

On the assessment of autoignition delay for Diesel fuel and Biodiesel B20

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Abstract. The use of bio-fuels is a necessity nowadays, regulated by European legislation, which imposes to the EU-countries an increase in the substitution rate of classic fossil Diesel fuel. Biodiesel (B) fuel proves to be a reliable agent to fulfil this requirement, but a certain number of aspects have to be ameliorated regarding the compatibility of this kind of fuel with the existent compression ignition engines. One of these problems relies on the autoignition delay, on which the research results are still dispersed. The paper proposes an analysis of this autoignition delay when using a compression ignition (CI) engine fuelled with Diesel fuel and with blends of Diesel and Biodiesel fuels (B20 – 20% volumetric fraction of Biodiesel), starting from several correlations given by the literature, which are based on single-cycle analysis and application of the integral Livengood-Wu method. The obtained results offer an image of the in-cylinder processes complexity and of the B20 fuel behaviour related to the tested engine operation.

1 Introduction

Biofuels as an alternative to classical petroleum derived fuels mixed in different fractions have become increasingly used in the last few decades due to worldwide regulations concerning emissions. Market policies are nowadays encouraging the expanding of biofuels limits in mixtures and their use in an efficient way in internal combustion engines. Among these, combined mixtures of Diesel-Biodiesel and Diesel-Biodiesel-Alcohols play a more significant role in the whole chain of the cylinder processes, from the injection phase until the end of combustion. Therefore, evaluating and controlling the autoignition period has direct consequences on the global engine performance parameters. It is known that a larger content of alcohol (ethanol or butanol) leads to an increase of autoignition delay because of its lower cetane number (CN) value and to a decrease of the premixed air-fuel temperature due to its higher heating value (ethanol), inhibiting the NO_x formation, despite its higher molecular content of oxygen; on the contrary, the use of a predominant amount of Biodiesel leads to a decrease of this delay, ensuring a better control of the injection timing in good connection with the main variables defining the engine operation [1-3].

From the whole range of Diesel-Biodiesel fueling mixtures, B20 is a promising prospect regarding a number of evaluation criteria, such as ID (Ignition Delay – see Fig. 1, defined as the duration between the start of injection, SOI and the start of combustion, SOC [4]), BTE (Brake Thermal Efficiency), soot, CO, THC and NO_x concentrations, peak fire pressure, maximum rate of the

firing pressure, according to Multi-Criteria Decision Making method (MCDM) [5]. By using Biodiesel as an additional fuel, it could also become necessary to modify the characteristics of the engine original injection system, to adjust the split-injection arrangement, the nozzle dimension, and the spray patterns, as many studies have proven [6-9].

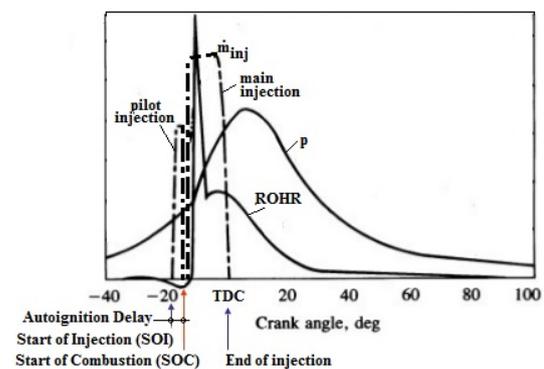


Fig. 1. Pressure p , rate of relative heat release (ROHR) and split injection characteristics in a compression ignition (CI) engine cylinder [4].

Many of the approaches used to approximate the autoignition delay are based on Arrhenius correlation and have been proposed in the case of using Diesel fuel [10], but in the case of using Biodiesel fuel there is still a lack of theoretical information. By exception, one formula [11] could be relevant, as its form was properly adjusted as following:

$$\tau_{ign}, ms = C p^a \Phi^b C_n^c \exp(E_A / (R_M T)) \quad (1)$$

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in which C, a, b, c are constants, p is the in-cylinder mean pressure, atm, Φ is the equivalence ratio, C_n is the length of the carbon chain, E_A is the activation energy, kcal/mol, R_M is the gas universal constant ($1,987 \times 10^{-3}$ kcal/(mol·K)) and T is the in-cylinder mean temperature, K. A particular concern is the calculation of the activation energy, with different values when the fuel content varies [12].

Previous studies [10,13-15] have provided an acceptable similarity between experimental and simulation results, using the AVL-BOOST, AVL-FIRE software tools, with the pressure and the temperature picked as averaged values from a group of successive operating cycles. The present work is based on the analysis of each individual cycle from the acquired batch of consecutive cycles, when discussing pressure and temperature values, applying the Livengood-Wu method [16].

2 Hypotheses to calculate the autoignition delay

This paper uses the experimental results obtained by testing a naturally aspirated Diesel engine in tractors. Its main features, together with all the test bed systems have been discussed in a previous work [10]. Using this experimental basis, 200 individual pressure traces have been recorded, for each engine operating condition.

The autoignition delay was firstly determined experimentally and then established by considering a relationship of type (1). There is a large variety of coefficient values to form this expression, the authors propose a diversity of mathematical influences on the result. The presented paper considers the form proposed by Assanis [14], in which the pressure, p is given in bar, Φ is the equivalence ratio [-] and T is the absolute temperature, in K:

$$\tau_{ign}, \text{ms} = 2,4 p^{-1,02} \Phi^{-0,2} \exp(2100/(T)). \quad (2)$$

The calculation of the engine in-cylinder autoignition delay has two extremely sensitive and difficult to measure components. The first one is the start of injection (SOI), marked by the start of the injector needle lifting. The second one, even more difficult to evaluate, is that of the start of combustion (SOC). This process adds energy in cylinder leading to a pressure increase, its rate being a parameter experimentally recorded.

Paper [13] presents several methods of establishing SOC, by taking into account the 1st, the 2nd and the 3rd derivations of the pressure. Due to the sensitivity of the measurement system and since numerical derivation is an unsteady process, the obtained results were inconclusive.

Another approach consists of the relative heat release (ROHR) calculation. This is given by the sum of the piston mechanical work and the gas internal energy variation, diminished by the heat transferred to the walls during the compression process. At the end of compression both mechanical work and the heat transferred to the walls get negative values, therefore the heat release becomes also negative. It can be assumed that

combustion starts corresponding to an angle for which this variable becomes positive and begins to increase.

The calculation of the autoignition delay could be achieved by calculating the pressure and the temperature average values in between a considered range period, or by calculating the relative delay on each such a range; this method is known as Livengood-Wu [16]:

$$\int_{t_1}^{t_2} \frac{dt}{\tau_{ign}(t)} \approx 1, \quad (3)$$

where t_1 is injection time and t_2 is the value of ignition time. In this equation t_2 is the unknown value.

These two procedures are practically equivalent, are based on the same principle, but for the second one there is a possibility to conduct a linear interpolation on the last range element to obtain a more precise result. In this paper there will be analyzed 200 individual cycles related to the autoignition delay, for an engine fuelled with Diesel and Biodiesel B20 fuels, when applying one of the proposed autoignition delay correlation and the integration calculus method. At the end of this computation a relative error analysis versus the measured value has also been completed.

3 Calculation Results

The measurements on the tested engine have been presented in [10] and listed in Table 1 (by extraction from Fig. 1):

Table 1. Injection and start of combustion angle.

Case number	1	2
Fuel/Speed	Diesel/2400 rpm	B20/2400 rpm
SOI	-5 CA	-5,5 CA
SOC	0,375 CA	-0,15 CA

where CA is the crank angle and SOC is the angle for the start of combustion.

For these cases the nominal torque was 175 Nm, corresponding to a nominal power of 44 kW.

The calculation of the autoignition delay has been developed for each single cycle and for each of them the corresponding angle where the integral (equation (3)) reaches the value 1 has been extracted and listed (see Fig. 2, Case 1).

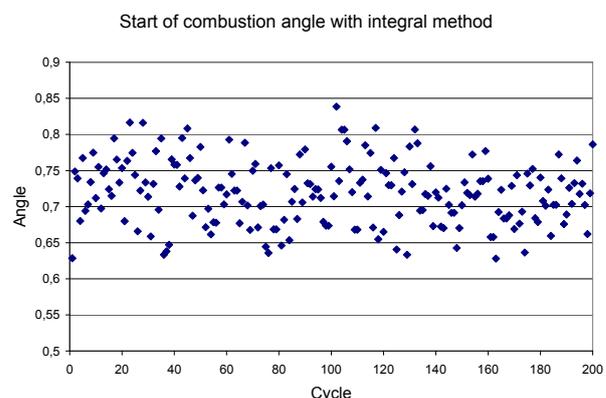


Fig. 2. Ignition angle for Case 1.

In this case, when the engine is fuelled with Diesel fuel, at full load the relative air-fuel ratio is 1.5. For these operating conditions, the angles for which the integration is 1 are included in the range 0,6 ... 0,8 deg.CA (ATDC, see Fig. 2). The average value for these data is 0,72 deg.CA as compared to the experimental average value of 0,38 deg.CA, there is a difference of 0,34 deg.CA.

Using the experimental data obtained in Case 2, when fuelling the engine with B20 fuel, the results appear more dispersed. For the ignition moment the average value is 0,3 deg. CA, very close comparing to the experimental results (0,375 CA). The experimental data for each individual cycles for start of combustion are located in domain -0,5 and 1,7 deg.CA (see Fig. 3).

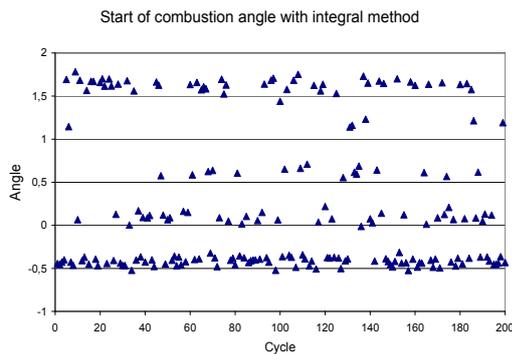


Fig. 3. Ignition angle for Case 2.

To be able to use Assanis's formula with the help of the temperature and pressure average values it is useful to expose them inside a domain of interest limited between SOI and by some points relative to top dead center (TDC). The average values for pressure and temperature from SOI to current position (where end of compression TDC = 0) are listed in Table 2.

Table 2. Pressure and temperature in cycle.

Case/CA	-5	-4	-3	-2	-1	0	1
Case 1 p	44,5	44,8	45,0	45,1	45,2	45,2	45,1
Case 1 T	1017	1016	1014	1012	1009	1007	1003
Case 2 p	46,1	46,3	46,5	46,6	46,7	46,7	46,6
Case 2T	1053	1051	1049	1046	1043	1040	1038

From this stage further the autoignition delay values for each range, starting from SOI and reaching -5 deg.CA BTDC are as follows (see Table 3, where A_s , ms is the value for Assanis formula and dt , ms is time elapsed from the SOI angle; in this table are presented only the values around top dead center, respectively -1, 0, 1 degree):

Table 3. Time evaluation for average values.

	-1CA		0CA		1CA	
	A_s	dt	A_s	dt	A_s	dt
Case 1	0,42	0,34	0,42	0,41	0,42	0,48
Case 2	0,38	0,34	0,38	0,41	0,38	0,48

For the analyzed engine operating conditions, applying the proposed formula, the average values define SOC in the range of -1... 0 deg.CA in the case of Biodiesel and in the range 0 ... 1 deg.CA in the case of Diesel fuel, values to be found also in most of the individual cycles.

Another analysis mode is that in which for each single cycle the adopted average values for temperature and pressure are those calculated for the period following SOI. When fuelling with Diesel (Case 1), this procedure offers values that are relatively close to the results obtained with the integral method, the average value for the integral is 0,72 CA and for the other calculation 0,69 CA (see Fig. 4).

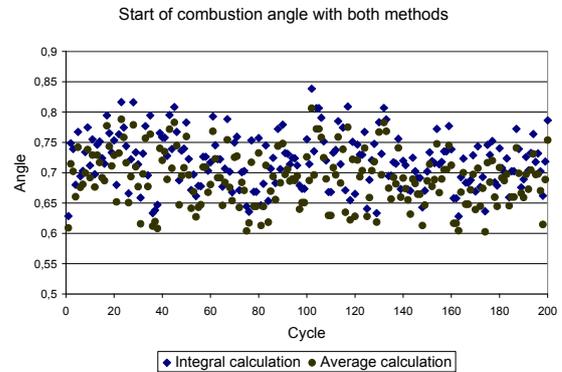


Fig. 4. Results for Case 1.

Comparing these two procedures is possible in the mean cycle obtained as an average of the 200 individual cycles. Averages for temperature and pressure are those obtained by calculating the averages over the 200 cycles and these ones resulting from the range values situated between SOI and the adopted angular limit after TDC.

Fig. 5 presents the cylinder pressure and temperature traces for the values involved in the Case 1 calculation. The mean trace represents the average values over the 200 consecutive cycles and the average trace is obtained from the values starting from the injection point.

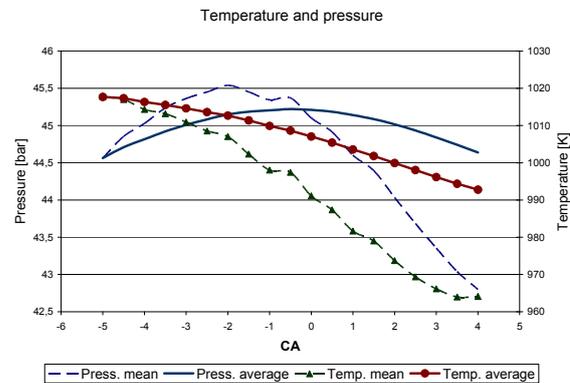


Fig. 5. Pressure and temperature traces for calculation Case 1.

Calculations were made with the following correlations (4):

$$p_{\alpha mean} = \frac{1}{200} \sum_1^{200} p_{\alpha i}, \quad (4)$$

where $p_{\alpha i}$ is the pressure measured at angle α for each individual cycle.

In order to use the Assani's formula it is necessary to define the average values for cylinder pressure and temperature in the ignition delay period. These values are calculated with the correlation (5):

$$p_{\alpha \text{ average}} = \frac{1}{\alpha_{inj} - \alpha} \sum_{\alpha_{inj}}^{\alpha} p_{\alpha}, \quad (5)$$

where α_{inj} is the injection angle. The temperatures are calculated with the same relations.

When we plot both methods on a single diagram, we obtain insignificant differences which lead to the decision that both could be applied with same degree of certainty (see Fig. 6).

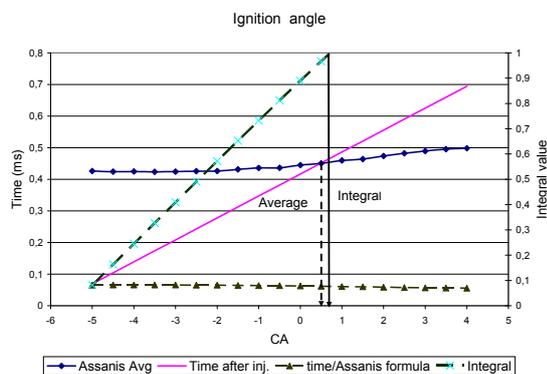


Fig. 6. Example calculation for both methods for Case 1.

When fuelling with B20 fuel, the use of the average values related to the autoignition delay reduces the dispersion of the results obtained by integration method. Using this second procedure, the range of the ignition angles becomes 0 ... 0,5 deg.CA (see Fig. 7.).

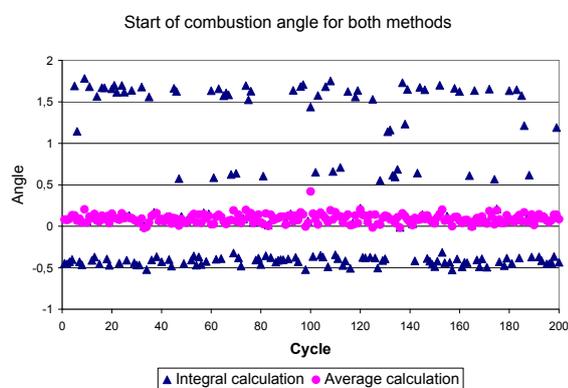


Fig. 7. Results obtained for Case 2.

In terms of the mean values obtained over 200 cycles applying both methods/procedures, the results on the SOC angle for both cases are listed in Table 4.

Table 4. Mean values of SOC angle for both cases.

	Integral calc.	Average calc.
Case 1	0,71	0,69
Case 2	0,29	0,10

4 Conclusions

The paper presents experimental data obtained when fuelling a tractor Diesel engine with Diesel and B20 Biodiesel-Diesel B20 mixture (20% vol. Biodiesel). An analysis was made to evaluate a simple calculation

relationship for the autoignition delay (Assanis), depending on the in-cylinder pressure, the global uniform temperature during the autoignition delay period and the air-fuel ratio for the analyzed operating condition.

In this computation individual cycles were used, for each of them two mathematical evaluation methods have been proposed: integrating the autoignition delay relative time and evaluating the average values of temperature and pressure on a certain angular range.

The results show small differences between the two calculation modes of the autoignition delay, lower than 0,5 deg.CA.

The cyclic variability caused probably during the compression process by the variation of the inlet process combined with the different air-fuel mixture formation in case of B20 leads to an increased dispersion of SOC.

The differences calculated for both types of fuels are inside the variability domain, consolidating the conclusion that from the perspective of the autoignition delay the behaviour of these two fuels (Diesel and B20) is practically the same.

The existing deviations of the theoretical results relative to the experimental data obtained for the two different fuels range between 0,25 to 0,5 deg.CA.

This study will be continued by analyzing other engine operating conditions to extend the soundness of these conclusions.

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