

**A METHOD TO CORRECT MEASURED METALLIC CONCENTRATIONS IN
USED OIL SAMPLES****METODO PARA CORREGIR LAS CONCENTRACIONES METALICAS
MEDIDAS EN MUESTRAS DE ACEITE**

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Abstract: In engines diagnostic thru oil analysis, used oil samples are taken and a set of analysis to quantify symptoms such as contaminant concentrations and oil properties, are done. Contaminant concentrations are obtained in a spectrometer but its results do not characterize engine wear if they are not manipulate in a suitable way, so they don't generate wrong information on its condition. Present work expose a method to correct spectrometric analysis results by considering the main factors that can influence oil metallic concentrations: engine and oil service time, oil refill, oil consumption, crankcase volume and oil composition. Proposed method is based on an oil contamination model which consider exponential contamination speed and homogenous and instantaneous lube mixing.

Resumen: En el diagnóstico de motores mediante análisis del aceite, se toman muestras del lubricante usado que se someten a una serie de análisis para cuantificar síntomas tales como las concentraciones de contaminantes y las propiedades del aceite. Los valores de las concentraciones se determinan por medición espectrométrica pero sus resultados no caracterizan el desgaste del motor del que provienen si no se tratan de manera adecuada, pudiendo producir falsas interpretaciones sobre su estado. En el presente trabajo se expone un método para corregir los resultados obtenidos por el análisis espectrométrico teniendo en cuenta los principales factores que pueden influir sobre las concentraciones de los contaminantes metálicos del aceite como son: el tiempo de funcionamiento del motor y el de uso del aceite, los añadidos y el consumo de lubricante, la capacidad del deposito y la composición del aceite. El método se basa en un modelo de contaminación del aceite con velocidad de contaminación exponencial y mezcla del lubricante homogénea e instantánea.

Keywords: Predictive maintenance, fault diagnosis, oil analysis, condition monitoring, internal combustion engines.

1. INTRODUCTION

When spectrometric analysis is used to quantify wear particle content in used oil samples, measurements are generally deviated from its actual value and they do not express the real oil contamination, since they are affected by a set of factors, which in general diminish them. Therefore, it is necessary to make a previous treatment of the results, to calculate the standardized concentrations that assume would exist in the oil, if the causes that originate this behavior did not appear; mainly: oil leakage, oil refill and oil filtering.

In present work a method to calculate the standard concentrations that must have the oil if all the contaminating particles remain and distribute uniformly on it, is exposed. The calculation is important for diagnostic, because besides to represent the real contribution of metallic particles to oil, it serves to produce a more exact evaluation of engine wear speed, being able to better quantify the severity and risk of involved faults (Fygueroa et al., 2006).

2. OIL REFILL, CONSUMPTION, FILTRATION AND COMPOSITION EFFECT

Oil refill, originated by oil consumption or oil leakage, have an attenuation effect on contaminating concentrations: therefore, it is necessary to correct his effect on results.

When oil consumption appears it takes out the contaminants, therefore the concentration of the remaining oil does not change, but its total volume diminishes; this implies, if this oil is not added a new particle contribution will manifest like a greater concentration than the one it would had if there were no consumption. On the contrary, new oil added produces a dilution effect, which reduces concentration.

Oil filter retains an important amount of particles whose quantity depends on filter state, filter retention efficiency and its distribution in oil. At the moment the filter retention efficiency is greater than 90% for particles greater than 10 μm (Staley, 1988). When oil contains additives in whose composition are present some of the elements that desire to measure, it is clear that its amount will be added to the measured one, increasing artificially the concentrations.

3. PRECEDING MODELS

In 1961 Rigaux with the objective of obtaining a model for calculate engine oil metallic particle concentrations, carried out a concentration lines theoretical study considering constant contamination speed and oil consumption. He does not consider neither oil filter effect nor refill oil and obtained the following expression for oil metallic contaminant concentration $C(x)$ as a function of service kilometers, x :

$$C(x) = \frac{r}{q}x + \frac{rc}{2q^2}x^2 + C \quad (1)$$

Where: c = oil consumption per km [kg/km].
 q = crankcase oil mass [kg].
 r = Metallic contaminant mass generated per engine service unit [kg/km].

In 1976 Perez developed a mathematical model to calculate oil average contamination speed P_a and obtained the following equation:

$$P_a = \frac{2V_o}{T} \frac{1 + \frac{A}{V_o} - \frac{A}{nV_o}}{2 - \frac{A}{nV_o}} \quad (2)$$

Which considers the oil refill effect supposing constant oil addition intervals. This expression take into account the number of times n , in which during time T the refill ones are made. From the existing concentrations at the beginning and the end of the interval constant contamination average speed calculations during the considered interval, are made. Eq. (2) represents an important advance in engine wear study because, although it gives a constant contamination average speed, it considers the real contamination speed variation during oil service time, as it happens really.

Other authors as Fitch (1973) and Kjer (1982) attained the same conclusions about oil concentrations variation; for a zero initial concentration they obtained:

$$C_i = \frac{P_i}{k} (1 - e^{-\frac{kt}{V}}) \quad (3)$$

Where C_i is the i dimension particle concentration [mg/l] after time t , P_i is the same size [mg/l] particles contamination speed, k is the volumetric quantity removed [l/h] and V the total crankcase oil volume [l].

In 1982 Hubert *et al.* published a study about contamination speed measurement and modeling, and diesel engine oil filter efficiency using ferrography, that showed a mathematical model to predict crankcase oil concentration behavior. From a system mass balance, they obtained the following expression:

$$C(t) = C_0 - \frac{m}{eQ} e^{-\frac{eQt}{V}} + \frac{m}{eQ} \quad (4)$$

Where $C(t)$ [mg/l] is the crankcase oil concentration after a time t , C_0 [mg/l] is the crankcase particle concentration at $t=0$, m [mg/min] is the contamination speed, ϵ is the filter retention efficiency, Q [l/min] is the system circulating volumetric oil flow and V [l] is the total crankcase oil volume. According to this model the oil concentration changes exponentially reaching a dynamic equilibrium concentration C_{eq} , when the contamination speed equals the contaminant loss speed; its value obtained taken $t = \infty$ in Ec. 4 is: $C_{eq} = m/eQ$.

4. PROPOSED MODEL

Next we present a more real model to calculate oil contamination speed and engine wear, based on a model proposed by Espinoza (1990) that considers the filter, oil consumption, oil refill and clean oil composition influence supposing constant contamination speed: in practice, the more frequently observed case.

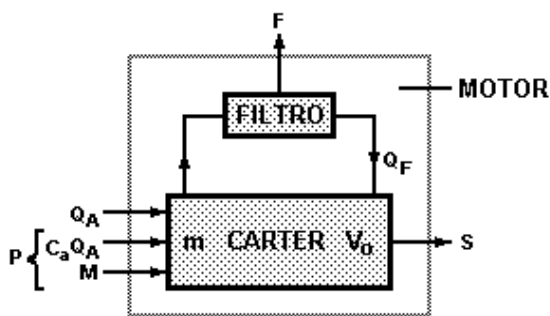


Fig. 1. Engine oil flows

The model is based in the following hypotheses:

- Wear particles are mixed homogenous and instantaneously with oil.
- Oil filter volume is zero.
- Constant flow oil losses equivalent to oil refill.

- Oil flow through filter, total oil volume and filter efficiency do not vary with time.
- Contamination speed is time independent.

Contaminating agents mass conservation equation applied to engine control volume, Fig 1, gives the following expression:

$$\frac{dm}{dt} = P - F - S \quad (5)$$

Where: m = metallic contaminants mass at instant t [mg].

P = oil contamination speed [mg/min].

$$P = M + C_a Q_A$$

M = wear contamination speed [mg/min].

C_a = unused oil metallic concentration [ppm].

Q_A = Refill oil mean volumetric flow [l/min]. $Q_A = A/t$; A is the total added oil [l] during oil permanence time t [min]. $C_a Q_A$ = refill oil contamination speed [mg/min].

F = oil filter retention speed [mg/min].

$$F = \epsilon Q_F m / V_0$$

ϵ = filter efficiency.

Q_F = oil mean volumetric flow circulating thru the filter [l/min].

V_0 = crankcase total oil [l].

S = contaminants mass loss speed by oil consumption [mg/min]. $S = Q_A m / V_0$

The total contaminants mass loss speed $F+S$, is

$$F + S = \frac{\epsilon Q_F + Q_A}{V_0} m = Zm \quad (5)$$

Replacing Eq. (6) in Eq. (5), we have:

$$\frac{dm}{dt} + Zm - P = 0 \quad (6)$$

Eq. (7) is the general expression that governs oil contamination process by solid particles. It is a constant coefficients first order linear differential equation, since Z and P are constants, whose solution is:

$$C = C_0 e^{-Zt} + \frac{P(1 - e^{-Zt})}{Q_A} \quad (7)$$

Where:

C = metallic concentration after time t [ppm].

C_0 = oil bath initial metallic concentration [ppm].

From this equation contamination speed can be obtained:

$$P = \frac{(C - C_0 e^{-Zt}) Q_A}{1 - e^{-Zt}} \quad (8)$$

And the wear contamination speed:

$$M = \frac{(C - C_0 e^{-Zt}) Q_A}{1 - e^{-Zt}} - C_a Q_A \quad (9)$$

Since the oil bath standard concentration (real wear) after time t is:

$$C_n = C_0 + \frac{M}{V_0} t \quad (10)$$

Considering the measured concentration C_m equals the concentration C after time t and replacing Eq. (10) in (11) we find a general expression to obtain the standard concentrations:

$$C_n = C_0 + \frac{(C_m - C_0 e^{-Zt}) Q_A}{1 - e^{-Zt}} - C_a Q_A \frac{t}{V_0} \quad (11)$$

Eq. (12) gives the crankcase concentration considering the combined effects of consumption, refill, filter and oil composition supposing constant contamination speed. If do not consider consumption and oil composition Eq. (12) match Hubert equation. Studies conducted by the authors (Figueroa, 1994) have demonstrated that if concentrations are measured with a spectrometer, since the apparatus detects only particles whose size is smaller than $5 \mu\text{m}$, the filter effect can be transcurated. Therefore, if $e=0$ in Eq. (6) we obtain:

$$Z = \frac{Q_A}{V_0} = \frac{A}{tV_0} \quad (12)$$

As a result Eq. (12) is:

$$C_c = C_0 + \frac{A}{V_0} \frac{(C_m - C_0 e^{-\frac{A}{V_0} t})}{1 - e^{-\frac{A}{V_0} t}} - C_a \quad (13)$$

Which is the expression to calculate the standard concentration considering refill and clean oil composition.

When clean oil does not contain metals coinciding with measured ones and the oil bath initial concentration is zero $C_a=C_0=0$ and Eq. (14) agrees with Fitch expression.

When clean oil contains metals coinciding with measured ones and there is not wear; spectrometric analysis result is a concentration C_a , namely $C_m=C_a$ and since for the unused oil bath $C_0=C_a$; from Eq. (14) we obtain $C_c=C_a$; expected value because there are not wear.

In Eq. (8), $1/Z$ is the time constant: the time in which the wear particle concentration reaches a certain percentage of its equilibrium concentration.

Concerning the relation between oil metallic elements concentration and its service kilometers, it is obvious that, still for a normal wear, the last increases directly with the former; this growth is exponential since the oil metallic particles increase produces a wear that generates more particles, which originate more wear as well and so on; that is, the effect is more accused as the service kilometers increase (Figueroa et al., 2006). This exponential behavior is refill compensated, since oil dilution reduce particle concentration, so the resulting behavior is linear, specially if the oil service does not extend excessively; therefore:

$$\frac{C_{n1}}{C_{n2}} = \frac{K_1}{K_2} \quad (14)$$

Where C_{n1} and C_{n2} are one element metallic standard concentrations in oil at K_1 and K_2 kilometers respectively.

5. CONCLUSIONS

Analyzing the model equations we reach the following conclusions:

- When filter efficiency increases, time constant reduces and equilibrium concentration is reached more quickly.
- When contamination speed increases, equilibrium concentration grows linearly.
- Oil refill causes a measured concentration reduction.
- When contamination speed increases, equilibrium concentration increase.
- To maintain equilibrium concentration as contamination speed increases, filtering efficiency must increase.
- If the filter efficiency is considered, its influence on measured concentration is much greater than consumption one.

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