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Measuring injectors fouling in internal combustion engines through imaging

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Abstract

The use of liquid fuels derived from biomass in internal combustion engines, based on direct fuel injection, involves the formation of a large amount of carbon deposits on the tip of injectors which significantly influence emissions and engine performance. Currently most of the research activities are focused on the physical and chemical evaluation of deposits, using GC/MS (gas chromatography/mass spectrometry) analysis of alcoholic solutions with dissolved samples and FESEM (Field Emission Scanning Electron Microscopy) and EDS (Energy Dispersive X-ray Spectroscopy) analysis to characterize their microstructures. There are few methodologies to quantify the temporal fouling on the injectors in order to define a correlation between fouling, fuel and engine performance. The development of a methodology to compare the different effects of fouling obtained diversifying the fuel input of a direct injection engine is the aim of this work. The methodology is based on photography and post-processing of images to obtain a pixel count linked to a fouling index. The effect of lighting and visual angle is taken into account and a preliminary qualitative evaluation of the performance of the methodology is carried out. This methodology was also carried out to determine the minimum number of photos required to quantify the deposit independently by the orientation.

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Keywords: ICE (Internal Combustion Engine), Injector, Fouling, Tip, Pixel, Index

Nomenclature

GC/MS	Gas Chromatography/Mass Spectrometry

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FESEM	Field Emission Scanning Electron Microscopy
EDS	Energy Dispersed X-ray Spectroscopy
CFME	Chicken Fat Methyl Ester
SEM	Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectroscopy
ICE	Internal Combustion Engine
CI	Cocking Index
CCD	Charge-Coupled Device

1. Introduction

Crude and waste vegetal oils represent a renewable fuel for internal combustion engines. Diesel engines require specific modifications to optimize their operation with vegetal oils. Whether a single tank in diesel engines with pre-combustion chamber, or two tanks in case of direct injection or common rail, oil preheating is usually carried out. Information is available in the Literature for different renewable liquid fuels ranging from crude and waste oils, biodiesels and waste oils from pyrolysis and gasification of biomass [1-7]. The use of these fuels is connected to the formation of carbon deposits on the injectors and indirectly to an increase in particulate emissions [8]. The formation of deposits strongly depends on the temperature to which the injected fuel is exposed. With increasing temperature and duration of the heat exposure the solubility of the deposits becomes more and more reduced until eventually complete insolubility is reached [9].

Deposits may be measured through visual analysis like high-speed spray imaging, optical microscopy and scanning electron microscopy (SEM) while their characterization can be made through elemental analysis including energy dispersive X-ray fluorescence spectroscopy (EDX or EDS) and compositional analysis as Fourier Transform Infrared Spectroscopy (FTIR) and Gas chromatography coupled with mass-spectrometer namely GCMS which is able to identify and quantify volatile compounds [10]. Galle et al. [11] carry out an investigation based on SEM analysis that revealed different causes of injectors failure, including plastic deformation, erosion and clogging of the injector’s passages, affected by chemical and physical composition of the fuel.

Liaquat et al [12] evaluated through EDS analysis the deposits at the tip of an injector of a diesel engine, single cylinder, after 250 operation hours, comparing the fossil diesel with a 20% mixture of biodiesel showing a significant increase in the carbon percentage of the deposit.

Injection technology has evolved because of more stringent regulations on emissions and the engines have become more sensitive to the formation of deposits on injectors changing the fuel quality [13]. Richards et al [14] evaluated the variation of the spray pattern with the accumulation of deposits at the tip injector highlighting many differences especially in terms of opening angle of the cone and its penetration inside the chamber with loss of engine’s efficiency.

Also Pos et al [15] showed that the presence of deposits on/in the nozzle of a diesel injector leads to changes in the fuel spray evolution increasing spray cone angle by 10 – 140% compared to the fuel spray cone angle from a new injector. Consequently the anomalous shape of spray cone angle lead to an alteration of combustion quality in an engine when the injector are fouled.

Magno et al. [16] investigated the injection and the combustion evolution of an optical single cylinder compression ignition engine equipped with a 16 valves Euro 5 multi-cylinder head through a non intrusive 2-D digital imaging. Optical investigation was carried out to measure the jets length, the luminous intensity along the jets axis and the pollutant formation. Most of the actual research evaluates chemical and physical fouling with costly and time consuming approaches.

For a fast method for fouling measurement Peterson et al. [17] estimated the fouling at the tip of the injectors through analysis of images and varying the fuel. Later a photographic bench equipped with a specific injector housing and a lighting system placed behind the area of the tip was realized [18, 19]. The image was captured by the CCD camera (Charge-Coupled Device). The study led to the definition of a fouling index called CI (Cocking Index) and given by the ratio between the fouling area of the i-th fuel and the same area of the diesel as the reference fuel. The areas were calculated as the sum of black pixels.

A similar approach was followed in this work to determine a fouling index by way of a capturing images with a low cost camera (Panasonic Lumix TZ5) and post processing the resulting image.

2. Methodology

2.1. Definition of the fouling measurement method and the test bench construction

A low cost test bench was built with a specific guide hole for the injector to allow fixed rotations. The repeatability of the rotation was obtained by implementing the bench with 12 notches placed at 30 degrees up to 360 and the injector seat with a single reference notch. The distance between the lens of the camera and the tip of the injector was considered with respect to specific focus common to low cost digital cameras.

Two 100 W incandescent lights sources were mounted and shielded to guarantee diffused illumination and minimize reflexes. Photos were taken in a self-timer mode to avoid interference due to the complete closure of the box and to exclude the uncertainty due to the natural light. Artificial fouling of the tip of the injector was provided using coal dust. The image of the tip of the injector shows an increase in deposits due to two contributions: an increase in the profile of the injector (as the increase in the area of the tip) and a color change of the surface of the tip exposed to the camera.

Using a homemade MatLab subroutine the image of the tip of the injector was analyzed to evaluate the variation of fouling. The subroutine provides a matrix of values of light intensity, where the generic element i,j corresponds to the relative pixel i,j of the scanned image.

The RGB (Red-Green-Blue) matrix related to a color image is given by the overlap of three intensity values of the color tones in each pixel (respectively red, green and blue); a grayscale image is represented by a matrix where each element (pixel), can assume a value in the 2^8 levels of intensity; the level 0 represents black while level 255 represents white. Therefore grayscale images were considered.

The difference between the clean injector and dirty injector picture relatively to the same position of the injector was primarily evaluated.

The two images having the same resolution can be subtracted from each another in terms of intensity of each pixel. The result is a matrix made of the same size as the original photos in which each pixel is represented by an intensity value given by the difference of the intensity values of the corresponding pixels common to the two pictures.

Deposits are shown as a white level as the value of the pixel intensity increases. The black pixels show no change of intensity and therefore no fouling (see for example the background).

In order to remove lighting errors the calculation area of the image was limited to a small area near the tip (Figure 1) using relative reference coordinates.

This method with respect to others available in the Literature allows fouling evaluations also on the front surface of the tip helping to understand deposit removal due to mechanical and/or thermal stress and use of additives [20].

Fig. 1. Clean injector (sx), dirty injector (middle) and difference (dx)

3. Results

By analyzing the "difference matrix" (Figure 2) a column vector representing the number of pixels that show the same variations in intensity is obtained.

Then a numerical weight was assigned to fouling by multiplying this column vector for a vector of equal size in which the first element is equal to 0 (for not considering the unchanged pixels), the second equal to 1 etc. The sum of all the values obtained gives a number called "Fouling Number Difference".

To take into account the effect of lighting and of slight movement due to the clicking of the camera button 30 pictures were taken with the clean injector and 30 with the fouled injector.

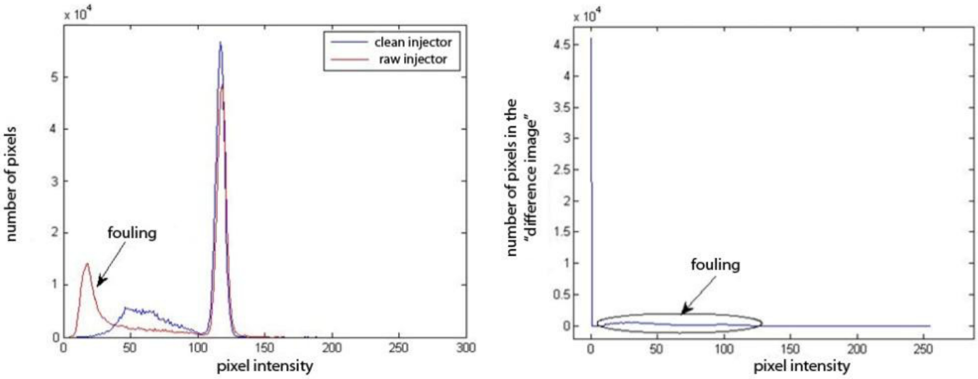


Fig. 2. Hystogram of the matrices "clean injector" and "raw injector" (sx) and "matrix difference" (dx)

Test showed a small variation only at the very small pixel intensities (Figure 4) and therefore pixel intensities variations below 10 were discarded. A reduction on dispersion from 8,57% to 1,11% was then observed. The overall index however is also reduced by 5,6%.

3.1. Test of the method

The test was based on the evaluation of the weight of four different foulings in the following way:

- weighing of the clean injector and execution of 12 photos turning the injector by 30°;
- weighing the dirty injector and execution of 12 photos turning the injector by 30°
- repetition of this step for other 3 increased deposits;

- images processing of different foulings and "fouling index" defined in (1) definition related to every fouling and injector orientation;
- for each fouling the calculation of a "fouling index" related to groups of all the combinations of 2, 3 and 4 photos was carried out.

This was carried out in order to determine the minimum number of photos required to asses the deposit with an acceptable dispersion of data for the fouling index. In other words, assuming that the operator is photographing the injector without particular care in choosing the view, how many different views should he photograph to asses correctly the weight of the deposit?

The weights of fouling in table 1 were defined as the arithmetic average of 20 weighings, one every five minutes, carried out a half before and a half after the execution of the photos. The fouling index for each group of photos was calculated in the following way:

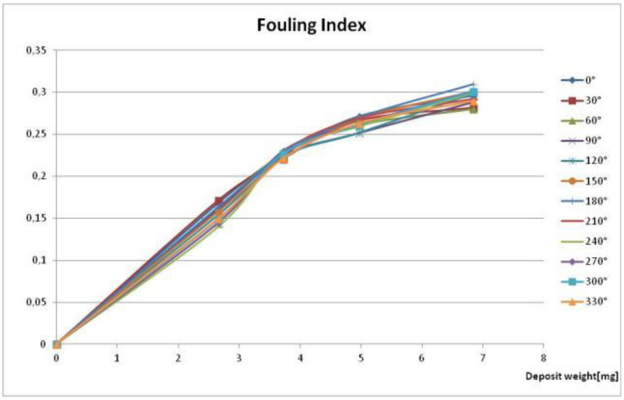
$$\mathrm{FI}_n = \frac{\sum_i^n (\text{Fouling Number Difference})_i}{\sum_i^n (\text{Clean Injector Number})_i} \tag{1}$$

where "n" is the number of photos as a group, "Fouling Number Difference" is the sum of the number of pixels per their relative intensity values and "Clean Injector Number" is derived from the number of pixels of clean image weighed by intensity. The trend of the indexes as a function of the weight of deposits was evaluated.

The results in terms of "fouling index", linear regression, medium value and standard deviation are shown in figure n. 3 to 6.

Table 1. Weight of injectors and fouling

	Injector weight [g]	Stand. Dev. [mg]	Deposit weight [mg]
Clean	205,0595	0,282	0
Fouling 1	205,0622	0,154	2,7
Fouling 2	205,0632	0,146	3,7
Fouling 3	205,0645	0,336	5
Fouling 4	205,0664	0,211	6,8



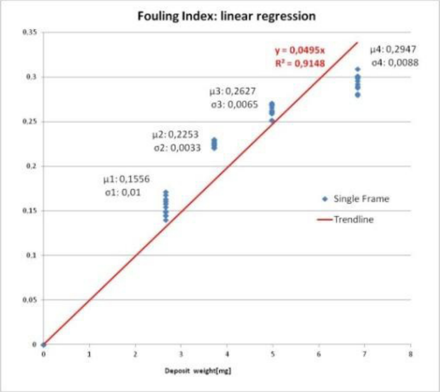


Fig. 3. Fouling index and linear regression for single casual picture

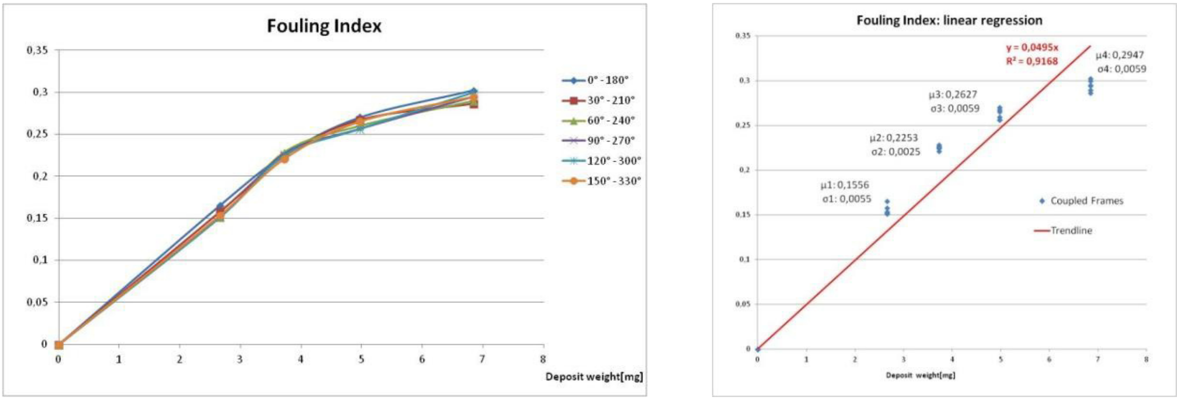


Fig. 4. Fouling index and linear regression for two injector rotations at 180°

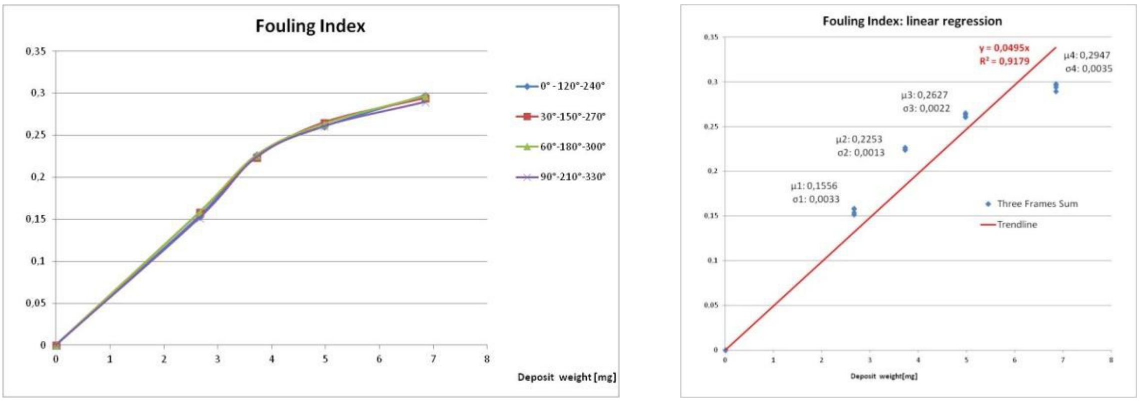


Fig. 5. Fouling index and linear regression for three injector rotations at 120°

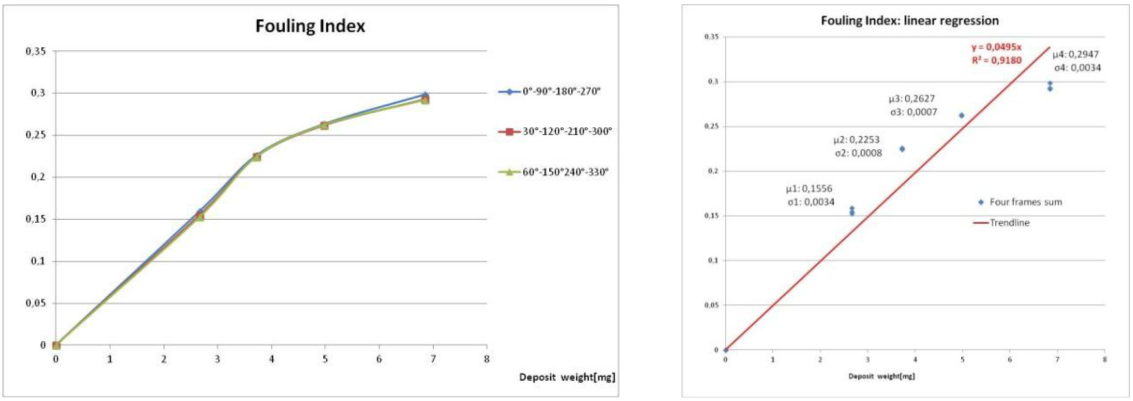


Fig. 6. Fouling index and linear regression for four injector rotations at 90°

The minimum square regression line was built by imposing its passage through the origin since zero deposits requires a fouling index equal to zero. The graphs show a growth of "Fouling Index" with an increase in the deposits on the injector, a higher accuracy is evident when the index is calculated on the basis of larger groups of photos. For the single picture case (figure 5) the index is varying considerably when rotating the injector with an overall error exceeding 20% . When considering two pictures (figure 6) of opposed view of the injector, hence a 180° rotation, the overall error is considerably reduced and it is below 10%. For three pictures (120° rotation, figure 7) or four pictures (90° rotation, figure 8) the error falls below 5%.

4. Conclusions

The use of fuels in diesel ICE involves the formation of deposits on injectors causing a loss in engine efficiency but also significant increases in terms of particulates emission. To characterize the amount of these deposits a methodology based on imaging analysis with simple and low cost digital camera was considered. Through the use of conventional and available materials, a closed box containing an housing for the injector and for the camera and two 100 W lights for a diffuse illumination was built. Pictures were processed in a matrix of pixels and a fouling index was defined with respect to the clean injector. The fouling index linearity with increasing weight of the deposit was confirmed. It was shown that the calculation of the "Fouling Index" is more reliable when calculated on the basis of growing groups of photos. The maximum value of R^2 and the minimum value of the standard deviation are obtained respectively for groups of 3 and 4 photos. Comparing R^2 in the two cases, this differs by 0.011%, while the standard deviation decreases in the case of 4 photos only for the second and third fouling. However the results obtained for two opposing photos may be considered acceptable for quick on field measurement.

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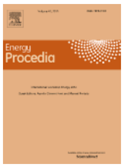

Biography

Michele D'Amico received the Environmental Engineering degree in 2006, and Ph.D. in Industrial Engineering in 2010, from University of Perugia. His research interests are sustainable, renewable and distributed energy generation, thermo-chemical processes and technologies for biomass to biofuels converting, biofuels combustion mechanisms, computational thermo-fluid dynamics analysis for designing and optimizing energy systems.