IGNITION AND COMBUSTION CHARACTERISTICS OF PURE VEGETABLE OILS TO BE USED AS DIESEL FUEL

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ABSTRACT: The ignition and combustion behaviour is of vital importance for a fuel to be used in diesel engines. For vegetable oils only little information is available concerning the ignition and combustion behaviour. Thus, target of the project was to determine the ignition and combustion behaviour of different vegetable oils in a Fuel-Ignition-Tester. The study was done by using ten different vegetable oils and two mixtures of vegetable oils. The vegetable oils were characterised by using their fatty acid composition. Based on that, the average number of double bonds and the average number of carbon atoms of the fatty acids were calculated. The results were evaluated using a multivariate regression analysis. The analysis showed that the average number of carbon atoms had no significant effect on the ignition delay. Between the average number of double bonds and the ignition delay a linear relationship with a high coefficient of determination was observed. It was recognized, that an increasing number of double bonds leads to a longer ignition delay. The longer the ignition delay the higher the amount of fuel burning in the first, premixed combustion phase. In the subsequent combustion phases the vegetable oils showed no differences.
Keywords: biofuel, combustion, characterization, internal combustion engine, vegetable oil

1 INTRODUCTION

Rapeseed oil is the most commonly used pure vegetable oil fuel in Germany. Using rapeseed oil has many benefits for the environment and rural economy. Following the Renewable Energy Directive of the European Union the savings in greenhouse gas emissions for rapeseed oil fuel are 57 % (default value) [1]. Rapeseed oil fuel can be produced in small-scaled decentralised oil mills [2] and is a chance to raise the regional value added in rural regions. Furthermore, rapeseed oil is characterised by a high biodegradability and a low exposure for water pollution. Also, rapeseed oil is one of the renewable fuels with the highest energy density. Hence, rapeseed oil is an excellent fuel for purposes where high power is needed in environmentally sensitive areas like agriculture and forestry.

The usage of pure rapeseed oil as fuel for agricultural machinery was demonstrated in several fleet tests in Europe [1]-[7]. In the fleet tests mainly rapeseed oil fuel was used. The fleet tests showed that vegetable oil compatible tractors can be reliably operated with rapeseed oil fuel of high quality. The quality requirements for rapeseed oil fuel are defined in the German standard DIN 51605 [8]. For other vegetable oils a pre-standard DIN SPEC 51623 [9] was released in September 2012. At European level a CEN Workshop Agreement CWA 16379 [10] was established for vegetable oil fuel.

In the German national standards a requirement for the ignitability is defined. For testing the ignitability a constant volume combustion chamber (CVCC) apparatus shall be used. Methods to determine a cetane number (CN) with a CFR- or BASF-engine are not applicable for vegetable oil [11]. EN 15195 [12] and EN 16144 [12] describe methods to determine a derived cetane number (DCN) using CVCC devices. Both methods are based on the measurement of the ignition delay (time between start of injection and start of combustion) after injection of the fuel sample into a heated and pressurized CVCC. The standards include equations to calculate a derived cetane number using the ignition delay.

In DIN 51605 and DIN SPEC 51623 some necessary adaptions of EN 15195 are stated to determine a derived cetane number for vegetable oils. The adaptions are a defined initial combustion chamber pressure of 2.2 MPa, an initial combustion chamber temperature of 530 °C and a fuel temperature of 75 °C. Furthermore, the derived cetane number is not calculated using a common equation but through comparison with a calibration curve based on reference fuels of known cetane number. Still, there are uncertainties of the application and precision of this adapted method. In DIN 51605 and DIN SPEC 51623 it is stated that this parameter cannot be used for legal disputes.

By Freedman et al. [14] it was mentioned that some fatty acid methyl esters and some triacylglycerides have a higher cetane number than cetane (hexadecane) itself. Hence, the applicability of the cetane scale to evaluate the ignition quality of fatty materials has to be questioned. Furthermore, Freedman et al. [14] recognized that the fatty acid composition of fatty acid methyl esters and technical triacylglycerides is influencing the derived cetane number. Further research on the influence of the fatty acid composition on the ignition behaviour in CVCC was made for fatty acid esters [15]-[21]. For vegetable oils hardly any information is available.

Thus, target of the research was to determine the ignition behaviour of pure vegetable oils in a CVCC device and to search for relationships to the fatty acid composition of the vegetable oils. Furthermore, the combustion behaviour of vegetable oils in a CVCC should be analysed.

2 MATERIALS AND METHODS

2.1 Vegetable oils

For the research ten vegetable oils were used: coconut oil, palm oil, high-oleic sunflower oil, jatropha oil, rapeseed oil, corn oil, soybean oil, sunflower oil, camelina oil and linseed oil. The fatty acid composition of the oils was analysed according to ISO 5508 [22].

Out of the fatty acid composition the two structure indices average number of carbon atoms *AC* and average number of double bonds *ADB* were calculated using following equations.

$$AC = \frac{\sum\left(FA_i \cdot n_{C,i}\right)}{\sum FA_i}$$

$$ADB = \frac{\sum\left(FA_i \cdot n_{DB,i}\right)}{\sum FA_i}$$

Hereby $n_{C,i}$ is the number of carbon atoms of the fatty acid *i*, $n_{DB,i}$ is the number of double bonds of the fatty acid i and FA_i is the mass fraction of the fatty acid *i*, taken from the fatty acid composition. By this we got two structure indices that account for the two most important differences of the fatty acids in the triacylglycerides of the vegetable oils.

2.2 Constant volume combustion chamber (CVCC)

For the determination of the ignition and combustion behaviour a Fuel-Ignition-Tester (FIT^{TM}) was used. The technical specifications of the FIT are listed in **Table I** and a schema of the FIT is given in **Figure 1**.

Table I: Technical specification of the used Fuel-Ignition-Tester (FIT^{TM})

Property	Value/type
CC* volume	630 ml
CC* pressure	max. 3.5 MPa
CC* temperature	max. 800 K
Injection nozzle	Single hole nozzle
Nozzle hole diameter	0.25 mm
Nozzle opening pressure	33.0 MPa
Injection pump	Single cylinder injection pump
Pressure sensor	Kistler RHU B01V0238
Sampling rate	20 kHz

*CC: Combustion chamber

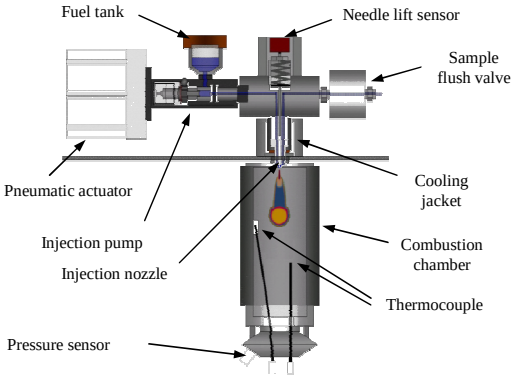

Figure 1: Schema of the Fuel-Ignition-Tester (FIT^{TM}) (reference: Fueltech, modified)

The FIT was operated with an initial combustion chamber pressure of 2.2 MPa, an initial combustion chamber temperature of 525 °C and the fuel temperature was set to 75 °C. Except of the combustion chamber temperature, the other settings were chosen according to the specifications of the vegetable oil standards DIN 51605 and DIN SPEC 51623. The combustion chamber temperature was set 5 K below the recommended setting, because our FIT was not able to reach 530 °C initial combustion chamber temperature.

After injection of the fuel sample into the combustion chamber and after the ignition delay, the fuel starts to burn. The heat release due to combustion leads to a pressure rise inside the chamber. This pressure rise is detected by a sensor. The ignition delay is defined as the time between the start of injection (detected by a needle lift sensor) and the first pressure rise of 0.2 MPa in the combustion chamber. For the determination of the ignition delay the trials were made in triplicate for every fuel. One trial is based on 20 injections into the combustion chamber. Furthermore, we regularly checked the correct function of the FIT between the trials by measuring a diesel reference fuel CEC RF 0603.

Because of the uncertainties on the applicability of the cetane scale for fatty compounds we focused on the measured ignition delay as scale for the ignitability and did not try to derive a cetane number.

The evaluation of the combustion behaviour was made by using the speed of pressure rise within the combustion chamber. The speed of pressure rise was determined by calculating the average pressure rise of the 60 single injections of every fuel sample. The average pressure rise was smoothed using a Savitzky-golay filter of second order over a time period of 1 ms. Afterwards, the smoothed data was differentiated to get the speed of pressure rise.

The speed of pressure rise enabled us to make a qualitative classification into the three combustion phases that are typical for direct-injection combustion. The first combustion phase is the premixed combustion, the second is the mixing controlled combustion and the third is the late combustion. Further information on the direct injection combustion phases is available in Heywood [23].

A multiple linear regression analysis was made to identify relationships between the structure indices of vegetable oils and the measured ignition delay.

3 RESULTS AND DISCUSSION

3.1 Properties of the vegetable oils

The fatty acid compositions of the tested vegetable oils are listed in **Table II** and **Table III**. Coconut oil is characterised by a high amount of saturated acids (lauric and myristic acid) whereas linseed oil consists mainly of unsaturated fatty acids (linolenic, linoleic and oleic acid).

Table II: Fatty acid composition of coconut oil (CC), palm oil (PA), high-oleic sunflower oil (HO), jatropha oil (JA) and rapeseed oil (RA)

Fatty acid		CC	PA	HO	JA	RA
Caproic	C6:0	0.6	<0.1	<0.1	<0.1	<0.1
Caprylic	C8:0	7.7	<0.1	<0.1	<0.1	<0.1
Capric	C10:0	6.0	<0.1	<0.1	<0.1	<0.1
Lauric	C12:0	45.4	0.2	<0.1	<0.1	<0.1
Myristic	C14:0	17.6	0.9	<0.1	<0.1	<0.1
Palmitic	C16:0	9.0	42.6	3.5	13.5	4.8
Palmitoleic	C16:1	1.9	0.2	0.1	0.9	0.3
Stearic	C18:0	2.6	4.6	3.2	5.7	1.7
Oleic	C18:1	7.0	39.6	83.5	39.0	62.2
Linoleic	C18:2	1.6	10.7	7.6	39.9	20.5
Linolenic	C18:3	<0.1	0.3	0.2	0.5	7.8
Arachidic	C20:0	0.1	0.4	0.3	0.2	0.6
Gadoleic	C20:1	<0.1	0.1	0.3	<0.1	1.2
Behenic	C22:0	0.2	<0.1	0.9	<0.1	0.3
Erucic	C22:1	<0.1	<0.1	<0.1	<0.1	0.3
Lignoceric	C24:0	0.1	<0.1	0.3	<0.1	0.1

Table III: Fatty acid composition of corn oil (CR), soybean oil (SO), sunflower oil (SU), camelina oil (CA) and linseed oil (LI)

Fatty acid		CR	SO	SU	CA	LI
Caproic	C6:0	<0.1	<0.1	<0.1	<0.1	<0.1
Caprylic	C8:0	<0.1	<0.1	<0.1	<0.1	<0.1
Capric	C10:0	<0.1	<0.1	<0.1	<0.1	<0.1
Lauric	C12:0	<0.1	<0.1	<0.1	<0.1	<0.1
Myristic	C14:0	<0.1	<0.1	<0.1	<0.1	<0.1
Palmitic	C16:0	10.9	8.4	6.0	5.8	5.2
Palmitoleic	C16:1	0.1	0.2	0.1	0.1	<0.1
Stearic	C18:0	1.9	3.5	3.4	2.5	4.6
Oleic	C18:1	30.8	37.3	31.6	18.2	23.7
Linoleic	C18:2	53.3	40.4	56.2	20.4	16.4
Linolenic	C18:3	1.3	8.0	1.0	32.6	48.9
Arachidic	C20:0	0.6	0.5	0.3	1.7	0.2
Gadoleic	C20:1	0.3	0.7	0.3	14.1	0.2
Behenic	C22:0	0.2	0.5	0.7	0.3	0.2
Erucic	C22:1	<0.1	0.2	<0.1	3.0	<0.1
Lignoceric	C24:0	0.2	0.2	0.2	0.2	0.3

The calculated structure indices average number of carbon atoms *AC* and average number of double bonds *ADB* are shown in **Table IV**. *ADB* is varying from 0.121 for coconut oil to 2.040 for linseed oil. *AC* was 18.08 ± 0.33 for most of the vegetable oils. Only coconut oil and palm oil had a lower *AC*. To get a better variation of *AC* two mixtures with coconut oil were prepared. Additionally to the variation of *AC* it was a target to reach the *ADB* of palm oil. Mixture 1 was made of 42.1 g of coconut oil and 57.9 g high-oleic sunflower oil. Mixture 2 was prepared by using 73.6 g coconut oil and 26.4 g linseed oil.

Table IV: Average number of carbon atoms *AC* and average number of double bonds *ADB* of the vegetable oils

Vegetable oil	*AC*	*ADB*
Coconut	13.04	0.121
Palm	17.10	0.624
Mixture 1	15.91	0.629
Mixture 2	14.33	0.628
High Oleic	17.99	0.998
Jatropha	17.72	1.216
Rapeseed	17.96	1.287
Corn	17.82	1.423
Soybean	17.89	1.433
Sunflower	17.93	1.477
Camelina	18.38	1.755
Linseed	17.93	2.040

3.2 Combustion behaviour

The combustion behaviour of the vegetable oils was assessed using the speed of pressure rise in the combustion chamber. The speed of pressure rise of selected vegetable oils is shown in **Figure 2**.

After the start of injection the speed of pressure rise is in the range of 0 MPa/ms. This indicates that the combustion chamber pressure is not varying much. After about 2 ms the speed of pressure rise is beginning to increase for coconut oil. This indicates the start of combustion and the end of ignition delay.

The first, premixed combustion phase is usually characterised by a high heat release rate. This results from the rapid combustion of the injected fuel that has mixed with air within its flammability regions during the ignition delay [23]. Because of the high heat release rate the pressure in the combustion chamber is raising fast which can be seen in the high speed of pressure rise.

Figure 2 already shows that the ignition delay of the vegetable oils is differing. A longer ignition delay leads to a later start of combustion and a higher local maximum of the speed of pressure rise. This indicates an increasing amount of fuel burning in the first combustion phase.

The premixed combustion phase is followed by the mixing-controlled. In this phase the heat release is controlled by the rate at which mixture becomes available [23]. For coconut oil and mixture 1 the speed of pressure rise is in the same range (0.08 to 0.10 MPa/ms) for a longer period. For the other vegetable oils the mixing controlled combustion phase is hardly to identify because of the intensive premixed combustion phase.

In the late combustion phase no differences in speed of pressure rise between the vegetable oils have been recognized. This indicates similar combustion behaviour in this phase.

The main difference in the combustion behaviour of the vegetable oils is the intensity of the first, premixed combustion phase. This is caused by the different ignition delays. When the first combustion phase is finished, the speed of pressure rise is about the same for all vegetable oils. This indicates that in the subsequent combustion phases the vegetable oils have similar combustion behaviour.

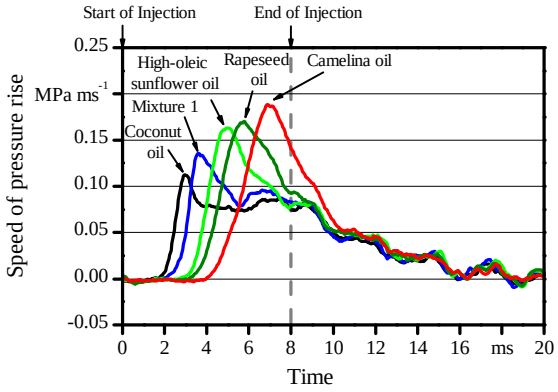

Figure 2: Speed of pressure rise in the combustion chamber of the FIT after injection of coconut oil, mixture 1, high-oleic sunflower oil, rapeseed oil and camelina oil

3.3 Ignition delay

The ignition delay of the vegetable oils is shown in **Table V**. The ignition delay varied from 2.58 ms to 5.93 ms. The most saturated vegetable oil (coconut oil) had the shortest ignition delay and the most unsaturated vegetable oil (linseed) had the longest. The vegetable oils are listed in **Table V** according to increasing average number of double bonds *ADB*. In about the same order the ignition delay is rising. This already shows that the ignition delay seems to have a relation to *ADB*. The ignition delays of the mixtures were close to the ignition delay of palm oil. Palm oil and the mixtures were characterised by nearly the same *ADB* but with different *AC*. Also it could be recognized that with increasing *AC* the ignition delay is increasing in tendency.

Freedman et al. [14] also recognized an increasing ignition delay (decreasing derived cetane number) with increasing *ADB* and increasing *AC* for technical triacylglycerides. The influence of *ADB* was higher than that of *AC*. This is in agreement with the present study using pure vegetable oils.

Table V: Arithmetic mean of the ignition delay τ_{id} of the vegetable oils determined in the Fuel-Ignition-Tester (vegetable oils listed according to increasing *ADB*)

Vegetable oil	Ignition delay τ_{id} in ms
Coconut oil	2.58
Palm oil	3.14
Mixture 1	3.13
Mixture 2	3.12
High-oleic sunflower oil	3.98
Jatropha oil	4.11
Rapeseed oil	4.50
Corn oil	4.48
Soybean oil	4.56
Sunflower oil	4.41
Camelina oil	5.48
Linseed oil	5.93

The multiple linear regression analysis using *AC* and *ADB* as independent variables to estimate the ignition delay showed that *AC* is insignificant. Hence, *AC* was removed from the model and a simple linear regression analysis using only *ADB* as variable was performed. The resulting model was significant (performing a t-test) with a high adjusted coefficient of determination of 0.963. The result of the regression analysis is shown in **Figure 3**.

In **Figure 3** the ignition delay of the diesel reference fuel CEC RF 0603 is included. The ignition delay of the reference diesel fuel (with a cetane number of 53.9) is in the range of the ignition delay of vegetable oils with an *ADB* of 1.0 to 1.2. Coconut oil, palm oil and the vegetable oil mixtures had a shorter ignition delay than the used diesel fuel, which indicates a better ignitability under the tested conditions.

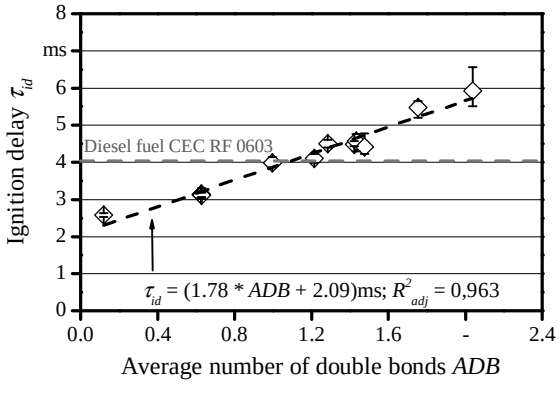

Figure 3: Arithmetic mean and maximum deviation of the ignition delay τ_{id} of vegetable oils in relation to the average number of double bonds *ADB* and compared to diesel fuel

4 CONCLUSIONS

Vegetable oils are differing concerning their ignition and combustion behaviour. Main differences are in the duration of the ignition delay and in the first, premixed combustion phase. The longer the ignition delay the higher the amount of fuel burning within the first combustion phase. In the subsequent combustion phases no differences were recognized between the vegetable oils. Hence, the ignition delay seems to be the most important difference between the vegetable oils that influences the following combustion phase.

The ignition delay of vegetable oils is related to their fatty acid composition. In this study the structure indices average number of carbon atoms *AC* and average number of double bonds *ADB* were used to find relations. The ignition delay of the vegetable oils is increasing with rising average number of double bonds *ADB*. The average number of carbon atoms *AC* showed no significant effect on the ignition delay under the tested conditions. The saturation of the vegetable oils seems to be the most important factor influencing the ignition behaviour.

Within the study a model could be developed to predict the ignition delay of vegetable oils in the Fuel-Ignition-Tester by using the average number of double bonds *ADB* as independent variable.

Concerning the standardisation of vegetable oil fuel it can be concluded that the ignition delay is an adequate measure for the ignitability. Because of the linear relation between the ignition delay and the structure index *ADB* the determination of a derived cetane number seems to be not necessary. Furthermore, an inclusion of *ADB* and the ignition delay model into the standards would enable the user of the standard to identify the use of ignition improvers in vegetable oil fuel. Further research is necessary to get more data about the repeatability and reproducibility of measuring the ignition delay and the determination of *ADB* based on the analysed fatty acid composition.

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6 ACKNOWLEDGEMENT

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