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Research article

# Ignition characteristics of straight vegetable oils in relation to combustion and injection parameters, as well as their fatty acid composition

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ABSTRACT

Straight vegetable oils may be a promising alternative to fossil diesel fuel. Fuels to be used in compression ignition engines have to meet several specifications, including the requirement of a certain ignition characteristic. The ignition characteristic is described by the cetane number of a fuel and measured using engine or constant volume combustion chamber device based methods. However, none of these standardized methods is directly applicable for straight vegetable oils. As a result cetane numbers of vegetable oils with the same origin and indicated in literature can vary by several cetane number units. Furthermore, the known cetane numbers of commonly used oils such as rapeseed or soybean oil are lower than that of conventional diesel fuel. In contrast, emission testing of these oils using modern diesel engines under high load conditions indicated an ignition behavior comparable to that of diesel fuel. Thus, the task of this research was to determine the ignition characteristic of nine different straight vegetable oils and two oil mixtures using a constant volume combustion chamber device equipped with a high pressure fuel injection system. The ignition characteristic was provided using primary reference fuel calibration. The calibration was done at different combustion chamber temperatures and injection pressure levels representing various engine load conditions. The determined ignition characteristics were expressed in terms of an estimated cetane number of vegetable oils (ECNO). In contrast to conventional diesel fuel, the ECNO of vegetable oils was found to be strongly influenced by both, combustion chamber temperature and injection pressure. With rising temperature and injection pressure, the ECNO was observed to increase and exceed that of diesel fuel for certain vegetable oils. Thus, it was recommended to use two ECNO to provide a meaningful definition of the ignition characteristic of vegetable oil fuels. One should reflect the ignition characteristic at low load engine points and was determined with an injection pressure of 500 bar and a combustion chamber temperature of 852 K. The other one should be valid for intermediate and high engine load conditions. This was determined using an injection pressure of 1000 bar at a temperature of 923 K. A high linear correlation could be found between the degree of saturation of the fatty acids present in the oils and their ECNO. The ECNO was higher for oils with a low amount of monounsaturated and especially polyunsaturated fatty acids.



## 1. Introduction

Liquid alternative fuels for internal combustion engines have been attracted significant interest over the last years with regard to the reduction of greenhouse gas emissions and the preservation of fossil fuel resources. Among these vegetable oil based fuels are promising candidates for diesel fuel substitutes. Vegetable oils can either be directly used in combustion engines [1,2] or converted to fatty acid methyl esters or hydrotreated vegetable oils [3,4]. In agricultural machinery, for instance, the usage of pure vegetable oils has been successfully demonstrated as an alternative fuel [5,6].

In order to enable reliable engine operation, vegetable oil fuels should meet the requirements given in the German national fuel standards DIN 51605 [7] for rapeseed oil fuel or DIN 51623 [8] for vegetable oil fuel. In this physical properties, such as density or kinematic viscosity, and quality parameters, such as oxidation stability, are specified. However, the specification of the ignition characteristic of vegetable oil fuel according to DIN 51623 [8] is still missing because the data base is too small.

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The ignition characteristic describes the tendency of a fuel for autoignition [9]. In case of diesel engine combustion, liquid fuel is directly injected into the high temperature and high pressure atmosphere of the combustion chamber. The period between the start of fuel injection and the autoignition of the fuel–air mixture is called ignition delay. Ignition delay depends on the physical and chemical properties of the fuel as well as on engine characteristics [9].

The reference test method to quantify the ignition characteristic of diesel fuel in terms of the cetane number is described in the standard ISO 5165 using the CFR engine [10]. Fuels with a high tendency to autoignition have a high cetane number. According to EN 590, a cetane number of at least 51 is required for conventional diesel fuel [11].

Several efforts were undertaken to develop alternative methods for cetane number determination using constant volume combustion chamber (CVCC) devices [12–17]. The advantages of CVCC-based methods are: low sample volume needed, less time-consuming measurement and ability to automate the measurement procedure [17,18]. Currently there exist four CVCC devices for cetane number determination: the Ignition Quality Tester (IQT) [19], the Fuel Ignition Tester (FIT) [20], the Cetane Ignition Delay (CID) [21] and the Advanced Fuel Ignition Delay Analyser (AFIDA) [22]. In contrast to the engine-based methods, ignition delay is variable in the CVCC-based methods. The measured ignition delays are related to the corresponding cetane numbers using a non-linear correlation formula with fixed parameters [19,21] or by primary reference fuel calibration [17,22]. As the cetane number determination differs from the engine based methods, the resulting ignition characteristic is called a derived cetane number in the case of the FIT, IQT and CID [19–21] or a generic cetane number in the case of the AFIDA [22].

While various methods exist for cetane number determination, none of them enables the direct use of pure vegetable oils [23]. Attenberger and Remmele [24] developed a method for derived cetane number determination for rapeseed oil using the FIT. The method was specified in the standard for rapeseed oil fuel [7] and may also be applicable for other vegetable oils [8]. However, the method is only calibrated for derived cetane numbers between 40 and 60 [8]. In addition, several efforts were made to determine the cetane number of vegetable oils using engine based-methods.

For rapeseed oil, cetane number given in literature ranges between 38 using the CFR engine [25,26] and 29 using the BASF engine [27] while it was found to be 44 or more using the FIT [8,28]. The large difference between the cetane numbers obtained from engine- and CVCC-based methods holds also true regarding other vegetable oils. The cetane number of neat linseed oil determined in the CFR engine ranged between 27.6 and 34.6 [25,26]. Comparing the cetane numbers of cottonseed oil, the difference between the CFR engine-based and FIT-based numbers was more than eight cetane number units [26,28]. Regardless of the method used, certain vegetable oils may be termed as fuel with a low ignition characteristic compared to diesel fuel EN 590. This may be attributed to the operating points and the measurement devices used for cetane number determination [29].

A strong dependence of the ignition and combustion behavior of vegetable oils on engine load has also previously been reported for several types of diesel engines [30–33]. Especially at low load operation or idle, poor ignition quality was observed, while at full load operation, the ignition and combustion behavior might be equal or even better than that of diesel fuel [31,32,34]. This suggests that the combustion and ignition behavior of vegetable oils are more influenced by ambient combustion conditions such as combustion chamber temperature or injection pressure than that of conventional diesel fuel. However, none of the current cetane number test methods are able to address those impacts on the ignition characteristics of vegetable oils.

Therefore, the task of the current study was to investigate the influence of combustion parameters on the ignition characteristics of vegetable oil fuel. Using the Advanced Fuel Ignition Delay Analyser, the ignition characteristics should be related to that of primary reference fuels making up the cetane number scale. Different sets of combustion chamber temperatures and injection pressures should be researched in order to gain the dependency of ignition characteristic on combustion parameters. Finally, the ignition characteristics should be correlated to the fatty acid composition of the oil enabling prediction of the ignition characteristics of further vegetable oils.

## 2. Material and methods

### 2.1. Primary reference fuels and diesel fuel

The ignition characteristics of the vegetable oils were evaluated compared to those of primary reference fuels. The primary reference fuels scaling up the cetane scale are n-hexadecane with an assigned cetane number of 100 and 1-methylnaphthalene with an assigned cetane number of 0 [35]. Because of the low oxidative stability of 1-methylnaphthalene, heptamethylnonane with an assigned cetane number of 15 was introduced as reference fuel for the lower end of the cetane scale [35]. However, 1-methylnaphthalene could still be used as reference fuel as it is stated in EN 16906 [36] for the BASF engine-based method, ISO 5165 [10] for the CFR engine-based method and IP 617 [22] for the generic cetane number determination using the AFIDA. Therefore, seven binary mixtures of the two primary reference fuels 1-methylnaphthalene and n-hexadecane were used in the current study. The cetane number of the binary mixture corresponds to the volume percentage of n-hexadecane in the mixture. Mixtures with a cetane number of 35, 40, 46, 53, 60, 70 and 82 were used. The primary reference fuel mixtures originated from Analytik-Service Gesellschaft mbH, Germany.

Furthermore, a CEC RF 06-03 reference diesel fuel was used for comparing the ignition characteristics of vegetable oils to fossil diesel fuel. The kinematic viscosity at 313 K was 3.25 $mm^2/s$ using ISO 3104 [37] and the density at 288 K was 843.1 $kg/m^3$ using ISO 12185 [38]. The cetane number according to ISO 5165 [10] was 52.4.

### 2.2. Vegetable oil fuel

The properties of vegetable oils can be described using their fatty acid composition. The fatty acid composition can be transformed to structure indices such as the number of carbon atoms and double bonds per fatty acid. These structure indices could be used to form a pseudo-triglyceride consisting of three equal fatty acids with the same average number of carbon atoms and double bonds per fatty acid as the real oil [39,40]. In this study, the two structure indices of the average number of carbon atoms (*AC*) per fatty acid and the average number of double bonds (*ADB*) per fatty acid were used to analyze the influence of the fatty acid structure of vegetable oils on their ignition characteristics. The *AC* and the *ABD* were proposed by Emberger et al. [41] and were calculated by Eqs. (1) and (2) using their fatty acid composition. $n_{c,i}$ denotes the number of carbon atoms of the fatty acid $i$ and $n_{db,i}$ the number of carbon–carbon double bonds inside the fatty acid $i$. $w_i$ is the mass fraction of fatty acid $i$ and $M_i$ its molar mass.

$$AC = \frac{\sum \left(\frac{w_i}{M_i} \cdot n_{c,i}\right)}{\sum \frac{w_i}{M_i}} \tag{1}$$

$$ADB = \frac{\sum \left(\frac{w_i}{M_i} \cdot n_{db,i}\right)}{\sum \frac{w_i}{M_i}}. \tag{2}$$