

Monte-Carlo Simulation of the Filtration Processes of Metallic Discrete Impurity in Oil System of Gas-Turbine Aircraft Engines

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Abstract—The paper considers the deposition of metallic particles on the main oil filter of aircraft gas turbine engines (GTEs) depending on the filter parameters. It was shown that the filter presence includes systematic error in the measurement of the mass fraction of wear particles independent of the measurement equipment. The influence of the filter parameters on the steady state value of particles mass fraction is discussed. It's shown that in modern engines that use 10 μm fine oil filters the mass fraction is less than 0.01 ppm and can't be used as a diagnostic feature for engine technical state evaluation. Oil filter wash samples carry the bulk of the wear particles and consequently, the most diagnostic information. Thus, the oil filter wash sample should be used together with oil sample for reliable evaluation of the technical state of the engine.

Keywords— *Monte-Carlo simulation; filtration process; system of gas-turbine; aircraft engines*

I. INTRODUCTION

Spectral analysis is used more than 30 years for evaluation of technical state of oiled parts and units of aircraft gas turbine engines. The mass fraction of element in oil sample taken from the front drive box is used as an indicator of the wear.

According to work [1], it is not necessary to account for wear particles on the oil filter, because the particles that proceed out of the filter contain enough information for engine diagnostics. And it's enough to measure just single parameter – mass fraction. Also it's stated that it's enough to measure not absolute value of mass fraction but its change which contains information about wear intensity unlike the absolute value which is measured with substantial error, depending on particle size and measuring equipment. This approach results in formulation of identical change principle for differing size mass fractions. According to that principle, change of mass

fraction for any particle size range is equal to change of mass fraction of all particles in oil samples. Simple calculations show that this approach is not without flaws [2].

Work [2] shows that direct proportion between mass fractions of particles of arbitrary size persists only when parameters of wear particle size distribution are independent of time.

The particle filtration in the engine makes that only the small-sized particles are available for analysis in oil sample. Thus, even if some equipment would be able to measure mass fraction of particles of any size in oil sample, it won't be related to engine technical state.

Furthermore, filter does not just restrain particles of specific size. In general, it skews particle size distribution parameters, making particles of different sizes proceed with different probability [3, 4].

Full theoretical examination of the problem can be carried out. This work uses the simple model instead.

Aim of the paper is to study oil filter influence on the wear particle features that are deposited on the filter with regards to analysis of engine technical state.

II. THE OIL SYSTEM AND PARTICLE MODELS

Simplified model of the engine oil system was used in the work. It can be described with the following. The oil pump works the oil from the tank to the friction units where the wear particle generation takes place. Resulting mixture proceeds through the filter and returns back to the tank. Some of the particles are deposited on the filter and some (small-sizes) proceed further through the oil system. To study the processes

in such a system Monte-Carlo method for statistical simulation was used.

Particle generation is modeled by lognormal size distribution function (1):

$$P(D, \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma D} \exp\left[-\frac{(\ln D - \mu)^2}{2\sigma^2}\right] \quad (1)$$

where D – particle size, σ – dispersion. Additional definitions: $\mu = \ln D_\mu$ and $\sigma = \ln D_\sigma$.

This statistical distribution law is supported by many researchers and experimental data.

We'll generate lognormally distributed particles until the mass fraction for all particles would reach specific value for a given oil volume (40 L, usual aircraft volume). The result of the model for iron particles with usual distribution parameters is presented in table 1. For each mass fraction value and distribution parameters pair there were three numerical experiments so mean and standard deviation of the results could be calculated.

The table demonstrates that the particle generation process is stable and relative error of the modelled parameters does not exceed 1 % for a big oil volume and low mass fraction of the particles.

It should be noted that particle count changes drastically for insignificant change of distribution parameters. This is due to high asymmetry of lognormal distribution. Fig. 1 shows particle distribution histograms for mass fraction of 3 ppm.

III. THE FILTER MODEL

It is hard to describe analytically the processes that take place when the oil mixed with wear particle passes through the filter. We'll model the filter with the following statistical approach. Every particle either will pass the filter or will stuck in it with some probability. It depends on filter cell uniformity, particle shape, oil flow hydrodynamics and various others. Statistics say that multiple simultaneously interacting random processes will result in a process with Gauss probability distribution.

Thus, probability of passing the filter with each particle can be written as:

$$F(D, D_\mu^\phi, D_\sigma^\phi) = 1 - \int_{-\infty}^D \frac{1}{\sqrt{2\pi}D_\sigma^\phi} \exp\left[-\frac{(x - D_\mu^\phi)^2}{2D_\sigma^{\phi 2}}\right] dx \quad (2)$$

Here, D_μ^ϕ – mean diameter of the filter cells, D_σ^ϕ – dispersion. Probability of particle passing the filter with parameters, typical for aircraft filters ($D_\mu^\phi = 20 \mu\text{m}$, $D_\sigma^\phi = 5 \mu\text{m}$) is shown on fig. 2.

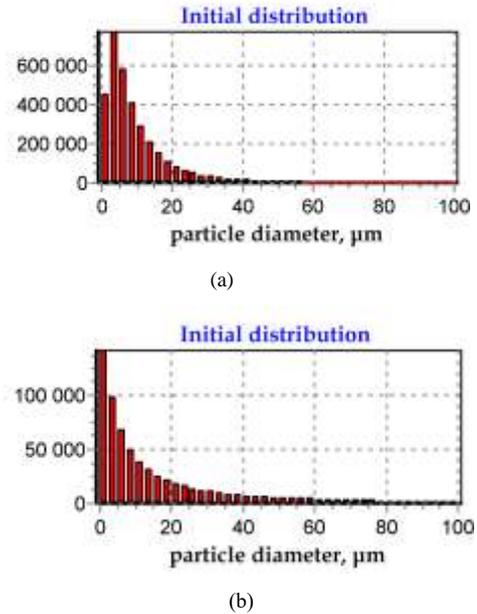


Fig. 1. Initial particle distributions with parameters of $D_\mu = 7 \mu\text{m}$, $D_\sigma = 2.5 \mu\text{m}$ (a) and $D_\mu = 10 \mu\text{m}$, $D_\sigma = 5 \mu\text{m}$ (b) for mass fraction value of 3 ppm

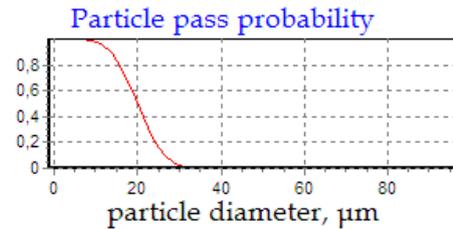


Fig. 2. Transfer function of the Gauss wear particle filter ($D_\mu^\phi = 20 \mu\text{m}$, $D_\sigma^\phi = 5 \mu\text{m}$).

TABLE I. DATA OF THE NUMERICAL EXPERIMENTS

Specified mass fraction, ppm	$D_\mu = 7 \mu\text{m}$, $D_\sigma = 2.5 \mu\text{m}$				$D_\mu = 10 \mu\text{m}$, $D_\sigma = 5 \mu\text{m}$			
	Resulting mass fraction		Particle count		Resulting mass fraction		Particle count	
	mean, ppm	disp.	mean, 10^6	disp.	mean, ppm	disp.	mean, 10^6	disp.
1	1.00	<0.01 %	1.14	0.44 %	1.00	<0.01 %	0.22	0.77 %
2	2.00	<0.01 %	2.27	0.22 %	2.00	<0.01 %	0.44	0.40 %
3	3.01	0.01 %	3.41	0.21 %	3.00	<0.01 %	0.66	0.21 %
10	10.02	0.01 %	11.36	0.19 %	10.00	<0.01 %	2.20	0.12 %

Fig. 3 shows one iteration of filtering the particles with parameters $D\mu=7 \mu\text{m}$, $D\sigma=2.5 \mu\text{m}$ (fig. 1, a) using such filter.

The oil is pumped through the filter at 40 L/min in field situation. So, the whole oil volume will pass the filter 60 times a hour.

Figure 4 shows mass fraction, particle count and mean diameter $D\mu$ for particles after and before the filter depending on time.

The plots show that mass fraction of the particles after the filter is reduced by an order in time span of several minutes. I.e. if wear is not constant, oil is filtered almost fully.

It's curious to check the behaviour of wear particle parameters after one hour filtration depending on the initial distribution parameters (fig. 5).

The plot graphically shows the problems of using the mass fraction as a diagnostic feature. Indeed, even for ideal equipment that would be able to precisely measure the mass fraction the result will depend on particle sizes. For example, 0.1 ppm post-filter mass fraction can be measured both for setup of initial mass fraction 5 ppm and $D\mu = 2.5 \mu\text{m}$, and also for setup of initial mass fraction $>10 \text{ ppm}$ and $D\mu = 3.5 \mu\text{m}$.

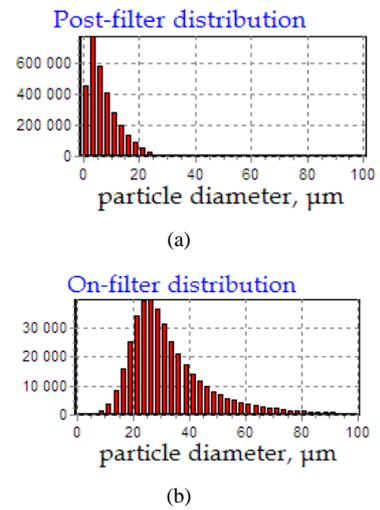


Fig. 3. Particle size distribution ($D\mu = 7 \mu\text{m}$, $D\sigma = 2.5 \mu\text{m}$) after one iteration of filtration using ($D\mu^\phi = 20 \mu\text{m}$, $D\sigma^\phi = 5 \mu\text{m}$) filter. a – particles that passed the filter, b – particles that were deposited on the filter.

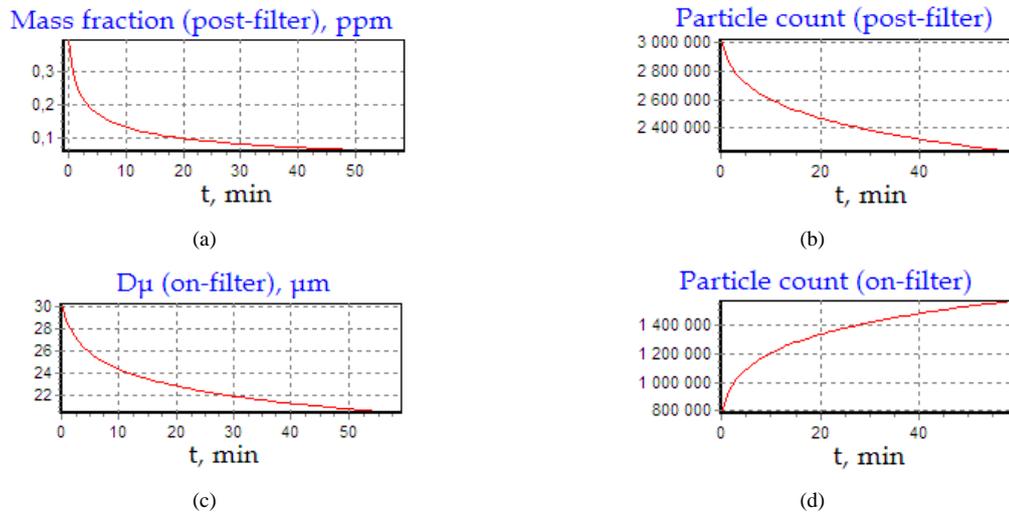


Fig. 4. Wear particle parameters through one hour of filtration: a – mass fraction of particles before the filter, b and d – particle count before and on the filter, c – $D\mu$, mean diameter of the particles on the filter.

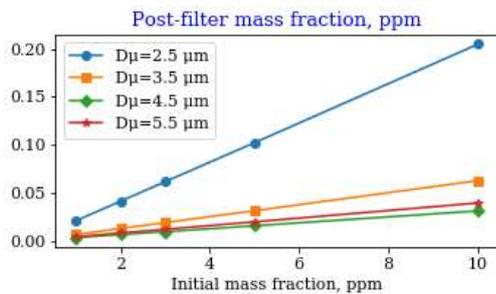


Fig. 5. Dependency of post-filter mass fraction on its initial value after one hour of filtering for various mean diameters of the initial distribution. Filter parameters are $D\mu^\phi = 20 \mu\text{m}$, $D\sigma^\phi = 5 \mu\text{m}$.

IV. THE CONSTANT WEAR MODEL

The generation of wear particles in the oil system is determined by the surface area of friction units. The higher the quantity of them, the more of the parts mass comes off into the oil.

There is also a loss of the particles through the oil that gets pushed out through the gaskets and flows out of the control volume. This loss has its own mean and dispersion.

Let's account for probabilistic nature of filtration process. We'll divide the particle of all sizes K classes of specific size. The mass balance equation for each class will be written as:

$$k = 1, \dots, K$$

$$M = \sum_{k=1}^K M_k \quad (3)$$

$$\frac{dM_k}{dt} = Q_k - L_k$$

Q_k is a value, proportional to friction surface area.

We'll choose class quantity K and max size out of the premise that histogram represents the size distribution with sufficient accuracy.

For a typical wear particle size range (1 – 100 μm) and steady state mass fraction of 1 ppm and oil volume 40 L, particle count is 1 million, and class quantity can be chosen to be 100.

Let's use equation (3) to get particle count per class while assuming particle size to be the same and respecting following relations:

$$M_k = \frac{\rho_q \pi N}{6} \int_{D_k}^{D_{k+1}} D^3 F(D, \mu, \sigma) dD \approx N_k m_k$$

$$N_k = N \int_{D_k}^{D_{k+1}} F(D, \mu, \sigma) dD = N P_k \quad (4)$$

$$m_k = \frac{\rho_q \pi D_k^3}{6}$$

Where m_k – is a mass of the particle in a class k , P_k – is the probability particle to be in class k .

The resulting equation is written as:

$$\frac{dN_k}{dt} = \frac{Q_k - L_k}{m_k} \quad (5)$$

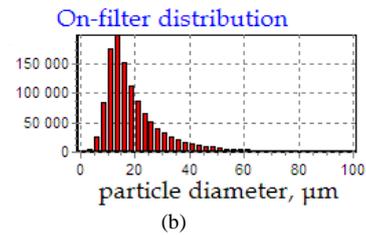
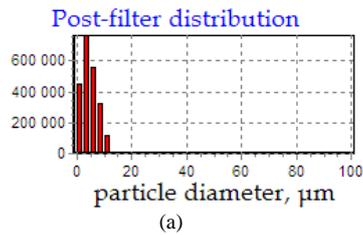


Fig. 6. Particle distribution by size with constant wear source: a – post-filter, b – on the filter

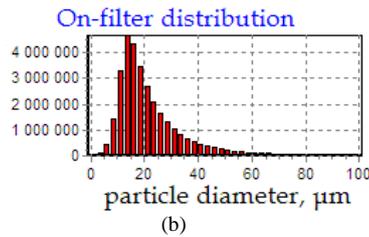
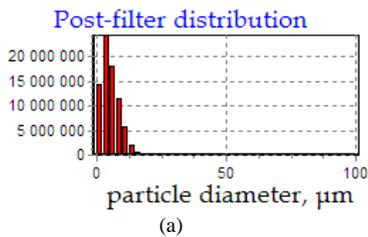


Fig. 7. Particle distribution by size without constant wear source: a – post-filter, b – on the filter

The expression for a particle source:

$$Q_k = m_k \frac{dN_k^q}{dt} \quad (6)$$

$\frac{dN_k^q}{dt}$ – particle appearance rate for class k .

This gives expression for $N^q(t)$, a (7):

$$N_k^q = N^q(t) \int_{D_k}^{D_{k+1}} F^q(D, \mu(t), \sigma(t)) dD = N^q(t) P_k^q(t) \quad (7)$$

Here, F^q is size distribution probability density of the particles; $N^q(t)$ - total quantity of generated particles at the moment t ; $P_k^q(t)$ - particle generation probability for class k . Premising that particle appearance rate and distribution parameters are constant i.e. $P_k^q(t) = const$, the expression for the source can be written as:

$$N^q(t) = V_N t$$

$$Q_k = m_k \frac{dN_k^q}{dt} = m_k \frac{d(N^q(t) P_k^q(t))}{dt} = V_N P_k^q \quad (8)$$

V_N - is the total particle generation rate.

The results of a model with and without constant particle source are shown in table 2 and figures 6, 7. The initial data for generated sample: mass fraction 3 ppm, oil volume 40 L, $\rho_{oil} = 980 \text{ kg/m}^3$, iron particles ($\rho_{Fe} = 7870 \text{ kg/m}^3$), filtration rate 40 L/min, filtration time 60 minutes. Parameters of the loss and the source of the particles: wear particle appearance rate 2 mg/min, oil volume loss rate 16 ml/min.

TABLE II. RESULTS OF THE MODEL WITH AND WITHOUT CONSTANT WEAR SOURCE

	Post-filter distribution					Distribution on the filter			
	Mass fraction, ppm	Element mass, μg	Particle count, 10^6	$D\mu, \mu\text{m}$	$D\sigma, \mu\text{m}$	Element mass, μg	Particle count, 10^6	$D\mu, \mu\text{m}$	$D\sigma, \mu\text{m}$
Without wear source	0.06	2.4	2.22	4.10	1.99	115.4	1.179	17.85	1.68
With wear source	3.29	128.9	77.24	4.46	2.06	3656.8	31.42	19.62	1.65

V. CONCLUSION

It is shown that the mass fraction of metallic impurity decreases by order in time span of about 10 minutes for typical filter parameters. Thus, oil samples will not contain particles caused by fast excessive wear.

It is shown that filter produces systematic error in the measurement of mass fraction of metallic impurity independent of measuring equipment. The error depends on additional wear particle parameters and thus cannot be accounted for a-priori. So, mass fraction should not be used as a feature for evaluation of engine technical state. This is especially true for intensive wear.

The further development of the model will focus on simulating evolving and excessive wear to determine which maintenance measures will allow to timely detect it and prevent further damage and engine failure.

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