacts are not available. This occurs frequently in heritage sites (hangars), where stakeholders may need to limit the costs for corrosion monitoring. To mitigate the material corrosion and degradation, a ventilation and/or recirculation together with air filtration system will be designed in the next steps. Finally, the remote data collection and analysis will be processed by a dedicated decision support system for preventive protection.

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