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The effect of using diesel-biodiesel-bioethanol blends on the fuel feed pump of a small-scale internal combustion engine

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Abstract

Biofuels represent an environmental-friendly and feasible alternative to fossil fuels for internal combustion engines. The use of diesel-biodiesel-bioethanol fuel blends (ternary blends) is one of the most interesting solutions in terms of fossil fuels substitution. They provide an improvement of exhausts gas emissions without any significant sacrifices in terms of energy-conversion efficiency. However, engine operation may be affected by the fuel substitution especially in the auxiliary mechanical fuel-feed systems, traditionally designed for low-density and high-viscosity fossil fuels. In the proposed work, two easy-to-use experimental-based mathematical models have been obtained by using the response surface method to assess the behaviour of fuel feed-pumps when biofuels blends are used. Density and mass flow-rates have been measured for several fuel mixtures and at different temperatures. The proposed equations are intended to be used as a practical tool, based on the optimal behaviour of the fuel feed-pump, in order to choose the best ternary fuel-mixture composition and/or predict/infer the engine performances under non-tested conditions (i.e., other mixtures' compositions and temperatures, however within the inquired domain).

Keywords: Biodiesel, Bioethanol, Density, Feed-pump, Modelling, Optimization, Response Surface Method.

1. Introduction

The use of alternative fuels in internal combustion engines is growing in its popularity thanks to the recent greater attention to emissions levels and sustainability of fuels production and use. Indeed, internal combustion engines are deeply involved in the most crucial sectors facing environmental issues, such as transportation, electricity and heat production. In fact, both transportation and electrical-thermal energy conversion are globally responsible for the 64% of the whole carbon dioxides (CO_2) produced [1]. Moreover, other emissions, such as particulate matter (PM), hydro carbon (HC), carbon monoxides (CO) and nitrogen oxides (NOx) are hugely responsible for the air-quality deterioration and health problems such as asthma, asphyxiation and cancer; additionally, HC and NOx emission leads to the depletion of the ozone layer and to the green-house effect [2].

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Gasoline and diesel oil are the two main fuels satisfying the energy demand needed for transportation and small-scale energy conversion. As supported by many independent institutions [3,4], conventional oil production may face soon a decline due to lower availability and environmental limitations [5]. Additional future demand needs to be met by the exploitation of unconventional resources, which can lead to an increase of the price of petroleum-derived fuels [5]. Hence, unstable prices, the rapid reduction of fossil fuels reserves and the introduction of tighter emissions regulations are pushing researchers to enhance the chances of petro-fuels alternatives to be used in existing internal combustion engines. In this framework, biodiesel represents the strongest petro-diesel alternative on today's market for compression ignition engines. Biodiesel is mainly produced by a trans-esterification reaction from feedstock of different origins in presence of alcohol. This transformation technology is well-known and it has been used for more than one hundred years to extract glycerine from edible oils, giving methyl-ester (known as biodiesel) as a by-product [6]. Biodiesel is biodegradable, non-toxic, has a low-emission profile especially in terms of particulate matters, can be used in compression ignition engines without major modifications and is a renewable resource [7]. Due to its higher oxygen-concentration ratios, higher NO_X emissions [8] have to be considered as one of the main cons of the use of biodiesel in compression ignition engines [9]. Other possible causes of the higher NO_X formation are connected to the variation of the physical properties of the fuel, such as its density, its viscosity and bulk modulus. The response of the fuel injection system can be affected by these characteristics, involving a variation of the injection timing and mixture formation. A possible solution is to add a supplementary additive that, once mixed with biodiesel, allows to enhance the overall emission characteristics of the fuel mix without affecting significantly the engine performances [9]. In this regard, alcohol fuels have been adopted as a supplementary fuel-component with positive effects on NO_X emissions, as well as on PM [10]. On the other hand, the use of methyl-ester in diesel engines brings in problems like: carbon deposition, engine oil degradation, injector coking, corrosion, cold filter plugging and elastomeric compatibility [11]. Other important issues that must be assessed are the different lubrication characteristics of biodiesel in the fuel pump and the cooling effect on the injector [12]. However, proper fuel characteristics and flow rates must be granted whatever the fuelling.

The aim of the proposed work is to investigate some of the effects that biodiesel and bioethanol have in the operation of small compression ignition engines. In particular, the possible limitations on the fuel feed systems are assessed with specific regard to the effect of the variation of the fuel density and its temperature. This affects not only the combustion, the emissions and the engine output, but also the behaviour of auxiliary systems, with particular reference to the fuel pump. Due to the variation of the composition, the physical and fluid-dynamic characteristics of the fuel (mainly density and viscosity) might vary significantly, thus affecting the effective capability of the fuel pump and the fuel injection system to feed correctly the engine. Moreover, the fuel has also a lubricating effect on the fuel pump and a cooling effect on the injector and this is crucial for the long-term reliability of the engine. All these factors can be an issue, especially in small-scale engines that use mechanical volumetric fuel feed-pumps. Therefore, practical and simple relations to assess the correlations and the operative limitations in the use of alternative fuels are presented in this work to support and increase the share of biofuels in the use of ICEs.

2. Materials and methods

As the composition and the operative temperature of the fuel might change significantly depending on the share of alternative fuels in the considered mix, the evaluation of the fuel mixes' density is not straightforward; by varying the operating temperatures and the mixes compositions, the flow rate fuelling the engine might change, thus reducing the applicability of alternative fuels. Indeed, the problems are of two types:

- the density values of the fuel mixes components at the reference temperatures are generally not declared by the producers; even if they can be calculated quite simply by performing some lab experiments on samples of these biofuels, there could be practical difficulties of stabilizing thermally the fuel samples (this operation requires proper equipment);
- the equation representing the biofuels' volumetric expansion (or the volumetric-expansion coefficient, in case of a linear formulation of this equation) is completely unknown; even if this equation has a polynomial formulation, the deduction of the equation's coefficients requires many measurements of the density at different temperatures (at least a number of measures equal to the number of coefficients +1).

Another problem concerns the mass flow rate used by the engine: at a first sight, this quantity can have very different trends, strongly influenced by the biofuels blends' composition. Indeed, when analysing the data recorded in the tests, it is impossible to isolate the effective contribution of the density and, above all, of the blend viscosity, absolutely unknown without proper equipment and a thermostatic unit capable to reproduce all the situations happened experimentally. This fact has prevented to find a unique form for the trend lines if not including all the possible influencing factors, which cannot be performed with a straightforward analysis and requires complex equipment. Therefore, fuel density, temperature and mass flow have been measured and monitored for several binary (Diesel – Biodiesel) and ternary (Diesel oil – Biodiesel – Bioethanol) fuel blends at different temperatures. The main characteristics of the used biodiesel are reported in Table 1. Tests have been performed on a 3.9-kW single-cylinder water-cooled diesel engine ("Farymann 15W430"), equipped with a low-pressure volumetric fuel feed-pump that takes the fuel directly from the tank. The engine operates at a fixed rotational speed (3000 rpm) and serves a genset for electric power production. Tests were performed at full load fuelling the engine with several diesel oil (D), biodiesel (B) and bioethanol (E) blends. From pure diesel oil (D100) to pure biodiesel (B100), three binary blends have been realized: B25 (25% B – 75% D), B50 (50% B – 50% D) and B75 (75% B – 25% D). Bioethanol substitution has been introduced in the following blends: B0E3 (0% B – 97% D – 3% E), B25E3 (25% B – 72% D – 3% E), B50E3 (50% B – 74% D – 3% E), B75E3 (75% B – 22% D – 3% E), B97E3 (97% B – 0% D – 3% E). A Coriolis fuel mass flow meter ("Sitrans MASS 2100", with an accuracy equal to 0.1%) has been used to monitor the fuel flow rate and the density. Tests were repeated for different fuel temperature values ranging from 16.79 °C to 30.60 °C. Table 2 reports the experimental results obtained during the test campaign for the aforementioned fuel mixtures at different operating temperatures. It is worth to notice that the fuel flow rate of the volumetric feed pump strongly varies with the fuel composition and the temperature, highlighting that applicability limitations or issues in the fuel feed system might occur. These data are then used to carry on a statistical analysis to extend and generalize the obtained results.

Table 1 - Main properties of the biodiesel used in the tests

Biodiesel Properties		**Test**	**Biodiesel Properties**		**Test**
Ester content [% m/m]	98.5	EN 14103	Flash point [°C]	>160°	EN ISO 3679
Density at 15°C [kg/m^3]	883.1	EN ISO 3675	Cetane number [-]	>51	EN ISO 5165
Viscosity at 40° [mm^2/s]	4.1 – 4.7	EN ISO 3104	Water content [mg/kg]	210	EN ISO 12937

Table 2 - Experimental measurements regarding the used fuels (D100, B25, B75, B25E3, B75E3, B97E3)

Denomination of the mixture	***D [%]***	***B [%]***	***E [%]***	***Temp [°C]***	**Density [kg/m^3]**	**Mass flow [g/s]**
D100	*100*	*0*	*0*	*21.02*	824	1.88
D100	*100*	*0*	*0*	*27.10*	819	1.95
B25	*75*	*25*	*0*	*21.23*	829	1.85
B25	*75*	*25*	*0*	*27.30*	824	1.98
B75	*25*	*75*	*0*	*20.74*	856	1.60
B75	*25*	*75*	*0*	*26.34*	851	1.73
B25E3	*72*	*25*	*3*	*21.37*	827	1.62
B25E3	*72*	*25*	*3*	*26.15*	824	1.33
B73E3	*22*	*75*	*3*	*20.44*	856	1.67
B75E3	*22*	*75*	*3*	*26.20*	852	1.51
B97E3	*0*	*97*	*3*	*21.12*	867	1.45
B97E3	*0*	*97*	*3*	*27.28*	863	1.54

2.1. The response surface methodology

In order to assess and overcome the limitations evidenced in the previous paragraph, a very practical but effective methodology, based on a statistical analysis, was adopted. Specifically, for each of the above-mentioned quantities, an interpolating function was derived to estimate the value of the independent variables (here: the density ρ and the mass flowrate $\dot{m}$) by using the dependent variables values. From a formal point of view, the final formulation (and hence, the relations among the quantities) is completely independent from the physics of the represented process, being mainly oriented to obtain numerically-acceptable results within the validity domain and, therefore, a reliable prediction-capability. All the collected data, concerning the composition of the fuel mixes and the temperature, have been elaborated statistically. After an Analysis of Variance (ANOVA) test, aimed at evidencing the parameters of influence (*factors*) on the above-indicated quantity (*response*), a subsequent application of the Response Surface Methodology (RSM) allowed to calculate the regression function coefficients that describe the effects of the statistically-significant independent variables on the response. The RSM, differently from other mathematical tools such as artificial neural networks [13], is a very effective numerical tool that allows calculating, from a set of input data, an explicit polynomial regression-function that is the best approximation, in a limited validity domain, of the real function governing the phenomenon under study [14–18]. The proposed function for both the inquired responses is bilinear with interaction terms (i.e., a "2-FI model"). Higher-degree models could not be used in the present case, due to the possible occurrence of the aliasing phenomenon. In particular, the effect of the following numerical factors on the above-mentioned responses has been inquired (Figure 1):

- the gross volumetric composition of the fuel mix, in term of percentage parts of the three-base fuel-components (numerical factors controllable by the experimenters; both diesel oil and biodiesel range from 0 to 100 %, bioethanol can assume only two possible values: 0 % or 3 %);
- the temperature T of the considered fuel-mix (numerical factor consequent to the operational mode of the engine; values ranging from 16.79 to 30.60 °C, according to the measurements).

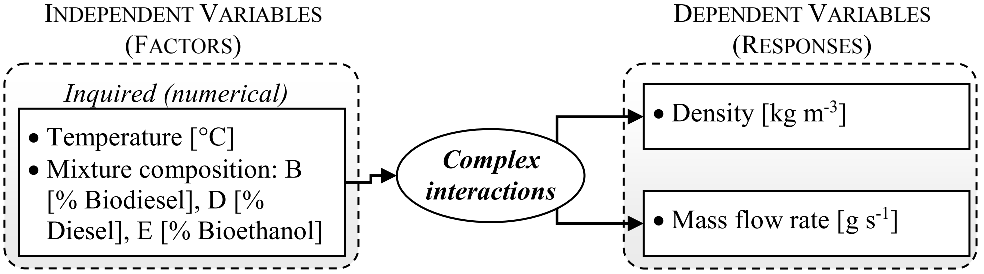

Figure 1 – Variables considered in the assessment of the physical properties of the fuel mixes.

The following paragraphs show the regression model resulting from the systematic backward elimination of not-significant terms (one by one) operated by the software beginning from the least significant term as resulting from the ANOVA.

3. Results and discussion

The following equation has been obtained applying RSM to predict fuel mixtures density values using experimental measurements:

$$\rho\left[kg/m^3\right] = 8.3775\cdot 10^2 - 8.1750\cdot 10^{-1}\cdot T\left[^\circ C\right] + 4.7057\cdot 10^{-1}\cdot B\left[\%\right] - 1.4491\cdot 10^0\left[\%\right] + 1.9059\cdot 10^{-2}\cdot B\left[\%\right]\cdot E\left[\%\right] \quad (1)$$

The predictive capability of this model is very high: R^2 is equal to 0.9857 and the Adjusted R^2 is 0.9845. Similarly, an equation based on a complete 2FI-model able to predict mass flow rates is proposed:

$$\dot{m}[g/s] = 1.7232 \cdot 10^{0} + 8.6526 \cdot 10^{-3} \cdot T[°C] - 8.5323 \cdot 10^{-3} \cdot B[\%] + 1.5189 \cdot 10^{-1} \cdot E[\%] \\ + 2.3014 \cdot 10^{-4} \cdot T[°C] \cdot B[\%] - 1.0902 \cdot 10^{-2} \cdot T[°C] \cdot E[\%] + 6.5806 \cdot 10^{-4} \cdot B[\%] \cdot E[\%] \qquad (2)$$

Also in this last case, the predictive capability is quite high: the R^2 value is equal to 0.8220 while the Adjusted R^2 is equal to 0.7886. Equation (1) shows that the biodiesel raises the fuel mix density, while bioethanol has a positive or negative contribution according to the percentage of biodiesel in the fuel mix, evidenced also by the first (partial) derivatives of the numerical model with respect to biodiesel (eq. 3.a, always positive) or bioethanol (eq. 3.b positive if B>76%).

$$(a) \quad \frac{\partial}{\partial B[\%]}\left\{\rho\left[kg/m^3\right]\right\} = +4.7057 \cdot 10^{-1} + 1.9059 \cdot 10^{-2} \cdot E[\%] \\ (b) \quad \frac{\partial}{\partial E[\%]}\left\{\rho\left[kg/m^3\right]\right\} = -1.4491 \cdot 10^{0} \cdot E[\%] + 1.9059 \cdot 10^{-2} \cdot B[\%] \qquad (3)$$

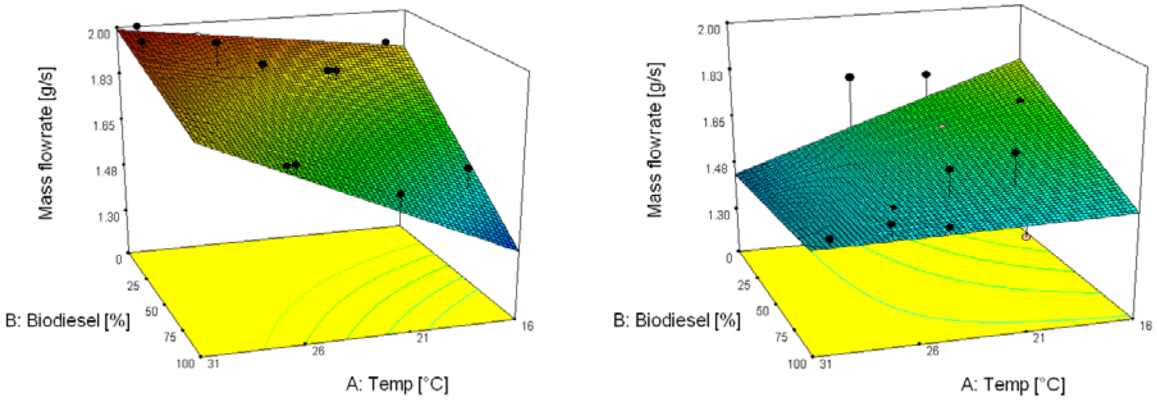

Figure 2 - 3D-graphs of the fuel mixes' flow rates as a function of the temperature and of the biodiesel percentage, with the 0 % (left) and the 3 % (right) of bioethanol in the blend.

Figure 2 shows the shape of the surface representing the mass flow rate values for an ethanol content of 0% (a) and 3% (b), modelled by eq. 2, as well as the experimental measurements (little spheres positioned within the inquired hyperspace; notice that many points are positioned under the represented surface and, hence, are not visible). The surfaces are quite warped, indicating a different influence on the response of the factors B and T in their ranges. Moreover, small variations of the percentage of bioethanol (from 0 to 3 %) correspond to very high modifications of the overall shape, as demonstrated by the first partial derivatives of the mass flow rate with respect to biodiesel (Eq. 4.a) and temperature (Eq. 4.b).

$$(a) \quad \frac{\partial \dot{m}[g/s]}{\partial B[\%]} = -8.5323 \cdot 10^{-3} + 2.3014 \cdot 10^{-4} \cdot T[°C] + 6.5806 \cdot 10^{-4} \cdot E[\%] \\ (b) \quad \frac{\partial \dot{m}[g/s]}{\partial T[°C]} = +8.6526 \cdot 10^{-3} + 2.3014 \cdot 10^{-4} \cdot B[\%] - 1.0902 \cdot 10^{-2} \cdot E[\%] \qquad (4)$$

Therefore, attention must be paid in the definition of the correct bio-fuel mixture in order to avoid a significant variation of the fuel flow rate that might influence the reliability and the performance of the engine, with particular reference to the high-pressure pump lubrication and cooling.

4. Conclusions

The proposed work has been carried out to provide some practical and easy-to-use mathematical correlations able to model density and mass flow rates of mixtures composed by different parts of diesel oil, biodiesel and bioethanol. Results show a high predicting capacity of the explicit polynomial regression-functions obtained through the response surface methodology, if used in the validity domain set by the experimental values. Carrying out deeper analyses of the proposed mathematical tools, an optimization strategy based on the behaviour of the fuel feed-pump can be easily implemented, thus facilitating the definition of the correct fuel mix to grant an acceptable reliability, performance and polluting emissions reduction of the motor under test. The results concerning the effect of biodiesel on fuel blends density are coherent with the actual state of the art. This innovative approach allows also to assess other aspects, such as the flow rate of the fuel feed pump, which are significant for the engine performance and reliability. Further interesting developments could include the effect of biofuels on viscosity.

References

[1] I.E.A. IEA, CO2 Emissions from Fuel Combustion 2017 - Highlights, Int. Energy Agency. 1 (2017) 1–162. doi:10.1787/co2_fuel-2017-en.

[2] H. Suhaimi, A. Adam, A.G. Mrwan, Z. Abdullah, M.F. Othman, M.K. Kamaruzzaman, et al., Analysis of combustion characteristics, engine performances and emissions of long-chain alcohol-diesel fuel blends, Fuel. 220 (2018) 682–691. doi:10.1016/j.fuel.2018.02.019.

[3] K. Alekkett, Peak oil and the evolving strategies of oil importing and exporting countries: facing the hard truth about an import decline for the OECD countries, Jt. Res. Cent. Discuss. Pap. - Int. Transp. Forum, OECD/ITF. (2007).

[4] International Energy Agency, World Energy Outlook 2008, 2008. doi:10.1049/ep.1977.0180.

[5] N.A. Owen, O.R. Inderwildi, D.A. King, The status of conventional world oil reserves-Hype or cause for concern?, Energy Policy. 38 (2010) 4743–4749. doi:10.1016/j.enpol.2010.02.026.

[6] J.G. Speight, S.K. Loyalka, Handbook of Alternative Fuel, (2007).

[7] A. Abbaszaadeh, B. Ghobadian, M.R. Omidkhah, G. Najafi, Current biodiesel production technologies: A comparative review, Energy Convers. Manag. 63 (2012) 138–148. doi:10.1016/j.enconman.2012.02.027.

[8] E. Alptekin, M. Canakci, Determination of the density and the viscosities of biodiesel–diesel fuel blends, Renew. Energy. 33 (2008) 2623–2630. doi:10.1016/j.renene.2008.02.020.

[9] A. Datta, B.K. Mandal, Engine performance , combustion and emission characteristics of a compression ignition engine operating on different biodiesel-alcohol blends, Energy. 125 (2017) 470–483. doi:10.1016/j.energy.2017.02.110.

[10] L. Zhu, C.S. Cheung, W.G. Zhang, Z. Huang, Emissions characteristics of a diesel engine operating on biodiesel and biodiesel blended with ethanol and methanol, Sci. Total Environ. 408 (2010) 914–921. doi:10.1016/j.scitotenv.2009.10.078.

[11] K. Nantha Gopal, R. Thundil Karuppa Raj, Effect of pongamia oil methyl ester-diesel blend on lubricating oil degradation of di compression ignition engine, Fuel. 165 (2016) 105–114. doi:10.1016/j.fuel.2015.10.031.

[12] I. Celik, O. Aydin, Effects of B100 Biodiesel on Injector and Pump Piston, Tribol. Trans. 54 (2011) 424–431. doi:10.1080/10402004.2011.556313.

[13] M. Bietresato, A. Calcante, F. Mazzetto, A neural network approach for indirectly estimating farm tractors engine performances, Fuel. 143 (2015) 144–154. doi:10.1016/j.fuel.2014.11.019.

[14] M. Bietresato, L. Sartori, Technical aspects concerning the detection of animal waste nutrient content via its electrical characteristics, Bioresour. Technol. 132 (2013). doi:10.1016/j.biortech.2012.12.184.

[15] M. Bietresato, S. Pavan, G. Cozzi, L. Sartori, A numerical approach for evaluating and properly setting self-propelled forage harvesters, Trans. ASABE. 56 (2013).

[16] M. Bietresato, G. Carabin, R. Vidoni, F. Mazzetto, A. Gasparetto, A parametric approach for evaluating the stability of agricultural tractors using implements during side-slope activities, Contemp. Eng. Sci. 8 (2015). doi:10.12988/ces.2015.56185.

[17] N. Maheshwari, C. Balaji, A. Ramesh, A nonlinear regression based multi-objective optimization of parameters based on experimental data from an IC engine fueled with biodiesel blends, Biomass and Bioenergy. 35 (2011) 2171–2183. doi:10.1016/j.biombioe.2011.02.031.

[18] L. Bortolini, M. Bietresato, Effect of seed-beds on the cultivation of Radicchio (Cichorium intybus L., Rubifolium group), Contemp. Eng. Sci. 9 (2016). doi:10.12988/ces.2016.6689.