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OPTICAL CHARACTERIZATION OF BIODIESEL AND DIESEL FUEL SPRAYS FROM A CR INJECTION APPARATUS

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ABSTRACT - The fuels from renewable resources have obtained an increasing interest for transport application in the last decade because of their biodegradability, potential improvements on exhaust emissions and benefits on the virtuous CO_2 cycle of the earth**.**
The different physic-chemical characteristics of the biofuel, respect to diesel fuel, affect the combustion phenomenon in diesel engines being different the droplets distribution in the combustion chamber and, consequently, the air-fuel mixture preparation in the ignition delay ready to be burned. The recent trend to enhance the spray atomisation, increasing the injection pressure and the hole number in the nozzle to better distribute the fuel, imposes a deep understatement of the spray characteristics in terms of tip penetration, cone-angle, droplet velocity, fragmentation and vaporization.
The modern Common Rail (CR) injection apparatus enable a management of injection strategy both in terms of injection pressure and injection number and timing per cycle. They allow to exploit all the potentiality of modulated combustion in engine for NO_x and noise reduction, acting on pilot and pre-injections, and matter particulate using post and late injections.
In this paper a study of overall behaviour of spray from rapeseed methylester (RME) biofuel and diesel fuel has been carried out in an optically accessible vessel filled with inert gas (N_2) with pressure ranging between 0.1 to 5.0 MPa. The injections were obtained by a CR apparatus driven by a Programmable Electronic Control Unit (PECU) enabling different strategies performances. The injector mounted an axially disposed cylindrical single hole nozzle (0.18 mm in diameter and 1.0 mm in thickness) and the investigated injection pressures have been 60, 90 and 120 MPa. The sprays have been lightened by a pulsed sheet (100 μm in thickness and 10 ns in duration) generated by the second harmonic of a Nd-YAG laser and matched at different instant from the start of injection. The jet images have been captured by a CCD camera collecting the light scattered at right angle and synchronized with the light sheet. A digital pulser/delayer has allowed finely investigating the entire spray duration (1.0 ms). The spray characteristics have been extracted by a digital image processing software. Tip penetration and spray cone-angle have been strictly measured while droplet velocities and nozzle discharge coefficient have been derived from the data.
The diverse characteristics of the investigated fuels have produced quite differences in sprays global performances in terms of penetrations and cone-angles. These differences have shown a no-monotonic behaviour during the spray duration and their relationships with the injection pressure have been observed.

INTRODUCTION - The Kyoto conference focused the attention of the international community on CO_2 reduction. In this direction the oxygenate fuels may produce an interesting improvement in exhaust emission of the internal combustion engines. Biodiesel is an oxygenated diesel fuel made from vegetable oils and animal's fats by conversion of the triglyceride fats to esters via transesterification.

The adoption of biofuel allows to get a global CO_2 balance very next to zero so contributing to obtain the 5% reduction of the introduction in atmosphere of this greenhouse gas for the year 2012.

The European Community established an ambitious objective to achieve within 2020 the substitution at least the 20% of the fuels for automotive use with alternative fuels, aiming to contribute to the attainment of the respect in climatic changes appointment. States Members should assure the coverage at least 2% of the total fuel consumption with renewable fuels within 2005 and of 5.75% within 2010.

The effectiveness of this solution is in its ability to fuel commercially available engines without significant modifications or implementations.

The advantages of the biofuel are well known: partial renewable sources; absence of sulphur and, accordingly, reduction of SO_x emissions; smaller toxicity of the PM; greater biodegradability and therefore greater safety in the tanking and transport; possibility of employment in the diesel engines without modifications.

Moreover, the study of the last years made by the authors [1-5] and worldwide researchers [6-11] stressed that there was a substantial reduction of the regulated emissions, exception made for NO_x, when compared with the use of commercial diesel fuel with no real penalties in terms of fuel consumption or engine performance. For conventional diesel fuel, the tradeoff between PM and NO_x emissions is well known. Normally, a decrease in particulate emissions produces an increase in NO_x emissions and vice versa. For a given injection system, a balance between NO_x and particulate emissions can be achieved by controlling the combustion process.

The chemical-physical characteristics of biodiesel, whatever origin, are different from mineral fuel and their behavior in injection and combustion processes could affect the engine performances and emissions. The recent progress in injection boarding by electronically controlled Common Rail (CR) injection apparatus enables a detailed fuel management by controlling the spray development and the air-fuel mixture ready to be burned in the ignition delay.

The increasing biofuel use, both in Europe and in USA, pushes the scientific community to study more and more the possibility of such fuels employment.

The control of injection timing with the modern electronic injection systems (CR) and the knowledge of the mixture formation of such fuels would allow to optimize its combustion and, therefore, the performances and the emissions.

In the this paper a comparative study of rapeseed methylester (RME) and ISO 4113 calibration fluid sprays is presented. The jets development has been analyzed in their spatial and temporal evolution respect to the start of injection (SOI). Comparisons between the two fluids in terms of tip penetration, cone angles and dispersion are reported.

EXPERIMENTAL APPARATUS AND PROCEDURES - The sprays, which the investigations have been carried out on, have been generated by a Common Rail (CR) injection system via a Programmable Electronic Control Unit (PECU) at injection pressures of 60, 90 and 120 MPa. The electro-injector was a VCO axial single hole nozzle with diameter and length of 0.18 and 1.0 mm, respectively. The jets developed in an optically accessible vessel via three large optical windows, controlled in pressure and temperature. In fig. 1 the vessel of the experimental setup is reported.

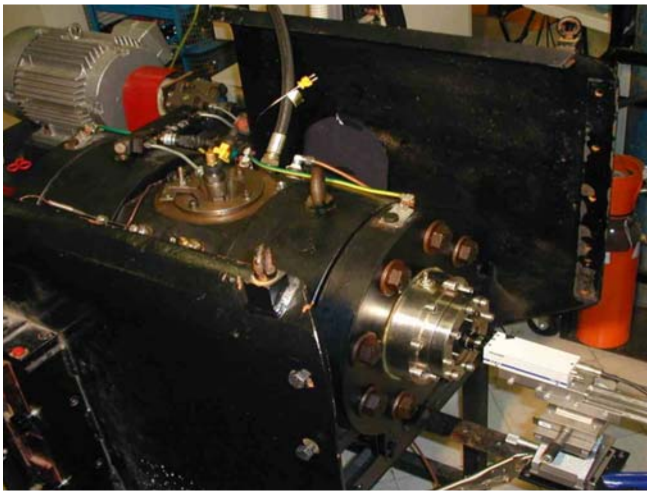


Fig. 1 – High pressure optically accessible vessel

The backpressures have ranged between 0.1 and 5.0 MPa. A single-shot electronic control and triggering system has been used to prevent fuel droplets fog in the vessel and windows dirty for free running work's conditions. It triggers the acquisition electronic chain at different instants from the SOI. The pressure bomb had a volume of $7*10^{-3}$ m^3 and was filled with inert gas (N_2).

Two different fuels have been used in this work: commercial biodiesel (rapeseed methylester oil - RME), which properties have been reported in the Tab. 1 in the next paragraph and the ISO 4113 calibration fluid as standard diesel fuel which some chemical-physical characteristics are reported in Tab. 2 (International Standard - 1998). A water/fuel heat exchanger has enabled to fix the fuel temperature at 20 °C with variations +/- 1°C.

Measurements of total amount of delivered fuel per stroke have been effected for both fuels at the programmed injection pressures and nominal time duration of 1.0 ms. Results are reported in fig. 2.

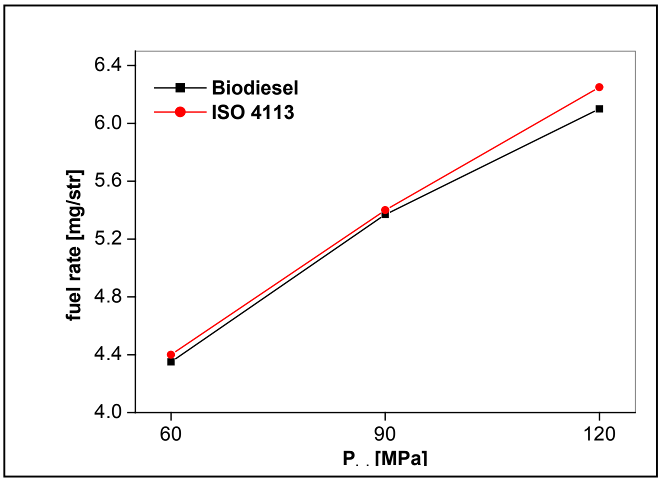


Fig. 2 – Fuel flow rate for the two fluid at the investigated injection pressures

The fuel rate increases versus injection pressures resulting the ISO 4113 curve higher then the biodiesel one. This behaviour is related to higher density (883 vs. 830 kg/m^3) and kinematic viscosity (4.5 vs. 2.45 – 2.75 cSt) of rapeseed oil respect to reference fuel (Tab. 1 – Tab. 2).

The sprays have been lightened, at different time from the SOI, by a pulsed laser sheet, 80 μm thickness and 12 ns duration, generated by a Nd-YAG laser operating on its second harmonic. A sketch of the experimental apparatus is reported in fig. 3. The injector/laser/CCD electronic command configuration has allowed carrying out planar images along the spray axis. A PULNIX TMC-6 CCD camera synchronized with the laser pulse has captured the images; then, they have been processed by professional software to extract the main parameters.

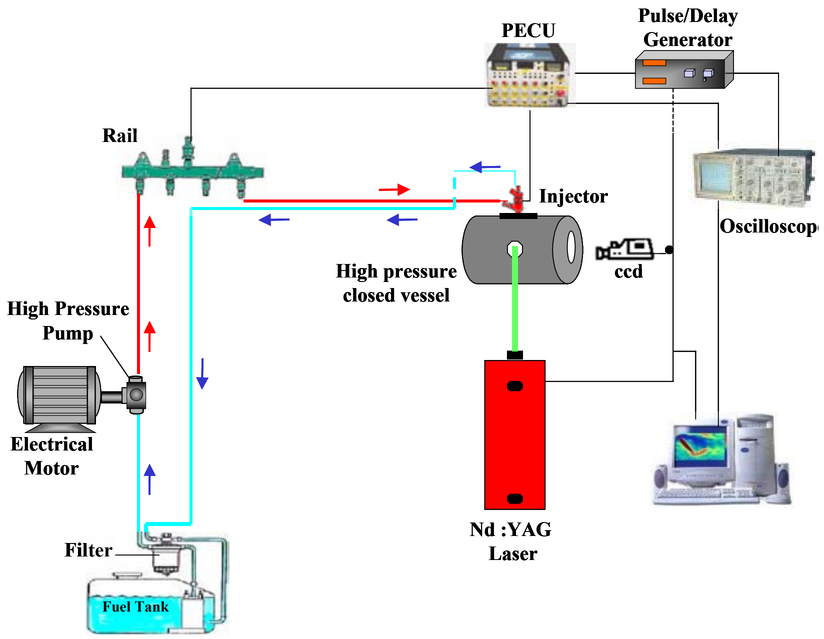


Fig. 3 – Experimental apparatus

Further details about experimental appar-atus and image processing procedures have been reported in [12,13]. Tip penetrations and cone-angles of the sprays have been measured at fixed time for fluid calibration and biodiesel at different instant from the SOI. A comparison be-tween their behaviour has been carried out.

FUEL CHARACTERISTIC PROPERTIES - A rapeseed methylester (commercial biodiesel - RME) in comparison with a reference fluid (ISO 4113) has been tested.

The properties of the fuels are reported in Tab. 1 and Tab. 2. In particular the Tab. 1 reports the chemical/physical characteristics of the adopted biodiesel versus the standard definition of a commercial biodiesel (UNI 10946) while in Tab. 2 some characteristics of commercial biodiesel, commercial diesel fuel and the ISO 4113 are compared.

Tab. 1

Properties	Commercial Biodiesel	UNI 10946 standards
Methyl ester content (wt%)	98.24	≥ 96.5
Density (kg/m^3)at15°C	883	860 ÷ 900
Viscosity (mm^2/s) at 40◦°C	4.5	3.5 ÷ 5.0
Flammable point (°C)	> 120	≥ 120
Sulfur (mg/kg)	< 10	≤ 10
Conradson carbonaceous residue (wt%)	0.15	≤ 0.3
Cetane number	53	≥ 51
Sulfated ash content (wt%)	0.01	≤ 0.02
Water (mg/kg)	312	≤ 500
Acidity (mg KOH/g)	0.49	≤ 0.5
Iodine number (g I_2/100 g)	115	< 120
Methyl ester of linolenic acid (wt%)	9.2	< 12.0
Methanol (mg/kg)	1100	≤ 2000
Bound glycerol		
Monoglycerides (wt%)	0.49	≤ 0.8
Diglycerides (wt%)	0.17	≤ 0.2
Triglycerides (wt%)	0.09	≤ 0.2
Free glycerol (mg/kg)	100	≤ 200

Tab. 2

	Commercial biodiesel	Commercial diesel fuel	ISO 4113
Cetane number	53	48	------
C/H/O (molar ratio)	19:34:2	16:30:0	-----
Density (kg/m^3 at 15 C)	883	840	830
Viscosity (mm^2/s at 40 °C)	4.7	3.3	2.45-2.75
Low heating value (kJ/kg)	36 000	43 000	-----
Stoichiometric air/fuel mass ratio	12.6	14.5	-----
Pressure vapor dyne/cm	23.75	----	33.02

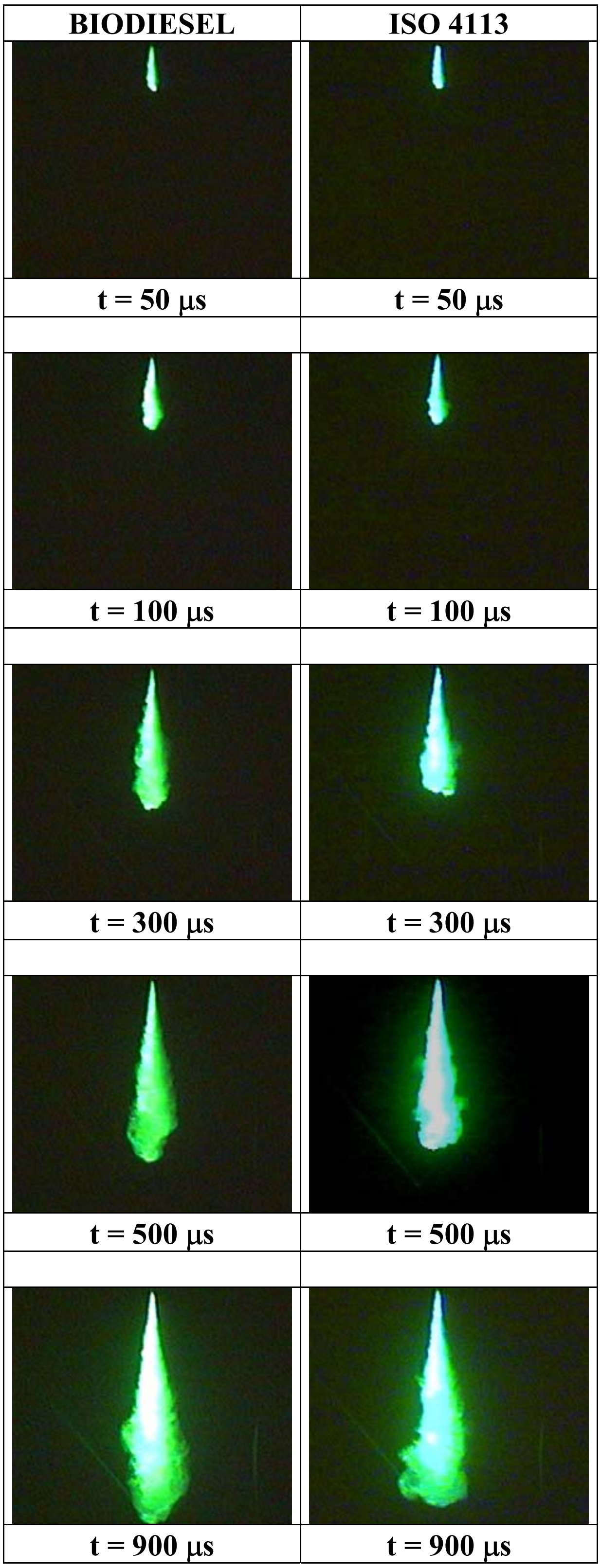


Fig. 4 - Spatial evolution of RME and ISO 4113 sprays at P_{inj}= 120 MPa; P_{ch}= 5.0 MPa

The biodiesel can be completely blended with the diesel fuel, does not contain aromatics or sulfur and contains about 11% by weight of oxygen. The biodiesel has a high cetane number due to the long linear chain of the fatty acid part of the ester.

RESULTS AND DISCUSSION - An effective combustion process is related to the air/fuel mixture preparation before the start of ignition. This mixture is connected to the disintegration process of fuel emerging from the nozzle and to the interaction with the air motion generated in the combustion chamber. The chemical-physical characteristics of the injected fuel and the fluidynamic conditions in the nozzle and at the exit are important parameters influencing the breakup of fuel bulk into ligaments and droplets of decreasing diameter. Literature is settled from this point of view [14, 15, 16].

The diversification of diesel fuel refinement and the introduction of renewable oils in internal combustion engine pose the necessity of understanding their behaviour in the short phase of the mixture preparation in terms of fragmentation, atomisation, vaporization and consequently on combustion. Differences, respect to the mineral fuel, translate immediately in changes of performances both in terms of power and exhaust emission [17, 18].

Target of this work is a comparative study of spray evolutions of mineral diesel fuel and of a well-characterized vegetable oil (rapeseed methylester - RME) and their interaction with the gas in the expansion chamber. The sprays are injected in different engine-like conditions regarding the injection pressure and backpressure but they are non-evaporative being the temperature of the gas kept constant at ambient value.

The jets of RME oil and ISO 4113 calibration fluid have been sprayed at three different injection pressures, namely 60, 90 and 120 MPa, with backpressure values of nitrogen in the vessel of 0.1, 1.2, 3.0 and 5.0 MPa. A single hole injector has been chosen for simplifying the experiment being the fuel injected in a confined volume in non-evaporative conditions. Differences in fluidynamic behaviour can be collected both for single hole and multi holes nozzles but the geometry in the first case is easier.

A pulsed laser sheet synchronizing with the CCD camera at different instant from the SOI has lighted the sprays. Different length and shapes images have been collected depending on the time and injection conditions. In fig. 4 comparative images of emerging fuel at 120 MPa injection pressure and 5.0 MPa backpressure are reported at fixed time from the SOI for biodiesel and ISO 4113. At early time the fuel emerges in a compact and continuous way from the nozzle travelling along the spray axis and spreading in a cone angle depending on the pressure of the gas in the vessel. The fuel is well confined in the spray envelope. At later time, instability waves appear on spray neighbour meaning a strong fluidynamic interaction with the gas. The front of the jet does not appear more dense and compact indicating a reduction of the density and a stronger atomisation. The overall characteristics are quite similar in the calibration fluid and biodiesel behaviour but slight

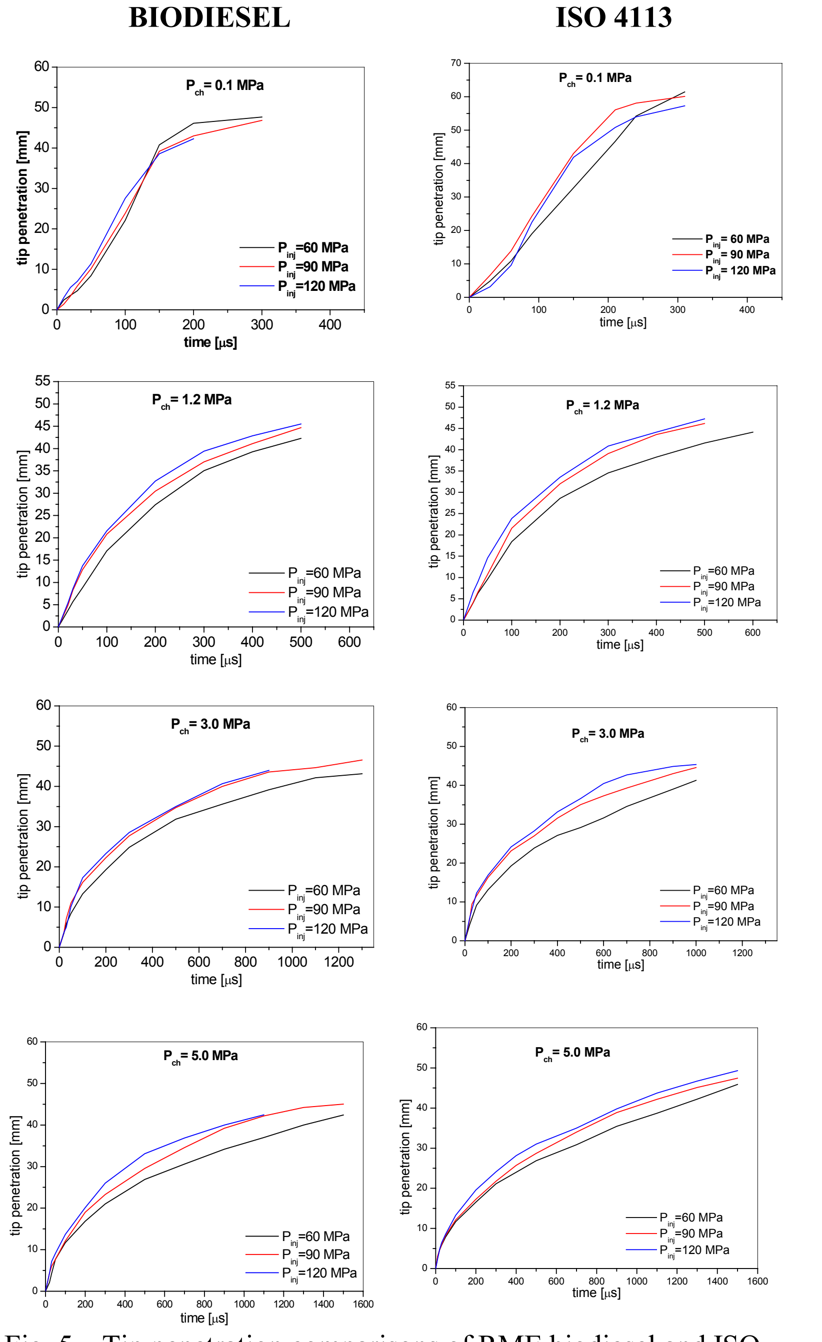


Fig. 5 – Tip penetration comparisons of RME biodiesel and ISO 4113 at all operative conditions

differences appear in the penetrations and cone angle.

The tip penetration of the spray at a given instant is worldwide defined as the distance between the front of the jet at that time respect to the nozzle exit along the spray axis while the cone angle is the angle between the tangents at the envelopes of the spray in its early part. These tangents must be drawn to compensate the instability waves present on the surface.

In fig 5 the tip penetration curves both for rapeseed methylester biodiesel and ISO 4113 fluid are reported versus injection time for the three injection pressures and at different backpressures.

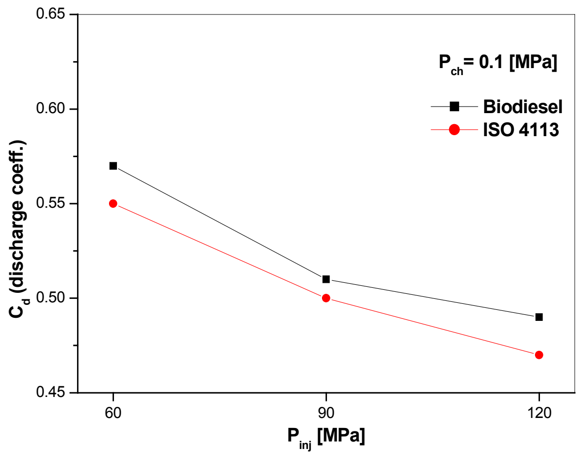
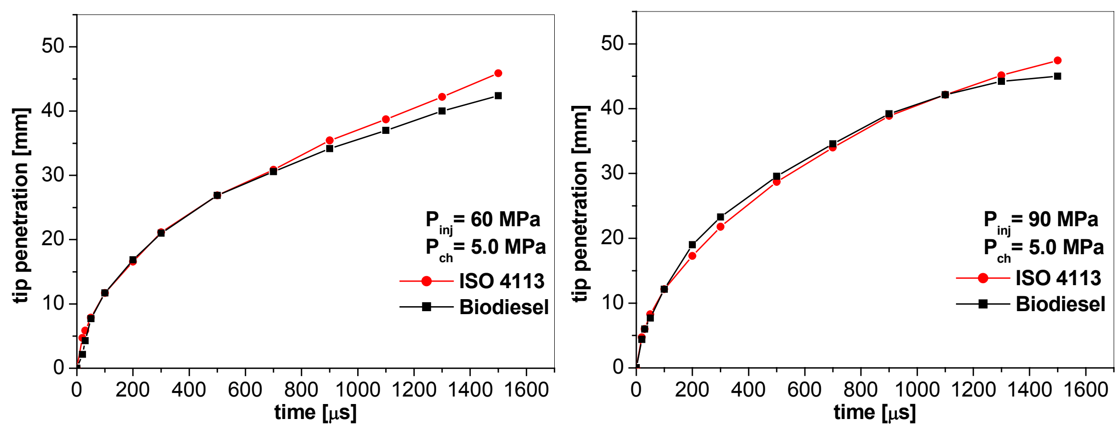


Fig 6 – Discharge coefficient C_d vs P_{inj}

Different behaviours of the penetration curves are distinguished versus time from SOI. At early time the penetration is straight and high sloped indicating a weak interaction of the droplets with the surrounding gas; the fuel penetrates unperturbed in the vessel and the pressure of the N2 does not affect the speed. At later time a bend with a slope variation in the curves appears so the penetrations tend toward lower values. The gas influences the breakup of the fuel ligaments and droplets producing a loss of momentum. Finally, at later time, the curves tend to asymptotic values, justifying the loss of kinetic energy.



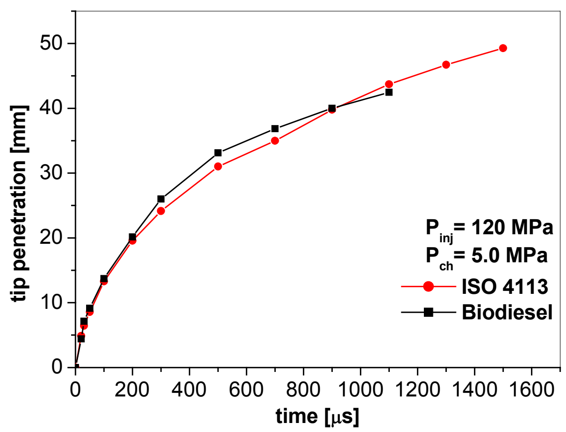


Fig. 7 – Tip penetration comparison between RME and ISO 4113 at 5.0 MPa backpressure and 60 (top-left), 90 (top-right) and 120 MPa (bottom-left) injection pressure

In the linear conditions of penetration, at early time, it is possible to calculate the velocities of emerging droplets as the ratio between their displacements and the time occurred to cover them. These real velocities and the Bernoulli relationship enable us to calculate the discharge coefficient C_d through the nozzle.

In Fig.6 the trend of C_d is reported at atmospheric backpressure. It ranges between 0.574 to 0.489 for RME and 0.551 to 0.473 for ISO 4113.

In Fig 7 a comparison between the tip penetrations of the two fuels are reported for the injection pressures of 60, 90 and 120 MPa and at 5.0 MPa backpressure in the chamber. Slight but indicative behaviour differences of the fuels can be noted. At lower injection pressure (top-left) the penetration curves overlap up to 700 μs from the SOI while, at later time, ISO penetrates rapidly. At the intermediate and highest injection pressures of 90 and 120 MPa (top-right and bottom) the RME biofuel starts to penetrate more quickly than ISO fluid up to about 900 μs, then it is overcome. The discrepancies in the range 0-900 μs are directly proportional to the pressure drop across the nozzle. It should seem that in this interval, at increasing injection pressures, the ISO 4113 fluid atomizes more rapidly than biodiesel so producing both in momentum drop and, consequently, in penetration. Later, the biodiesel atomization rate increases producing a reduction in the momentum and in the droplets speed.

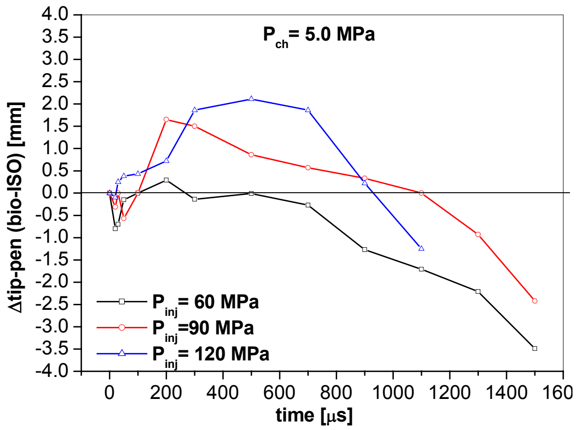


Fig. 8 - Δ tip penetration RME-ISO 4113

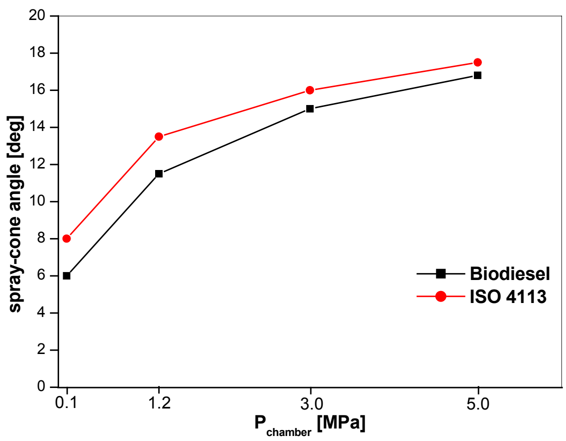


Fig. 9 – Cone angle behaviour versus vessel pressures for RME and ISO 4113

These results are summarized in Fig. 8.

The two investigated fluids have shown different behaviours regarding the spray-cone angles. Apart from the initial instabilities at early time of the emerging jets, the cone angle values, founded for the single fluid, are a function only of the backpressure and not of the injection pressure. Fig. 9 reports the spray-cone angle trend for the two fuels at different pressures in the injection chamber. The effect of the increased pressures of the gas causes a spatial redistribution of the fuel in terms of shape and density. The penetrations decrease and the cone angles increase resulting in shortness of the jets and in their enlargement. The ISO 4113 shows larger cone angles than rapeseed methylester biodiesel at all investigated backpressures. The calibration fluid cone angle varies between 8° (atmospheric gas pressure) and 17.5° (5.0 MPa) against 6° and 16.6° of RME oil, differences ranging between 30 and 6 %.

The experimental investigation, carried out in this work on the rapeseed methylester biodiesel and ISO 4113 calibration fluid, has shown a quite similar general behaviour of the two fuels concerning the distribution of the droplets in the jet envelopes. The penetrations and the cone angles show a dependence both on the injection pressures and backpressures. Nevertheless, some peculiarities have characterized the fluids. In fact, different mechanisms of fragmentation have appeared during the injection process. The atomization of the droplet follows different paths inside the spray development as a function of the time from the SOI. It is necessary to take into account as much as possible intrinsic characteristics of the two fuels because the breakup of the droplets is closely related to them and they are a function of the time. Some other global differences appear between RME and ISO such as the fuel rate, the discharge coefficient trough the nozzle and the cone angle also if the trend is monotonic and well defined. In the opinion of the authors more future work need to be carried out, both in numerical and experimental field, to correlate the spray behaviour to their intrinsic characteristics.

CONCLUSION - Renewable and biodegradable fuels, deriving from vegetable oils and animal fats, could play an important role in emission reduction of diesel engines and benefits on the virtuous CO_2 cycle of the earth. In particular benefits have been noted in decreasing of HC and CO, absence of SO_x and a reduction of smoke also if a rise of NO_x and aldehydes emissions have been noted.

The effectiveness of the combustion phenomenon in the engines has to take into account the different intrinsic proprieties of such fuels for preparing the mixture ready to be burned. The use of Common Rail injection apparatus, with their peculiarity of electronic control, enable a punctual management of fuels intake phase in the engines considering their different characteristics.

A comparative study of spatial and temporal behaviour of ISO 4113 calibration fluid, which physic-chemical properties are similar to mineral diesel fuel, and rapeseed methylester (RME) sprays have been carried out in this paper in engine-like conditions.

The penetration and dispersion of droplets injected at 60, 90 and 120 MPa injection pressure in an optically accessible high pressure vessel have been acquired at backpressure of inert gas (N_2) up to 5.0 MPa. The nozzle has been a single hole axially disposed with diameter and length 0.18 and 1.0 mm, respectively. The data have been extracted processing spray images collected by a CCD camera being the jets lighted by a pulsed laser sheet synchronized at different time from the SOI of the sprays.

The following results can be summarized:

- the difference properties between the two fluids slightly influence the intake flow rate resulting ISO higher;
- the penetration’s curves have the typical double slope indicating a weak interaction of the fuel with the gas at early time (high slope) while at later time from the SOI the droplets reduce the velocities with a lower penetration (low slope);
- the penetrations of the two fluids show different behaviours for the investigated injection pressures during the spray evolution (time dependence);
- the injection pressure does not influence the distribution of the fuel in the jet cone but it is strongly affected by backpressure in the vessel. The ISO 4113 cone angle results higher than RME at all the investigated range.

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