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A quantitative methodology to measure injector fouling through image analysis

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Abstract

The use of vegetables oils in a compression ignited internal combustion engine presents some critical issues as the large amount of carbon deposits on the tip of injectors, which significantly influence emissions and engine performance. A previous draft methodology was developed by the authors, based on images capture and post-processing. The carbon deposit was correlated with the number of pixels in the gray scale, so it was possible to determine a Fouling Index. First results showed interesting perspectives and some limits: the aim of the present work is the optimization of the test bench and methodology. At first an improvement of image acquisition, increasing sampling frequency and image resolution, is performed, replacing the old camera with a digital microscope and improving both injector and microscope positioning. The test bench prototype has been realized with the aid of 3D printing, obtaining fundamental mechanical components. Also an alternative methodology is proposed to evaluate carbon deposits volume through a Volumetric Index. The new methodology validation was done using images sampled with the previous test bench. The performances of the Fouling index and of the new Volumetric Index were compared and fouling was examined in the real case of a diesel engine, fed with diesel and sunflower oil. Results show a greater reliability of the new Volumetric Index.

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

Nomenclature

CCD	Charge-Coupled Device
EDS	Energy Dispersed X-ray Spectroscopy
FESEM	Field Emission Scanning Electron Microscopy
FI	Fouling Index
GC/MS	Gas Chromatography/Mass Spectrometry
ICE	Internal Combustion Engine
SEM	Scanning Electron Microscopy
VI	Volumetric Index

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1. Introduction

Crude and waste vegetable oils represent a renewable fuel for internal combustion engines [1-7], but the use of these fuels is limited because of carbon deposits formation on the injector's tip, caused by higher viscosity, incomplete combustion and exposition to high temperature that affect the deposit solubility [8], and indirectly to an increase in particulate emissions [9]. Deposits may be measured through visual analysis, like high-speed spray imaging or SEM analysis while their characterization can be made through energy dispersive X-ray fluorescence spectroscopy (EDS) and compositional analysis as Fourier Transform Infrared Spectroscopy (FTIR) or Gas chromatography coupled with mass-spectrometer namely GC/MS, which is able to identify and quantify volatile compounds [10].

Galle et al. 2012 [11] carried out an investigation based on SEM analysis, which 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 2013 [12] evaluated through EDS analysis the deposits at the injector tip of a diesel engine, single cylinder, after 250 operation hours, comparing the fossil diesel fueling and a mixture with 20% of biodiesel: results showed 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 deposits formation changing the fuel quality [13]. Some authors [14, 15] evaluated the variation of the spray pattern with the accumulation of deposits at the injector tip highlighting many differences especially in terms of opening angle of the cone and its penetration inside the chamber, leading to an alteration of combustion quality and loss of engine's efficiency. Magno et al. [16] investigated the injection and the combustion evolution inside an optical single cylinder compression ignition engine through a non intrusive 2-D digital imaging measuring: 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 captured in a photographic bench equipped with a specific injector housing, a CCD camera (Charge-Coupled Device) and a lighting system placed behind the area of the tip [18, 19]. 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.

A similar approach was followed in a first work, presented by the authors [20], to determine a Fouling Index, capturing images with a low cost camera (Panasonic Lumix TZ5) and post-processing the acquired data. In this work the new test bench for image acquisition, based on the use of new mechanisms and a digital microscope, is described together with a new methodology and a new index (Volumetric Index). The performances of the VI and the FI are compared at first using artificial deposits and then with a real case of combustion performed on a diesel engine fed with fossil diesel and sunflower oil.

2. Materials and method

2.1 Design and construction of the new test bench

A first low cost test bench, see [20]; was built with a fixed CCD camera positioning and a specific guide hole for the injector, its rotation was checked by implementing the bench with 12 notches placed at 30 degrees and the injector with a single reference notch. The rotation and images capturing were manual, which implied high uncertainty, a slow image capturing process and errors due to light infiltration and overlapping of images.

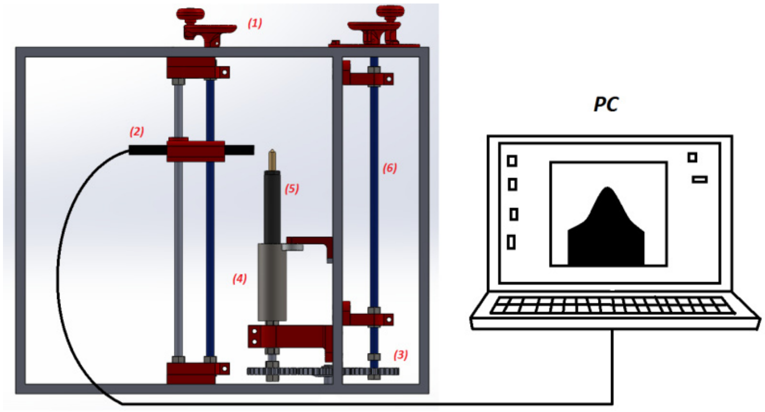

Figure 1: Test bench for image capture: (1) microscope height regulation mechanism; (2) USB microscope connected with PC, holder system (in red) and handling mechanism made by a linear bearing LM8UU and an M8 threaded rod; (3) gears with idle wheel for injector orientation; (4) cylindrical seat for the injector; (5) Deutz BF4M2011C injector; (6) threaded rod (in blue) which links the knobs to the gears

The new test bench project was based on the following improvements: substitution of the camera with an USB microscope; creating a mechanism for microscope height variation; injector rotation through a spur gear; light source positioned behind the microscope ensuring appropriate diffusion and reducing reflexes on the tip of the injector. Height and rotation are moved externally to the box. The USB microscope positioned at 17mm of distance from the injector tip, grants a zoom of 12X and a resolution of the picture of 640x480 pixel, increased of an order of magnitude respect to CCD camera using. The red components shown in figure 1 are produced in PLA, modeled through 3D CAD software and realized through 3D printing.

2.2 Methodology employed to calculate the Volumetric Index

The new proposed methodology is based on the concept that the image of the fouled injector shows an increase in his area profile respect to cleaned injector. Using a MatLab subroutine it is possible to convert a color image in 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 is given by the overlap of three intensity values of the color tones in each pixel (respectively red, green and blue); moving then to the grayscale each matrix element (pixel), can assume a value in the 2^8 levels of intensity; the level 0 represents black while level 255 represents white. The new methodology aiming at the measurement of the fouling was developed based on the grayscale images conversion. First step is to convert the matrix of, respectively, clean injector and fouled injector images in simple black and white pictures. The intensities of each pixel of the two images, having the same resolution have been subtracted.

Fig. 2. Clean injector (sx), dirty injector (middle) and difference (dx)

The resulting “matrix difference” (shown in fig. 2) presents the same size as the originals in which each pixel intensity value is given by the difference between corresponding pixels intensity values of the two pictures. The results is the deposits thickness shown as a pixels set (uniform area) having white color (255).After obtaining “matrix difference”, software executes a cut through the axis of symmetry of the tip, and continues with the calculation of the deposit volume through new submatrix processing.

This volume calculation is based on the following equation 1:

$$V_A = A * X_G * \phi \tag{1}$$

where: A = Area of the deposit section [mm^2]; X_G = Distance of the deposit section center of gravity respect to the revolution axis [mm]; ϕ = Rotation angle comprised between 0 and 2π [rad].

The deposits thickness center of gravity coordinates are calculated by its static moments and cross-sectional area ratio, and expressed, together with the area value, in conventional units. To this aim the surface of a single pixel is considered as the unit and, given the coordinates (i, j) of a pixel, the static moment respect to the vertical axis of the matrix:

$$Sy = \sum x_i * A_i \tag{2}$$

becomes:

$$Sy = \sum j_i \tag{3}$$

where i = 1,2…n and n is the number of white pixels. The area of the section of the deposit is defined as the sum of white pixels identified in the analyzed matrix. Then each value, expressed in pixel, has been converted in millimiters This method allows to quantitatively analyze the fouling on injector tip and, considering the presence of irregular profiles of the deposit on the entire surface, calculates total volume adding a series of volumes of revolution, which constitute parts of the entire deposit.

The number of the “subvolumes” depends on the number of pics (and injector rotation) considered and, referring to a generic groups of pictures, a Volumetric Index has been defined as the ratio between the volume of the deposit and the volume of the tip:

$$VI_n = \frac{\sum_1^j V_i}{V_{tip}} \tag{4}$$

with $j = 2n$. Referring to the case in which 3 pictures are taken rotating the injector with a step of 120°, the calculation of the volume of the deposit has been performed as shown in figure 3.

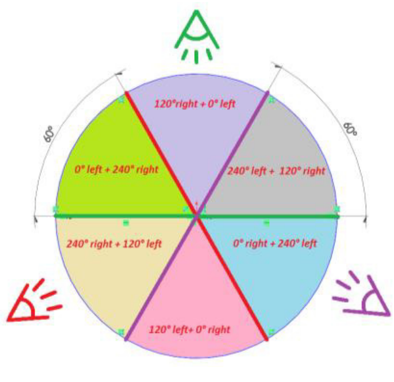

Figure 3. Partition of the injector tip, based on the acquisition of 3 images obtained rotating with a step of 120°C

The total volume of the deposit is obtained adding 6 subvolumes (Eq. 4), each subvolume is an average between the resulting values for two consecutive cross-sectional area (i.e. the "pink subvolume", shown in figure 3, obtained by right mid image with injector at 0° rotation and left mid image at 120°) calculated applying equation 1. The test of the methodology was performed to validate VI reliability and comparing it with that of the Fouling Index method, defined by D'Amico et al. 2015 [20].

3 Experimental campaign results

3.1 Test of the methodology

Both methods were validated through a test based on the artificial fouling of the injector, as reported in [20]. Evaluation of the weight of the clean injector and of four different deposits was performed; for the clean injector and after each artificial fouling 12 photos were captured turning the injector by 30°. The FI and VI were calculated for every injector orientation, using different groups of pictures (2, 3 or 4 photos) and correlated to the weight of the injector. This was carried out in order to determine the minimum number of photos required to assess the deposit with an acceptable dispersion of data for each method.

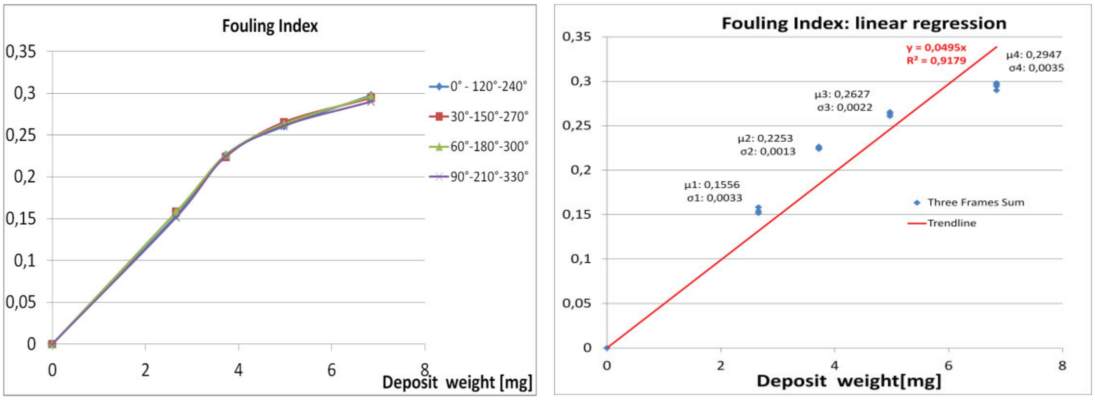

Fig. 4. Fouling index and linear regression for three injector rotations at 120°

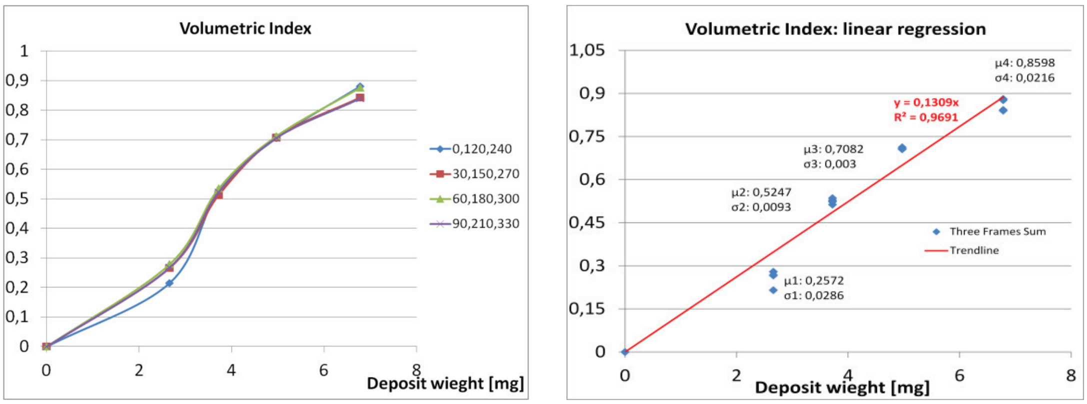

Fig. 5. Volumetric Index and linear regression for three injector rotations at 120°

The weights of fouling, as reported in [20] were defined as the arithmetic average of 20 weighings, one every five minutes, carried out a before and after the execution of the photos. The optimized results in terms of "fouling index" and "volumetric index", linear regression, medium value and standard deviation are shown in figure 4 and 5. For both methodologies the minimum number of images to obtain a reliable result is 3, rotating the injector of 120°. Concerning figure 4, where fouling index is presented, the minimum square regression line was built by imposing the intercept in the origin, since zero deposits correspond to a FI equal to zero. Figure 5 shows a growth of "Volumetric Index" with the increase in the deposits on the injector. The value of R^2 is definitely higher respect to the Fouling Index, this implies a higher correspondence between the volumetric index and the increase in weight due to fouling.

3.2 Comparison of the fouling caused by the combustion of vegetable oil and diesel in a ICE

On the basis of the results obtained by the validation test a comparison of the two methods was performed, analyzing the real fouling of the injectors of a Deutz BF4M2011C engine. The ICE is equipped with an injection system based on a low pressure pump that feeds the high pressure pumps of the injectors. It was fed at ¾ of the total load (26.5 kW) with fossil diesel and then with sunflower oil for a test duration of 2 hours. Table 1 shows the characteristics of the main fuels used [21].

Table 1. physical characteristics of sunflower oil and diesel fuel

	Sunflower Oil	Diesel
Dynamic Visc. at 50 °C (cPs)	22	2,7
Density (kg/m^3)	881	825
LHV (kJ/kg)	38553	43350

Table 2 shows the results of the calculation of FI and VI for each of the four injectors and underlines the limits of the fouling index. In this case the third injector deposit burning diesel (see figure 6a) is higher with respect to that obtained burning vegetable oil (see Figure 6b). This results do not agree with data reported in literature and with the results reported for the other 3 injectors. A similar discrepancy is not encountered for the Volumetric Index.

Table 2. Volumetric and fouling index for all injector with diesel and sunflower oil (SO)

Injector	FI Diesel	FI S.O.	VI Diesel	VI S.O.
1	0.0923	0.1152	0.1445	0.2634
2	0.1050	0.1331	0.1643	0.3790
3	0.1302	0.1019	0.1554	0.1824
4	0.0946	0.1068	0.2734	0.2885

In fact, even if the volume of the deposit is higher for sunflower oil, the fouling index for the injector tips running with fossil diesel present more black pixels. So the color of the picture depends from external parameters not linked with the deposit mass or volume.

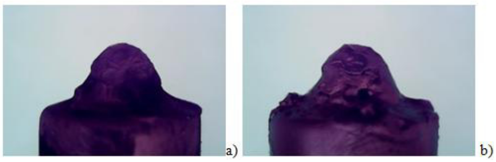

Fig. 6. Images at 0° of III fouled injector tip after running with fossil diesel (a) and sunflower oil (b)

4. Conclusions

The use of biofuels 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 new methodology based on image analysis using digital microscope and a subroutine for deposit volume calculation was considered. Pictures were processed in a matrix of pixels and a volumetric index was defined through the measure of the volume of the deposit. A test of the method was conducted to compare old (fouling index) and new (volumetric index) evaluation methodology: this second one showed more reliable results, because performs comparable standard deviation and error (< 5% of mean value), but R^2 of the Volumetric Index is higher (0.969) when compared to that of the Fouling Index (0.918). Comparing the two methods on the real case of the fouling, running a commercial CI engine with fossil diesel and vegetable oil, the results confirmed preliminary tests. The previously defined Fouling Index method has shown that for one of the four injectors the carbon deposit given by vegetable oil was lower, respect to that obtained with diesel, in disagreement with observed and literature data. The limit of the FI is due to possible variations in the color of the deposit or to errors due to light infiltration in the box where picture acquisition is performed. This can change the evaluation of the index, based on color scale. This criticality is overcome by the new methodology, which is based on a minimum of acquired images equal to 3.

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References

[1] M. Canakci, A. Necati Ozsezen, A. Turkcan, *Combustion analysis of preheated crude sunflower oil in an IDI diesel engine*, Biomass and Bioenergy, Volume 33, pp. 760-767, 2009, doi:10.1016/j.biombioe.2008.11.003.

[2] K. Srinivasa Rao, A. Ramakrishna, B.S.K Sundara Siva Rao, *Experimental studies on the characteristic of diesel engine with chicken fat methyl ester,* International Journal of Automotive Technology, ISSN: 2051-7831, Vol. 29, Issue 1, pp. 1114-1122, 2013.

[3] K. Kalogeras, S. Bezergianni, V. Kazantzi, Petros A. Pilavachi, *On the prediction of properties for diesel/biodiesel mixtures featuring new environmental considerations,* Computer Aided Chemical Engineering, Volume 28, pp. 973-978, 2010, doi:10.1016/S1570-7946(10)28163-4.

[4] N. Yilmaz, B. Morton, *Comparative characteristics of compression ignited engines operating on biodiesel produced from waste vegetable oil*, Biomass and Bioenergy, Volume 35, Issue 5, pp. 2194-2199, 2011, doi:10.1016/j.biombioe.2011.02.032.

[5] L. van de Beld, E. Holle, J. Florijn, *An experimental study on the use of pyrolysis oil and derivatives in diesel engine for CHP applications*, Applied Energy, Volume 102, pp. 190-197, 2013.

[6] A. Paethanom, P. Bartocci, B. D' Alessandro, M. D' Amico, F. Testarmata, N. Moriconi, K. Slopiecka, K. Yoshikawa, F. Fantozzi, *A low-cost pyrogas cleaning system for power generation: Scaling up from lab to pilot*, Applied Energy, Volume 111, pp. 1080-1088, 2013, doi:10.1016/j.apenergy.2013.06.044.

[7] N. Moriconi, P. Laranci, M. D'Amico, F. Testarmata, P. Bartocci, B. D'Alessandro, G. Cinti, A. Baldinelli, G. Discepoli, G. Bidini, U. Desideri, F. Cotana, F. Fantozzi, *Design and preliminary operation of gasification plant for micro-CHP with internal combustion engine and SOFC,* 69th Conference of the Italian Thermal Machines Engineering Association, ATI2014, Milano 10-12 settembre, 2014 (in press in Energy Procedia).

[8] P. Singer, J. Ruhe, *On the mechanism of deposit formation during thermal oxidation of mineral diesel and diesel/biodiesel blends under accelerated conditions,* Fuel, volume 133, 1 October 2014, pp. 245-252, doi:10.1016/j.fuel.2014.04.041.

[9] Li H., Lea-Langton A., Biller P, Andrews G. E. Hadavi S., Charlton A. and Richards P., *Effect of Multifunctional Fuel Additive Package on fuel injector deposit, combustion and emissions using pure rape seed oil for a DI diesel*, SAE International Journal of Fuels and Lubricants, March 2010, volume 2, pp. 54-65, 2009, doi: 10.4271/2009-01-2642.

[10] Hongming Xu, Chongming Wang , Xiao Ma , Asish K. Sarangi , Adam Weall , Jens Krueger-Venus, *Fuel injector deposits in direct-injection spark-ignition engines,* Progress in Energy and Combustion Science, vol. 50, 2015, pp. 63 – 80, doi:10.1016/j.pecs.2015.02.002.

[11] J. Galle, S. Verhelst, R. Sierens, L. Goyos, R. Castaneda, M. Verhaege, L. Vervaeke, M. Bastiaen, *Failure of fuel injectors in a medium speed diesel engine operating on bio-oil*, Biomass and Bioenergy, volume 40, 2012, pp. 27 – 35, doi:10.1016/j.biombioe.2012.01.041.

[12] A.M. Liaquat, H.H. Masjuki, M.A. Kalam, M.A. Fazal, Abdul Faheem Khan, H. Fayaz, M. Varman, *Impact of palm biodiesel blend on injector deposit formation,* Applied Energy, Volume 111, pp. 882-893, 2013, doi:10.1016/j.apenergy.2013.06.036.

[13] J. Barker and P. Richards, C. Snape and W. Meredith, *Diesel Injector Deposits – An Issue That Has Evolved with Engine Technology,* SAE Technical Paper, 2011, doi: 10.4271/2011-01-1923, Paper 2011-01-1923.

[14] Richards P., Walker R. D., Williams D., *Fouling of Two Stage Injectors – An Investigation into some causes and effect,* SAE Technical Paper, doi: 10.4271/971619, 2009, Paper 971619.

[15] R. Pos, R. Cracknell, L. Ganippa, *Transient characteristics of diesel sprays from a deposit rich injector*, Fuel volume 153 (2015) pp. 183–191, doi:10.1016/j.fuel.2015.02.114.

[16] Magno A., Mancaruso E., Vaglieco, B.M., Florio S., Gioco G., Rebesco E., *Study on spray injection and combustion of fouled and cleaned injectors by means of 2-D digital imaging in a transparent CR diesel engine,* SAE Technical Papers, volume 6, 2013, 11th International Conference on Engines and Vehicles, ICE 2013; Capri, Naples; Italy; 15 September 2013 through 19 September 2013; Code 10086, Paper: 2013-24-0062, DOI: 10.4271/2013-24-0062.

[17] L. Peterson , A. Korus and Jaiduk Jo, *A rapid engine test to measure injector fouling in diesel engines using vegetable oil fuels,* Journal of the American Oil Chemists' Society, Volume 62, Issue 11, pp. 1563-1564, 1985.

[18] L. Peterson, D.L. Reece, B.L. Hammond, J Thompson, S.M. Beck, *Processing, characterization and performance of eight fuels from lipids,* Applied Engineering in Agriculture, Volume 13, Issue 1, pp. 71-79, 1997.

[19] L. Peterson, T. Jones, *Used Vegetable Oil Fuel Blend Comparisons Using Injector Coking in a DI Diesel Engine,* Presented at 2001 ASAE Annual International Meeting, Sacramento, California, USA, Jult 30-August 1, ASAE Paper No. 01-6051, 2001.

[20] M. D'Amico, M. Zampilli, P. Laranci, B. D'Alessandro, G. Bidini, F. Fantozzi, Measuring injectors fouling in internal combustion engines through imaging, Energy Procedia, Volume 82, pp. 9 - 16, 2015, doi:10.1016/j.egypro.2015.11.873.

[21] B. D'Alessandro, G. Bidini, M. Zampilli, P. Laranci, P. Bartocci, F. Fantozzi, *Straight and waste vegetable oil in engines: Review and experimental measurement of emissions, fuel consumption and injector fouling on a turbocharged commercial engine,* Fuel , Volume 182, pp. 198 – 209, 2016, doi:10.1016/j.fuel.2016.05.075.

Biography

Eng. Mauro Zampilli received the degree in Mechanical Engineering, in 2010, and Ph.D. in Energy Engineering, in 2016, from University of Perugia (Italy). His research activities are focused on sustainable, renewable and distributed CHP generation systems, study of thermo-chemical processes and technologies for biomass to biofuels converting, combustion mechanisms of biofuels, numerical simulations for techno-economic assessment and optimization of energy systems.