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Pollutant emissions in common-rail Diesel engines in extraurban cycle: rapeseed oils vs Diesel fuel

Alessandro Corsini[a], Giacomo Fanfarillo[a], Franco Rispoli[a], Paolo Venturini[a]*

[a]*Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza Università di Roma, via Eudossiana 18, 00184 Roma, Italy*

Abstract

The new energy strategy of EU (i.e., Directive 2009/28/EC) requires increasing the use of biofuels in transports up to at least 10% of the total fuel consumption. In the last years, the share of Diesel engines in automotive applications reached about 55% in EU market, thus trying to widen the alternatives to Diesel fuel is very important. In this framework straight vegetable oils (SVO) can represent one of the available possibilities at least in some specific applications (i.e., public transportation, hybrid or marine propulsion, etc.). SVO properties may be very different form Diesel fuel, thus operating a Diesel engine with SVO might result in some problems, especially in automotive configuration where the electronic unit acts as if it is working with Diesel fuel. This reflects in possible engine power and torque reduction, maintenance problems, and pollutant emissions during vehicles running. The latter aspect is the focus of the present paper. In this work, we used a turbocharged, four stroke, four cylinders, water cooled, common-rail multijet Diesel engine in automotive configuration to simulate the extraurban cycle according to the EU standard, comparing pollutant emissions in case of SVO and gasoil fuelling.

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Keywords: rapeseed oil, pollutant emissions, Diesel engine, biofuels, common-rail

1. Introduction

The new energy strategy of EU aims at increasing the use of bio- or renewable fuels in substitution of fossil fuels. Within the Directive 2009/28/EC [1], recently approved be EU, among other and most known objectives for 2020, there is a particular goal concerning fuels in transport: by 2020at least 10% of the fuels used in this sector must be renewable. This seems a challenging objective considering that it involves all kinds of transports, thus requiring a big effort to develop a new generation of fuels and to enhance the use of those already available. Transport is a strategic sector from an energy point of view since it represents about 32% of the EU final energy consumption (Fig.1, [2]). The situation of transports

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* Corresponding author. Tel.: +39-0644585901
*E-mail address:*paolo.venturini@uniroma1.it.

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in EU (28 countries) is well summarized in [2]. In 2012, goods within the EU were transported with the following modal split: 44.9% road, 10.8% rail, 4.0% inland water-ways, 3.0% pipelines, 37.1% sea, 0.1% air. On the other hand, passengers, in the same year, used 82.4% road transports, 8.0% rail, 9.0% air (excluding extra-EU connections), and 0.6% sea (excluding extra-EU connections).It is evident that road transports are the most used in EU.

Even from the greenhouse gas (GHG) emissions point of view, transport represents an important sector, since it is responsible of about 20% of the GHG in EU in 2012 (Fig. 2, [2]). Road transport is again the most important, emitting about 72% of the total emissions of the sector (Fig. 3,[2]).

In the last years, Diesel engine (DE) vehicles became predominant also in the passenger cars, representing in 2013 more than 55% of the sold vehicles (Fig. 4, [3]).

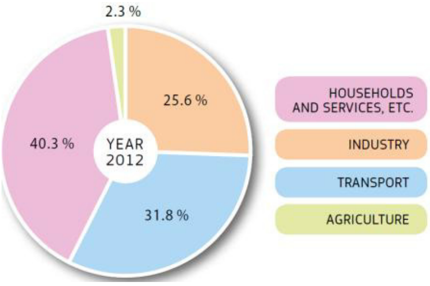

Fig. 1. Final energy consumption share by sector in 2012 [2].

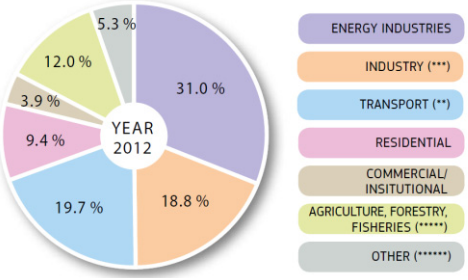

Fig. 2. GHG emissions share by sector in 2012 [2].

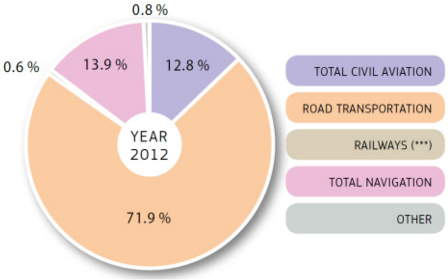

Fig. 3. GHG emissions share from Transport by modal share, in 2012 [2].

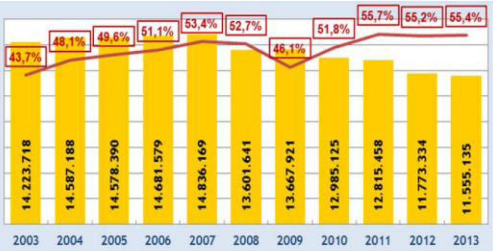

Fig. 4. 2003-2013 EU vehicles market: number of vehicles sold per year (bars), Diesel share (line) [3].

In this framework of reference, it is then clear the importance of reducing GHG emissions in road transports in general, and in DE vehicles in particular.

From the GHG emission point of view, the most suitable alternative to Diesel fuel (DF) nowadays is bio-diesel (BD), which is a bio-fuel mostly derived from vegetable oils. This bio-fuel has been widely studied and tested in the past years (i.e.,[4]-[8]) and its properties are very similar to those of DF, therefore it can be used both in blends with DF or alone. Besides BD, also straight vegetable oils (SVO) can be used as an alternative. The main issues related to the use of BD is its production cost[9]-[11], therefore to be economically attractive production of BD requires large volumes of oils, wand this limits the development of such production plants. The possibility of using SVO as a fuel would widen the alternatives to DF and making easier its production. This would result in a reduction of GHG emission both from production plants and from Diesel vehicles, and in a decrease of the dependence from fossil fuels. On the other hand, the availability of land that could be dedicated to oilseed crops is limited, thus SVO cannot be seen currently as a global alternative to DF. A rational use of SVO, however, can represent a solution in some niche applications, i.e., public transport, hybrid and marine propulsion, electricity generation units, etc. The situation may change with the use of oil from algae which are very promising ([12]-[14]).

Despite the large interest on this topic, the use of SVO in modern DEs in automotive configuration is not well studied so far, but a growing number of studies appear in scientific literature. Very interesting review papers, reporting all the technical problems deriving from fuelling DEs with SVO are those of Misra and Murthy [15] and Sidibè *et al.*[16]. In the very last years the growing interest about SVO gives rise to a number of studies dealing with both performance and pollutant emissions of DE fuelled with several SVO in a number of applications(see for instance [17]-[22]). In previous works some of the authors of this paper studied the performance and pollutant emissions due to rapeseed oil, waste cooking oil, and biodiesel, in a common-rail DE ([23]-[25]). In the present work we study pollutant emissions of the same engine fuelled with rapeseed oil in comparison with DF during a simulated extraurban cycle.

2. Materials and methods

2.1. Fuel properties

The present study is performed fuelling a DE (described in section 2.1)with rapeseed oil (RO) and DF. The main characteristics of the two fuels are reported in Table 1. RO has a net heating value smaller than that of DF, but conversely, its density is larger. The fuel physical property that most affects the engine behavior is the viscosity, because the larger the viscosity the more failures may happen to the feeding system. Moreover, fuel viscosity is responsible of deposit formation within the combustion chamber, the feeding channels, the filters, etc. Since viscosity is strongly affected by temperature, as reported in several studies ([15]-[22]), fuel pre-heating is a commonly used solution to reduce it. In [23] some of the authors found that in order to have a viscosity comparable to that of DF, RO should be heated up to about 90 °C, thus this is the temperature we adopted in our tests.

2.2. Experimental set up

Tests were performed using a FIAT 1.9 JTD, a 4 strokes, common-rail, multijet, turbocharged DE, the main characteristics of which are reported in ifferent fuels above described.

Table 2[26]. The engine, usually installed on vans for transport of goods and passengers, is in an automotive configuration equipped with a real electronic control unit. It is installed to the bench test at the laboratory of the Engineering Faculty of Sapienza Università di Roma. Some modifications have been maiden in order to adapt the engine to the test bench. The gear box and the flywheel were removed, and a bi-fuel feeding system was realized on purpose. This system is composed of two fuel tanks (for DE and RO or BD), and a small tank housing the original fuel pump and a thermocouple to measure the actual temperature of pumped fuel. The small tank is connected to a switching valve to fuel the engine alternatively with DF or RO. Each of the two fuel tanks are equipped with a fuel filter, which in the case of DF is a paper micro-fiber filter commonly used in cars, whilst in order to avoid problems due to the high viscosity of the vegetable oils, the second tank is equipped with a plastic filter commonly used in trucks and tractors. Temperature within the vegetable oil tank is controlled by an electronic unit Gefran 1000, which in turn activates/deactivates four RTDs immersed in the fuel. The bench test is equipped with a Schenck hydraulic brake, and a Bosch unit (BEA 350) is used to measure pollutant emissions; two thermocouples measure the fuel and engine lubricant oil temperature. A sketch of the whole measurement system is shown in Fig. 5.

2.3. Simulation of the extra urban cycle

Council Directive 91/441/EEC[27] defines the extra urban cycle that has to be performed with a vehicle in order to measure its pollutant emissions and other quantities that are used for comparison with other vehicles. The Directive establishes velocities, time to reach them, and gears that has to be used during tests. The whole extra urban cycle duration is about 400 s (Fig. 6). In the present study the cycle for light-duty vehicles (having a mass smaller that 2160 kg) is selected. Following the Directive, before the extra urban cycle a urban cycle has to be performed, but for the sake of simplicity we only simulated the extra urban one.

Since the engine installed in the laboratory of the Engineering Faculty is without gear box, some calculations were performed before simulating the cycle. In a first step, knowing the gear ratios for the given engine, the rotations per minute of the engine crankshaft at the different velocity-gear couples used during the test were computed. In the second step we calculated the driving resistance of the actual vehicle at the velocities requested by the extra urban cycle. Driving resistance R_{tot} is computed as a sum of rolling resistance R_{roll} and drag resistance R_{drag} .

The rolling resistance writes

$$R_{roll} = f \cdot m \cdot g \tag{1}$$

where f is the friction coefficient, m is the mass of the vehicle, and g is the gravity acceleration. f depends on the kind of paving f_0 and the velocity of the vehicle v ($f = f_0 + f_2 v^2$). Assuming asphalt as paving, f_0 can be set equal to 0.013; f_2 can be found in literature and here we adopted a value of 6.48E-6. $m = 1430$ kg is the mass of the vehicle (FIAT Doblò) equipped with the tested engine.

Drag force is expressed as

$$R_{drag} = (1/2)\rho_{air} S \cdot C_x \cdot v^2 \tag{2}$$

where $\rho_{air} = 1.202$ kg/m^3, $S = 2.24$ m^2 is the area of the surface exposed to flow, $C_x = 0.3$ is the drag coefficient of a FIAT Doblò.

By multiplying the driving resistance $R_{tot} = R_{roll} + R_{drag}$ with the velocity of the vehicle the power P_{tot} needed to keep the vehicle in motion is easily computed. P_{tot} should be the braking power applied to the engine in order to reproduce the actual test condition. Knowing P_{tot} , and considering that in the hydraulic break power and force are linked trough $P = F_{break} rpm/1000$, the braking force that should be applied through the hydraulic brake is easily computed.

At the end of this process, the extra urban cycle is converted into couples of values brake force-rpm that are used to simulate the real cycle.

Table 1. Main characteristics of the fuels used in the tests[26].

Fuel	Net heating value (MJ/kg)	Density at 20°C (kg/m^3)	Viscosity at 20°C (mm^2/s)
DF	43.3	868.88	4.15
RO	37.6	914.50	74.19

2.4. Measurements of pollutant emissions

In the present study we wanted to compare pollutant emissions, namely CO, HC, CO_2 and NO derived from the same engine but fuelled with the two different fuels above described.

Table 2. Main characteristics of the engine used for the tests.

Type	Charge	Fuel	Displacement	Power	Maximum torque
1.9 MultiJet	Turbocharge (with intercooler)	Diesel fuel	1910 cc	89.5 kW (120 hp)	200 Nm

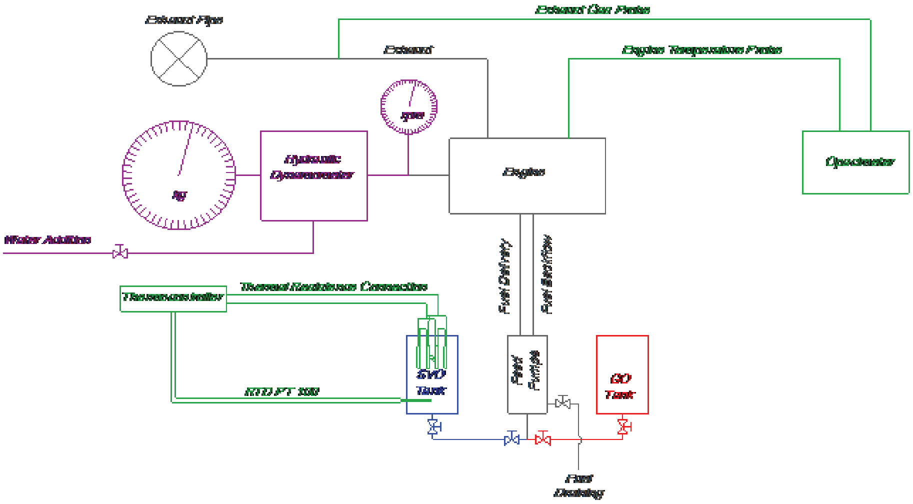

Fig. 5. Sketch of the measurement system.

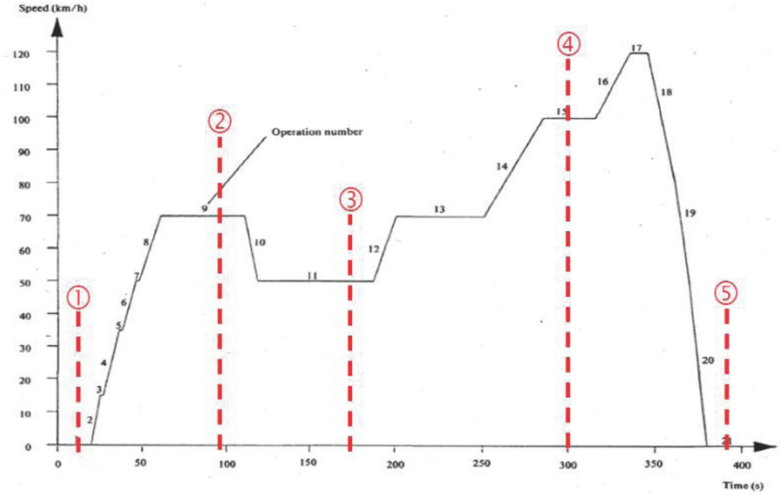

Fig. 6. Extra urban cycle for light-duty vehicle as reported in CD 91/441/EEC[27]; monitoring time instants: red dashed lines and numbers in circles.

Since the Bosch unit does not allows to store continuous data, we decided to measure pollutions at five time instants during the extra urban cycle, related to different operative conditions. The first monitoring instant is 10 s after the cycle start, point 2 at 95 s, point 3 at 170 s, point 4 at 300 s, and point 5 at 390 s. The monitoring time instants (MI) are shown in Fig. 6 by dashed lines and numbers 1-5 in circles.

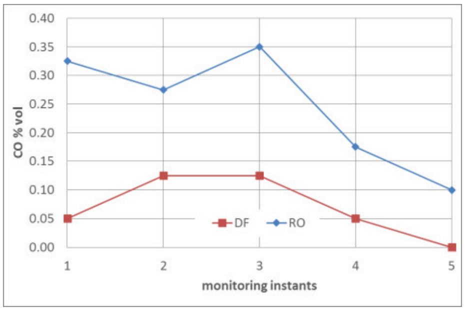

Fig. 7. CO emissions expressed in % volume.

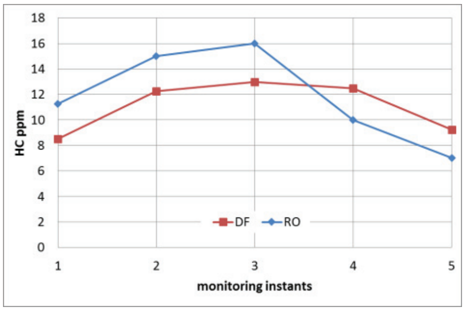

Fig. 8. HC emissions expressed in ppm.

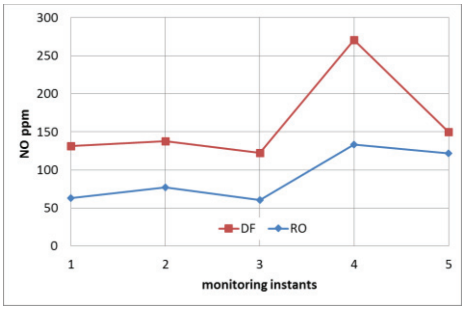

Fig. 9. NO emissions expressed in ppm.

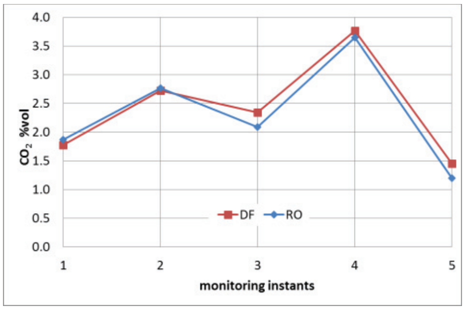

Fig. 10. CO_2 emissions expressed in % volume.

3. Results

The extra urban cycle was repeated four times for each fuel, then the values measured have been averaged.Therefore, Fig. 7 to Fig. 10show average pollutant emissions.

As shown in Fig. 7, CO emissions trends are not similar for the two fuels. DF curve starts from a small value (0.1 % vol at MI 1), increases up to its maximum (about 0.15) at MI 2 and 3, and then decreases to 0.1 at MI 4, and 0.0 at the last MI. On the contrary, the RO curve is a bit more rugged: it starts form about 0.33 at MI1, decreases to about 0.8 at MI 2, then icreases agin to its maximum value (0.35 at MI 3), and then decreases to about 0.17 at MI 4 and 0.1 at MI 5. In any case, the CO emission is larger for RO. This can be ascribed to several reasons, among wich two could play the main role: RO viscosity and chemical characteristics. Even at 90 °C RO viscosity is about twice that of DF at the same temperature, and this of course affects the injection process, since the more the viscosity the more difficult is nebulizing the fuel. A worst nebulization, in turns, results in a worst combustion, thus a larger CO emisisons. The other aspect that has to be accounted for, is that RO is composed of long chains of C-compounds that take given time to be broken. Since combustion in a common-rail DE is a fast process, probably the RO does not have enough time to break those C-chains.This is also confirmed by the HC emissions (Fig. 8). Unburnt hydrocarbons are due to a bad or uncomplete combustion, as well as the CO. HC emissions during RO fuelling are larger that those of DF up to MI 3, then they become smaller. This reversal trend can be due to the operative conditions of the engine, i.e., engine teperature, RO temperature, etc., and at the moment it is under investigation.

NO emissions are shown in Fig. 9. The trends for RO and DF are similar but RO produces smaller (about the half) NO emissions. This is consistent with data available in literature (i.e., [16]), and with what previously found by the authors ([23], [25]),and it is related to the heating value of the two fuels.

RO has a smaller net heating value (see Table 1) which results in a smaller peak temperature during combustion. This, in turns, leads to a smaller activity of the thermal-NO_x formation mechanism, which is the main responsible of NO_x emissions in internal combustion engine.

Emissions of CO_2 are reported in Fig. 10. This pollutant is important because it is the main responsible of the greehouse effect, which is the reason why emissions limits are more and more restrictive. It is worth noting that bio-fuels do not give a relevant contribution to CO_2 concentration in the atmosphere, since they cannot emit more CO_2 than that absorbed during the life cycle of the plants from which they derive. Therefore, from the greenhouse effect point of view, RO contribution is null. However, a part from the first MI, RO emits smaller value of CO_2 with respect to DF.

4. Conclusions

In the present work, we simulated the extra urban cycle defined in the Council Directive 91/441/EEC[27], and tested a four strokes, common-rail, multijet DE in automotive configurations, aiming at measuring pollutant emissions when the engine is fuelled with RO and DF.

Form the experimental campaigns it came out that emissions related to the efficiency of fuel combustion (namely CO and HC) are larger when fuelling with RO rather than DF. This is due mainly to the physical and chemical properties of the fuels. Viscosity and chemical compounds of the fuel affect the nebulization efficiency and time needed to complete the combustion. Therefore, RO is penalized from this point of view. On the other hand, pollutants such as NO and CO_2 encourage the use of RO rather than DF. CO_2 emissions for biofuels are assumed to be null, meaning that they do not contribute to the increase of CO_2concentration in atmosphere. Anyway, carbon dioxide emissions from RO are comparable with those from DF, being a bit smaller. Nitrogen oxides are affected by peak temperature within the cylinder, thus RO having a smaller heating value produces less NO_x.

Further developments should involve the electronic control unit to better understand the engine behavior and to try to set up a different mapping optimized for SVO, in order to minimize all the pollutant emissions without decreasing engine performance in a relevant way.

References

[1]. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Available at: eur-lex.europa.eu.

[2]. EU Transport in figures – Statistical poketbook 2014. European Commission, ISBN 978-92-79-37506-4doi:10.2832/63317.

[3]. L'industria automotive mondiale nel 2013, Associazione Nazionale Filiera Industria Automobilistica – Area Studi e Statistiche, 2014 (in Italian).

[4]. Canacki M., Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. Bioresource Technology 2007;98(6):1167-1175.

[5]. Wang G.W., Lyons D.W., Clark N.N., Gautam M., Norton P.M., Emissions from nine heavy trucks fuelled by diesel and biodiesel blend without engine modification. Environmental Science & Technology 2000;34(6):933-939.

[6]. Kalligeros S., Zannikos F., Stournas S., Lois E., Anastopoulos G., Teas Ch, Sakellaropoulos F., An investigation of using biodiesel/marine diesel blends on the performance of a stationary Diesel engine. Biomass and Bioenergy 2003;24(2):141-149.

[7]. Ramadhas A.S., Muraleedharan C., Jayaraj S., Performance and emission evaluation of a Diesel engine fuelled with methyl esters of rubber seed oil. Renewable Energy 2005;30(12):1789-1800.

[8]. Lapuerta M., Armas O., Rodriguèz-Fernàndez J., Effect of biodiesel fuels on Diesel engine emissions. Progress in Energy and Combustion and Science 2008;34(2):198:223.

[9]. F. Ma, M.A. Hanna, Biodiesel production: a review, Bioresource technology, 1999;70(1):1-15.

[10]. Y. Zhang, M.A. Dubé, D.D. McLean, M. Kates, Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis, Bioresource Technology, 2003;90(3):229-240.

[11]. G.C.S. Santana, P.F. Martins, N. de Lima da Silva, C.B. Battistella, R.M. Filho, M.R. Wolf Marciel, Simulation and cost estimate for biodiesel production using castor oil, Chemical Engineering Research and Design, 2010; 88(5-6):626-632.

[12]. Vijayaraghavan K., Hemanathan K., Biodiesel production from freshwater algae. Energy & Fuels 2009;23:5448-5453.

[13]. Scott S.A., Davey M.P., Dennis J.S., Horst I., Howe C.J., Lea-Smith D., Smith A.G., Biodiesel from algae: challenges and prospects. Current Option in Biotechnology 2010;21:277-286.

[14]. Demirbas A., Fatih Demirbas M., Importance of algae oil as a source of biodiesel. Energy Conversion and Management 2011;52:163-170.

[15]. Misra R.D., Murthy M.S., Straight vegetable oil usage in a compression ignition engine – A review. Renewable and Sustainable Energy Reviews 2010;14:3005-3013.

[16]. Sidibé S.S., Blin J., Vaitilingom G., Azoumah Y., Use of crude filtered vegetable oil as a fuel in Diesel engines state of the art: literature review. Renewable and Sustainable Energy Reviews 2010;14:2748-2759.

[17]. Labeckas G., Slavinskas S., Performance of direct-injection off-road Diesel engine on rapeseed oil. Renewable Energy 2006;31:849-863.

[18]. Rakopoulos D.C., Rakopoulos C.D., Giakoumis E.G., Dimaratos A.M., Founti M.A., Comparative environmental behaviour of bus engine operating on blends of diesel fuel with four straight vegetable oils of Greek origin: Sunflower, cottonseed, corn and olive. Fuel, 2011:90(11); 3439-3446.

[19]. Fontaras G., Kousoulidou M., Karavalakis G., Bakeas E., Samaras Z., Impact of straight vegetable oil-diesel blends application on vehicle regulated and non-regulated emissions over legislated and real world driving cycles. Biomass and Bioenergy 2011;35:3188-3198.

[20]. P. Pradhan, H.Raheman, D.Padhee, Combustion and performance of a Diesel engine with preheated Jatrophacurcas oil using waste heat from exhaust gas, Fuel, 2014:115: 527-533.

[21]. D.H. Qi, C.F. Lee, C.C. Jia, P.P. Wang, S.T. Wu, Experimental investigations of combustion and emission characteristics of rapeseed oil–diesel blends in a two cylinder agricultural Diesel engine, Energy Conversion and Management, 2014:77: 227-232.

[22]. D. Sonar, S.L. Soni, D. Sharma, A. Srivastava, R. Goyal, Performance and emission characteristics of a Diesel engine with varying injection pressure and fuelled with raw mahua oil (preheated and blends) and mahua oil methyl ester, Clean Technologies and Environmental Policy, 2014:17(6): 1499-1511.

[23]. Corsini A., Giovannoni V., Nardecchia S., Rispoli F., Sciulli F., Venturini P., Performance of a common-rail Diesel enginefuelled with rapeseed and waste cooking oils. In Proceedings of ECOS 2012 – The 25th International Conference on Efficiency, Cost, Optimization, Simulation of Environmental Impact of Energy Systems, June 26-29, Perugia, Italy.

[24]. G. ScarasciaMugnozza, S. Binotti, M. Napoleoni, F. Rispoli, F. Sciulli, P. Venturini, S. Babbini: Straight vegetable oil as fuel in an internal combustion engines for power and heat production. 4th Energy Conference – Palestine, 26-27 January, 2011, Ramallah, Palestine.

[25]. Corsini A., Marchegiani A., Rispoli F., Sciulli F., Venturini P., Vegetableoilsasfuels in Diesel engine. Engine performance and emissions, 69th Conference of the Italian Thermal Machines Engineering Association, ATI2014.

[26]. Altin R., Cetinkaya S., Husein S.Y., The potential of using vegetable oil fuels as fuel for diesel engine. Energy Conversion and Menagement 2001;42:529-538.

[27]. European Council Directive 91/441/EEC, amending Directive 70/220/EEC on the approximation of the laws of the Member States relating to measures to be taken against air pollution by emissions from motor vehicles, 26 June 1991.

Biography P. Venturini took his degree in Mechanical Engineer in 2004, and his Ph.D. in Theoretical and applied mechanics in 2009. He has now a post doc position at Sapienza University of Rome. His research interests are multiphase flows, renewable energy, biomass and biofuels.