PARTICLE SIZE DISTRIBUTION IN A TRANSPARENT CR DIESEL ENGINE FUELLED WITH RME AND GTL BY MEANS OF MULTIWAVELENGTH SPECTROSCOPY

S. Di Iorio, E. Mancaruso, B.M. Vaglieco
e.mancaruso@im.cnr.it
Istituto Motori-CNR, Via G. Marconi, 8, 80125 Napoli, Italia

Abstract
In this paper, broadband UV–NIR flame emission measurements were performed in an optical Common Rail (CR) diesel engine in order to evaluate the formation process of soot particles with high spatial and temporal resolution. The measurements were carried out in a direct injection (DI) CR transparent research diesel engine equipped of a Euro 5 multi cylinder head. Two alternative fuels, chosen as representative of the first generation biofuel, rapeseed methyl ester (RME), and of the second generation biofuel, gas to liquid (GTL), and a commercial diesel were used. A comparison between the soot (particle) size distribution measured into the cylinder by means of a numerical procedure applied to optical data and those at the exhaust by means of an electrical low pressure impactor (ELPI) was performed. The engine condition 1500 rpm x 2 of break mean effective pressure (BMEP) was analyzed because it is characteristic of the New European Driving Cycle (NEDC).

Introduction

The internal combustion engines (ICEs) always generates some undesirable products which are finally emitted at the exhaust. Several factors can contribute to the pollutant emissions: vehicle fuel systems give off unburnt fuel vapors, and open-vented engine crankcases give off escaped combustion products and vaporized lubricating oil. Nevertheless, the exhaust emissions are mainly influenced by the fuel combustion process. A perfect combustion of any kind of fuel would involve complete oxidation of the entire sample with maximum heat production and no pollutant emissions. This would require complete mixing of exactly reacting quantities of the pure fuel and O_2 with the addition of an appropriate amount of heat. For hydrocarbon fuels, the only products of combustion would be CO_2, water vapor and heat. Despite the improvement of the combustion and engine hardware a perfect combustion does not yet exist and particulate matter, NO_x and other pollutant are emitted. Concerns about the increasing crude oil price, the accelerated global warming and the particle emissions, have led to growing worldwide interests in renewable energy sources such as biofuels for their potential to reduce both CO_2 emissions and particulate

matter mass emissions. Biofuels are produced from renewable biological sources. They are generally divided into primary and secondary generation fuels. First generation biodiesel is produced from vegetable oils and animal fats through a transesterification process. The 2nd generation of alternative fuel was obtained from the well-known Fischer-Tropsch synthesis process. The combustion process and then the particle emissions are strongly influenced by the physical properties and chemical composition of the biofuel [1, 2]. In particular, a larger amount of particles smaller than 100 nm (ultrafine) are emitted [1, 2]. Their contribution on the mass is negligible, for this reason a particle number regulation has been introduced from Euro5b [3]. In order to reduce the particle emission it is necessary to understand the complex phenomena occurring in the cylinder engine in terms of their formation and oxidation.

In this paper, broadband flame emission measurements from UV to near IR were performed in an optical Common Rail (CR) diesel engine in order to evaluate the effect of biofuels on the formation process of soot particles. The measurements were carried out with high spatial and temporal resolution in the combustion chamber. Two alternative fuels: rapeseed methyl ester (RME) and gas to liquid (GTL), and a commercial diesel fuel were used. The in-cylinder measurements were compared with those at the exhaust by means of an electrical low pressure impactor (ELPI).

Engine, Engine Operating Conditions and Fuels

The optical single-cylinder research engine used for combustion diagnostics was equipped with the combustion system architecture and injection system of a four-cylinder standard Euro5 engine. The engine had bore of 85 mm, stroke of 92 mm and compression ratio of 16.5:1 and operated in continuous mode. It is also equipped with common rail injection system and a solenoid driven injector (7 hole nozzle, 440cm^3/30s). The exhaust gas recirculation (EGR) and variable swirl actuator (VSA) were managed by external devices. The amount of EGR and of VSA was set at 57% and 66%, respectively. More details and specifications are reported in the reference [4].

All the measurements were performed using a commercial European low sulfur diesel fuel (REF), a rapeseed methyl-ester (RME), representative of the most widespread FAME fuel, and GTL, representative of a FT fuels. The main properties of the fuels are reported in ref [4]. GTL had lower density and viscosity and higher cetane number (CN) and low heating value (LHV) than reference diesel. On the other hand RME had higher density and viscosity, and lower CN and LHV than REF. Moreover, RME had high percentage of oxygen in its formula (10.5%, m/m).

The engine operating condition investigated was representative of the engine behavior on new European driving cycle (NEDC) when installed on a D-class vehicle and was widely investigated in previous work [4]. It corresponds to 1500 rpm x 2 bar of brake mean effective pressure (BMEP). The injection parameters were set in the electronic control unit (ECU) that manages the Common Rail

injection system. The injection strategies consisted of two injections per cycle, pilot and main, with an injection pressure of 500bar at 1500 rpm. For all the fuels investigated the start of pilot and main injections were kept constant. The pilot energizing time also was fixed; while the main energizing times of RME were longer with respect to the others fuels.

Optical Experimental Apparatus and Theory

The engine layout with the experimental apparatus is widely discussed in reference [4, 5].The flame emissions were acquired through the piston crown window and 45° mirror, placed in the elongated piston. The broadband UV-near infrared (NIR) flame emissions were collected and focused on the entrance slit of a spectrograph through an UV objective (Nikon 78 mm f/3.8). Spectrograph had 15 cm focal length, f/4 luminous, and was equipped with a grating of 300 grooves/mm**,** with a dispersion of 3.1 nm/mm. An entrance slit width of 100 μm was used. The spectral image formed on the spectrograph exit plane was matched with a gated intensified CCD (ICCD) camera (512 x 512 pixels) with 24x24 μm^2 pixels. The ICCD had high sensitivity in the UV-Visible range. Data were detected with the spectrograph placed at a central working wavelength of 350 nm and with the intensifier-gate duration of 55 in order to have a good accuracy in the timing of the combustion onset. In particular, this time corresponds to 0.5 crank angle degrees at 1500 rpm. Moreover, in order to detect soot temperature and concentration by means of the two-color pyrometry method [6] digital imaging analysis was performed by a CCD camera too. The CCD camera with 640 x 480 pixels (pixel dimensions of 9.9 x 9.9 μm^2) and high sensitivity over a wide visible range was used in order to acquire the visible combustion. A BG-39 filter was placed in front of the CCD in order to shield it from the IR stimulation. This gave a detection window from approximately 400-700 nm.

Synchronization between the engine and the ICCD and CCD was controlled by the delay unit linked with the signal coming from the angle shaft encoder.

In order to have the absolute intensity of the flame emission spectra, these last were calibrated with Tungsten lamp with a known blackbody temperature, and the DeVos data were used [6, 7]. By the knowledge of the absolute flame emission intensity and the in-cylinder flame temperature, the soot emissivity was determined applying the Wien law:

$$I_\lambda(T) = \varepsilon_\lambda \frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right)-1\right]} \tag{1}$$

where λ is the wavelength, C_1 and C_2 are the first and second Planck constants, and ε_λ is the emissivity which is equal to the absorptivity α_λ according to the Kirchhoff's law. In more practical terms, the monochromatic emissivity of the diesel combustion flame can be assumed to vary as a power of the wavelength in accordance to the relationship developed by Hottel and Broughton [8]:

$$\varepsilon_\lambda = 1 - \exp\left(-\frac{KL}{\lambda^\alpha}\right) \tag{2}$$

where K is the absorption coefficient that is proportional to the soot concentration, L is the optical path length or flame thickness and α is the absorption index constant for a given wavelength range. The value of the parameter α depends on the physical and optical properties of the soot in the flame [9].

The extinction is considered as the attenuation of electromagnetic wave by the scattering and the absorption as it transverses a cloud of particles in a gas or a liquid or a flame. The extinction cross-section of the particle produced in a burning flame is a complex function of the chemical and physical properties. Assuming that the particles are spherical and constitute poly-dispersed system, the extinction coefficients are function of the particle diameter and the Mie theory can be applied. However, the Mie theory converges to the Rayleigh approximation in the case of small particle ($D_p \ll \lambda$) [10]. Moreover, this assumption permits to neglect the scattering contribution to the extinction and consider that the extinction coefficient is proportional to wavelength as $K_{ext} \propto \lambda^{-1}$ [6].

A numerical procedure was applied to experimental data to obtain the soot particles distribution. The inversion procedure was based on the minimization of the difference between experimental and theoretical spectrum widely applied in previous papers [11]. The procedure for the analysis of the spectrum of the natural flame has a lower accuracy as it depends on several parameters such as the refractive index, the in-cylinder conditions and so on. Moreover, the procedure assumes that the particles have a spherical morphology. It was seen that the approximation of the spherical particles for agglomerates yields errors around 17%.

Results and discussion

In a previous paper, the impact of alternative diesel fuels on the combustion performance and pollutants formation was analyzed. REF, GTL, and RME pure fuels was used in an optically accessible diesel engine equipped with the latest generation Euro 5 engine head running at 1500 rpm [4].

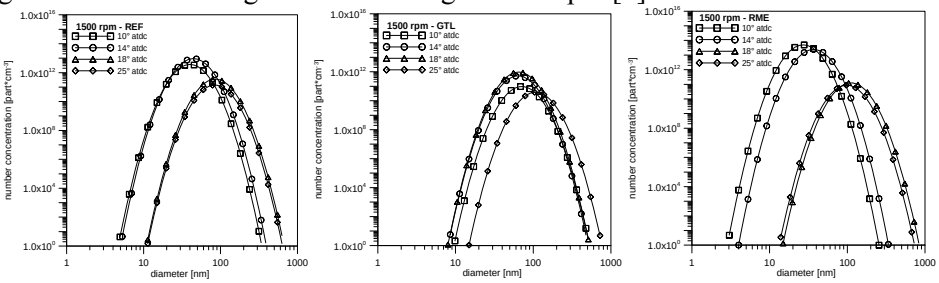

Figure 1. Particle size distribution estimated into the cylinder at several crank angles after top dead center for REF, GTL, RME fuels, respectively. Speed: 1500 rpm.

In Figure 1, the effect of biofuels on particle emissions in terms of size distribution and number, at 1500 rpm engine speed, is reported. The spectra of natural flame

emission intensity were acquired at several crank angles at the end of visible flames and for the three fuels, respectively, and then they were elaborated following the procedure described in the above paragraph. REF fuel shows an increase of the mean particle diameter and a decrease of the particle number advancing the crank angles. This is consistent with the oxidation process and the decrease of temperature that happen into the cylinder. Similar behavior was noted for the two biofuel. At fixed crank angle, GTL shows the smallest mean soot diameter and the lowest particle number concentration due to its better characteristic like density and viscosity, and distillation value. On the other hand, at early crank angles, RME had both diameter and number of particles very similar to the REF ones; but, advancing crank angles, they move to lower values. Also this result is in good agreement with the chemical and physical properties of the FAME fuel. It has larger oxygen content and the small particles produced during the combustion can be easily reduced during the oxidation phase.

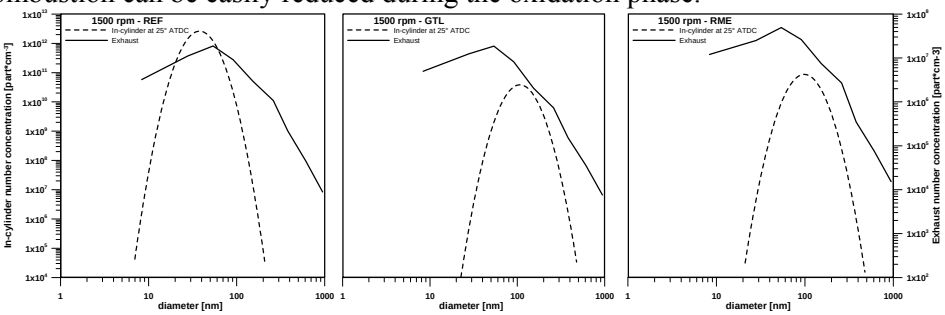

Figure 2. Particle size distribution estimated into the cylinder and at the exhaust of the engine for REF, GTL, RME fuels, respectively. Speed: 1500 rpm.

The comparison between the particle size distributions measured into the cylinder and at the exhaust for all the tested fuel was depicted in Figure 2. The number concentration of the particles smaller than 100 nm decreases of about 5 orders of magnitude from the cylinder to the exhaust pipe. Moreover, the particle size distribution is centered on larger diameter for REF and on smaller diameter for biofuels. The particle number reduction is due both to the particle oxidation during the last combustion phase and the growing processes occurring in the tailpipe such as agglomeration, condensation and nucleation. For REF fuel agglomeration prevails resulting in to a larger amount of accumulation particles. For GTL and RME the nucleation and condensation processes are favored because of the low accumulation mode. The accumulation mode reduction for biofuels is probably due to the effect of FAME-bound oxygen on the rates of pyrolytic and oxidation reactions in fuel rich zones within the combustion chamber, resulting in less soot.

Conclusion

In the present paper particles size distribution computed into the cylinder by means of a novel approach for the elaboration of the natural flame emission spectra was

determined and compared to the conventional measurements performed at the exhaust by ELPI. Into the cylinder, the GTL showed the lowest particle number concentration. Moreover, larger mean diameter than REF was measured. This is in good agreement with the low distillation values, density, viscosity and cetane number of the GTL fuel. On the other hand, the RME function distribution showed the strongest oxidation phase highlighted by the strongest particle number reduction. The oxygen content reduces the soot precursor formation. Moreover, the mean diameters were comparable to the GTL ones. The in-cylinder results were also in good agreement with those measured at the exhaust. The number concentration of the particles smaller than 100 nm decreases of about 5 orders of magnitude from the cylinder to the exhaust pipe. Moreover, larger particle diameters were measured at the exhaust pipe with respect to those detected within the cylinder due to the agglomeration phenomena.

Acknowledgements
The authors would like to thank Mr. Carlo Rossi and Mr. Bruno Sgammato for their precious help and technical support.

Nomenclature

ATDC	After Top Dead Center	*HC*	unburned Hydrocarbons
BMEP	Brake Mean Effective Pressure	*ICCD*	Intensified Coupled Charge Device
CCD	Coupled Charge Device	*IMEP*	Indicated Mean Effective Pressure
CN	Cetane Number	*NIR*	Near Infrared
CR	Common Rail Injection system	*NEDC*	New European Driving Cycle
ECU	Electronic Control Unit	*NOx*	Nitrogen Oxides
EGR	Exhaust Gas Recirculation	*PM*	Particulate Matter
FAME	Fatty-Acid-Methyl-Esters	*RME*	Rapeseed Methyl-Ester
GHG	Green House Gas	*UV*	Ultraviolet
GTL	Gas-to-Liquid	*VSA*	Variable Swirl throttle Actuator

References

[1] Burtscher, H., J. Aeros. Sci., 896:932(2005).
[2] Kittelson, D.B.; Watts, W.F.; Johnson, J.P., J. Aeros. Sci., 913:930, (2006).
[3] Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007, Official Journal of the European Union.
[4] Mancaruso, E., Vaglieco, B.M., Appl. Energy, 385:394, (2012).
[5] Mancaruso, E., Vaglieco, B.M., Fuel 511:520, (2011).
[6] Zhao, H. and Ladommatos, N., Engine Combustion Instrumentation and Diagnostics. SAE International, Warrendale, 2001.
[7] Vaglieco, B.M., Beretta, F., D'Alessio, A., Comb. Flame 259:271, (1990).
[8] Hottel, H. C. and Brougthon, F. P., Indus. and Eng. Chem. Anal. Ed., 166:175, (1932).
[9] Matsui, Y., Kamimoto, T. and Matsuoka, S., SAE paper 820464, (1982).
[10] Bohren, C. F. and Huffman, D. R., Absorption and Scattering of Light by Small Particles. Wiley-Interscience, New York. (1983).
[11] Di Iorio, S., Mancaruso, E., Vaglieco, B.M., Aeros. Sci. Technol., 272:286, (2012).

10.4405/35proci2012.II4