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Full Length Article

Effect of fatty acid composition on ignition behavior of straight vegetable oils measured in a constant volume combustion chamber apparatus

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HIGHLIGHTS

- Ignition behavior of eleven different vegetable oils was analyzed.
- Ignition behavior was correlated to their fatty acid composition.
- Increasing unsaturation of the oils led to longer ignition delays.
- Increasing chain length had a minor effect on ignition delay.

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ABSTRACT

Straight vegetable oils attracted attention several times as alternative fuel for mobile machinery. Certain efforts have already been undertaken to enable the usage of the high viscous oils in compression ignition engines. While physical properties are well specified for different kind of oils, only few information is available on the ignition behavior of vegetable oils under modern engine like conditions. Therefore, the ignition behavior of nine different vegetable oils and two oil mixtures was investigated using the Advanced Fuel Ignition Delay Analyser (AFIDA). The AFIDA is a modern constant volume combustion chamber apparatus equipped with a high pressure injection system. Analysis was performed at combustion chamber temperatures ranging from 796 K to 967 K and at air density levels of 4.7 kg/m^3, 9.3 kg/m^3 and 17.7 kg/m^3. Ignition behavior was correlated to the structure indices average number of carbon atoms and average number of double bonds. Both were calculated using the fatty acid composition of the oils. Ignition delay decreased with rising temperature and air density. Coconut oil ignited first at every temperature except for the lowest air density level. Start of combustion was always last for linseed oil, followed by camelina and soybean oil. Ignition delay increased linearly with rising average number of double bonds and decreasing average number of carbon atoms. The effect of the average number of double bonds on ignition delay was more pronounced than that of carbon chain length. Fatty acids with two or more carbon-carbon double bonds led mostly to a stronger increase in ignition delay compared to those with only one double bond.

1. Introduction

Alternative fuels for compression ignition engines can be obtained from oily biomass. Vegetable oil based fuels are mostly extracted from oil seeds and further processed to biodiesel or hydrotreated vegetable oils (HVO) [1,2]. Beside this, there is special interest using straight vegetable oils as an alternative fuel in environmental sensitive areas like agriculture, forestry or water transport [3–5]. The usage of straight vegetable oils as fuel in agricultural machinery has previously been successfully demonstrated in Europe [6–9]. Because of the physical properties of vegetable oils adaptions on the engine calibration as well as modifications on the fuel supply system are necessary [10–12]. Vegetable oils are commonly preheated to temperatures between 343 K and 363 K to reduce their high viscosities prior to injection [13,14]. In order to ensure reliable engine operation, vegetable oils should meet the requirements defined in the national German standards DIN 51605 [15] for rapeseed oil fuel and DIN 51623 [16] for vegetable oil fuel of any source. These standards include limits for physical properties like kinematic viscosity, density and energy content. Further specifications are referred to the quality

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Nomenclature

A	pre-exponential factor	PUS	polyunsaturated fatty acid
AC	average number of carbon atoms	RAP	rapeseed oil
ADB	average number of double bonds	SOY	soybean oil
AFIDA	Advanced Fuel Ignition Delay Analyser	m	mass
AFR	air to fuel ratio	M_{i}	molar mass of fatty acid i
CAM	camelina oil	n	pressure exponent
COC	coconut oil	n_{DB}	number of double bonds
COT	cottonseed oil	n_{C}	number of carbon atoms
CVCCA	constant volume combustion chamber apparatus	NTC	negative temperature coefficient
Eq	equation	p_{C}	pressure of air inside combustion chamber
HOS	high oleic sunflower oil	$\mathrm{R}^2_{\mathrm{adj.}}$	adjusted coefficient of determination
LIN	linseed oil	T_{C}	temperature of air inside combustion chamber
MLP	mixture of linseed oil, palm oil and coconut oil	w_{i}	weight percentage of fatty acid i
MCC	mixture of coconut oil and camelina oil	β	regression coefficient
MUS	monounsaturated fatty acid	$\hat{\beta}$	standardized regression coefficient
PAL	palm oil	ρ_C	density of air inside combustion chamber
PEA	peanut oil	Φ	equivalence ratio

and purity of an oil. Ignition quality in terms of derived cetane number is specified for rapeseed oil fuel whereas no limits are given for vegetable oil fuel.

While each of the requirements can be tested by experiments, several models exist to deduce the physical properties of fatty compounds using empirical correlations, e. g. for density, viscosity or higher heating value prediction [17–19]. Mainly, vegetable oils consist of triglycerides. Triglycerides are esters of three fatty acids and a glycerol molecule. The fatty acid composition gives the mass percentages of the different fatty acids present in a vegetable oil. Each fatty acid can be characterized by the number of carbon atoms (carbon chain length) and the number of carbon–carbon double bonds within the carbon chain [20]. As fatty acid composition determines the physical and chemical properties of an oil, it can be used to predict them [21,22].

Knowing the fatty acid composition vegetable oils can be described in different ways. Among them structural indices can be used to form a pseudo-triglyceride [23,24]. Emberger et al. [25] suggested the structural indices average number of carbon atoms (*AC*) and average number of double bonds (*ADB*). The *AC* gives the average chain length of the fatty acids while the *ADB* stands for the average number of carbon–carbon double bonds within the carbon chains. The resulting pseudo-triglyceride can be imagined as three fatty acids, each with a chain length of *AC* carbon atoms and *ADB* double bonds, bonded by an ester bond to the glycerol molecule.

Emberger et al. [25] used those structure indices to correlate the ignition behavior of vegetable oils to their molecular structure. The ignition behavior was analyzed in a constant volume combustion chamber apparatus (CVCCA). The CVCCA was equipped with a mechanical injection system and the fuel was injected with an injection pressure lower than 35 MPa. *ADB* was found to have a significant effect on ignition delay at a constant temperature of 796 K. The ignition delay extended linearly with increasing number of double bonds. In contrast, no significant effect of *AC* on ignition delay was observable for a constant combustion chamber pressure. However, using an Arrhenius type model *AC* showed the tendency to extend the ignition delay when the number of carbon atoms was increased. This was attributed to the contradictory effect of the AC on the chemical and physical part of ignition delay. Rising the *AC* was supposed to accelerate the chemical reactions, as it was known for straight alkyl chains or fatty acid methyl esters [26–29]. However, the kinematic viscosity as well as the boiling point of an oil increases with the increasing number of carbon atoms. Both would lead to a longer time for the oil to be evaporated and thus extend the part of mixture preparation. This effect was enhanced because of the low injection pressures and the low combustion chamber temperatures used in this study, resulting in longer ignition delays. Consequently, the authors supposed that the ignition delay was mainly affected by mixture preparation and thus a longer ignition delay with increasing *AC* was observed. An increase in ignition delay of vegetable oils with a rising number of double bonds and carbon atoms was also stated by Hellier et al. [30]. The authors related the extended ignition delay with increasing number of carbon atoms to the simultaneous increase in the number of double bonds. The latter was supposed to have a more prominent influence on the ignition delay resulting in the increase in ignition delay with increasing number of carbon atoms. The same has previously been observed by Freedman et al. [26] for technical triglycerides in a CVCCA operated at 853 K and with low fuel injection pressures. A rising number of double bonds as well as a rising number of carbon atoms reduced the ignition quality and therefore increased the ignition delay. This is partly contrary to the findings for straight alykl chains or fatty acid methyl esters [26–29,31]. As for vegetable oils, the decrease in ignition quality of fatty acid methyl esters in terms of cetane numbers correlates with an increasing number of double bonds within the fatty acids [24,27,26]. Fatty acid composition based models for cetane number prediction show a strong impact of fatty acids methyl esters with more than one double bond on lowering ignition quality [32,33]. In contrast to vegetable oils, rising number of carbon atoms increase the ignition quality and decrease the ignition delay of fatty acid methyl esters [26–29].

By now, analysis of the ignition behavior of straight vegetable oils using a CVCCA was only performed with out of date injection systems and low injection pressures. The influence of fatty acid composition on ignition delay of vegetable oils was previously stated for different operating pressures but influence of higher ambient temperatures is still missing. Further, there is still a lack of information if the rising number of carbon atoms present in a fatty acid chain of vegetable oils could promote ignition.

Therefore, the target of the present study was to investigate the influence of the fatty acid composition on the ignition behavior of vegetable oils using a new CVCCA with a modern high pressure fuel injection system. Different sets of ambient combustion conditions should be selected to investigate the effect of temperature on ignition process.