# Optical Investigation of Shock Induced Ignition of Different Biofuels

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# **1** Introduction

Due to the increasing amount of greenhouse gases in the atmosphere and the foreseen scarcity of fossil fuels the development and investigation of biofuels is in the focus of many research projects today. Ethanol is one common biofuel which can be produced in high yields. Several studies investigated this fuel in different types of experimental facilities beginning at fundamental investigations in shock tubes [1-5] and ending in application related setups, e.g. combustion engines [6-9]. Overall ethanol has the potential to reduce pollutant emissions and to reduce the dependence on fossil fuels. Nevertheless, ethanol has some disadvantages. It is hydroscopic and its energy density is relatively low. This motivates to look for alternative biofuels. As potential alternative biofuel candidates Methyltetrahydrofuran (2-MTHF) and 2,5-Dimethylfuran (2,5-DMF) have been identified by the Cluster of Excellence "Tailor made fuels from biomass" at the RWTH Aachen University. Literature data concerning these fuels is rare.

Several years ago MTHF has been tested as a fuel extender (10% blend) in an SI engine in comparison to ethanol, methanol, and methyltetrabutylether (MTBE) [10]. The MTHF blend shows a very similar behavior in comparison to the neat gasoline. Thus, the authors of this study state that it should be easily acceptable as an alternative liquid fuel for transportation. In a recent study the performance of a diesel engine using 2-MTHF as fuel has been investigated in comparison to standard diesel, bio-diesel, and BTL-fuel [11]. One major result is that at high loads soot emissions are drastically reduced for 2-MTHF.

2,5-DMF has the advantage that it has a higher boiling point, a higher energy density and a higher research octane number compared to ethanol [12]. Furthermore, 2,5-DMF is insoluble in water avoiding the possibility of ground water pollution in contrast to MTBE. As ethanol 2,5-DMF can be produced in high quantities so that it might be an attractive alternative to ethanol [12]. Recent studies present laminar burning velocities, markstein lengths for DMF measured in a constant volume combustion chamber [13] and laminar premixed flame investigations [14].

The main aim of the present study is to investigate the ignition process of both alternative biofuels 2-MTHF and 2,5 DMF in comparison to ethanol. Besides the usual pressure and emission measurements high speed Schlieren imaging has been used for visualizing the ignition process. Since no Schlieren data exists for the investigated fuels a more general discussion of the ignition behavior in comparison to previous studies of conventional fuels [15-17] will be given.

# 2 Experimental setup

For the experimental investigation a rectangular shock tube has been used. The shock tube has a rectangular driven section with a cross section of 54 mm x 54 mm and a length of about 6 m. The circular 5 m high pressure section is divided from the rectangular low pressure section by hostaphan foils with different strengths from 0.07 up to 0.13 mm. Six pressure transducers are mounted near the end wall for recording the parameters of incident and reflected shock waves. In the end wall a germanium photo diode is mounted for detecting ignition. Furthermore, two quartz glass windows allow optical access to visualize the flow field and ignition process up to 120 mm from the end wall. An ultra high speed camera capable to record 100 pictures with a maximum frame rate of 1 MHz was used to perform time resolved Schlieren imaging. Due to the low initial pressures no heating of the tube was necessary to keep the fuel vaporized. Ignition delay times are only determined from the photo diode signals since at low temperatures no significant pressure rise occurs due to ignition. Figure 1 depicts an overview of the experimental setup.



Figure 1: Overview of experimental setup

### **3** Results

In the present study stoichiometric fuel/air mixtures have been investigated. For all experiments synthetic air (79.5 %  $N_2$ , 20.5 %  $O_2$  – Westfalen) has been used. Pressures have been varied from 5 bar to 13 bar and temperatures from 920 K to 1300 K. Figure 2 shows the results for the ignition delay measurements for all investigated fuels referred to the conditions directly behind the reflected shock. As it is usual the ignition delay increases with decreasing temperature and pressure. At high temperatures all fuels show an Arrhenius type behavior. Correlation equations (Eqs. 1-3) are capable to describe this behavior whereby for 2,5-DMF only a few experiments without pressure variation have been performed. Thus, the data for 2,5-DMF can give only a rough approximation for the correlation without a pressure influence.

Ethanol [4]: 
$$t_{ign} / ms = 7.5 \cdot 10^{-6} \cdot (p / bar)^{-0.77} \cdot e^{\frac{14000 K}{T}}$$
, T > 950 K (1)

2-MTHF: 
$$t_{ign} / ms = 4.0 \cdot 10^{-5} \cdot (p / bar)^{-0.6} \cdot e^{\frac{12000 K}{T}}$$
, T > 1050 K (2)

2,5-DMF: 
$$t_{ign} / ms = 6.0 \cdot 10^{-6} \cdot e^{\frac{1}{T}}$$
, no temperature limit observed (3)

For all experiments high speed Schlieren movies have been recorded to visualize the ignition process. At high temperatures for all investigated fuels a similar behavior has been observed. Figure 3 shows one example of high temperature ignition of ethanol. The instants of the pictures are marked in the pressure history by vertical

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lines. Picture (1) depicts the typical formation of the lambda foot of the reflected shock due to the shock boundary layer interaction. This interaction results in a non-ideal increase in pressure at the wall as can be seen in the pressure histories. Furthermore, this interaction can transport cold gas towards the end wall which is believed to be a reason that ignition does not occur directly at the end wall [14]. Pictures (2)-(6) visualize the ignition process. Ignition starts in a cross section near the end wall followed by a short deflagration phase where a moderate pressure increase is observed. After this deflagration phase a detonation like reaction front is visible which results in sharp increase in pressure. This so called strong ignition behavior is very similar to literature results of different fuels [15-17].



Figure 2: Ignition delay times for stoichiometric fuel-air-mixtures, a) ethanol, b) 2-MTHF, c) 2,5-DMF



Figure 3: High temperature ignition near the end wall, fuel: ethanol,  $\Phi=1$ , T = 1135 K

At low temperatures so called mild ignition occurs for ethanol. In contrast to the high temperature ignition, where ignition occurs more or less homogeneous in one section of the tube, at lower temperatures ignition starts at local spots. This inhomogeneous ignition is followed by a deflagration of the fuel-air-mixture and no significant increase in pressure due to the combustion is observed in experiment (Fig. 4). Fieweger et al. [15] state that this so called hot spot ignition might arise from inhomogeneities in temperature, radical concentrations,

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or particles in the test gas. An inhomogeneous ignition at low temperatures has also been observed for 2,5-DMF (Fig. 5).



Figure 5: Low temperature ignition, fuel: 2,5-DMF,  $\Phi$ =1, T = 959 K

In contrast to the behavior of ethanol and 2,5-DMF low temperature experiments at very similar conditions with 2-MTHF do not show inhomogeneous ignition (Fig. 6). Here a much more homogenous ignition is visible. Furthermore, the reaction front propagates much faster for 2-MTHF compared to ethanol leading to a significant pressure rise. This homogeneous ignition of 2-MTHF is a strong indication that local spot ignition does not result only from inhomogeneities caused by facility effects like shock-boundary layer interaction and turbulence behind the reflected shock. These effects are present for each fuel and should more or less affect the ignition in the same way. Thus, inhomogeneous ignition is also strongly influenced by fuel chemistry. It has to be stated that the real mechanism responsible for inhomogeneous ignition at low temperatures is not yet understood.

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Figure 6: Low temperature ignition, fuel: 2-MTHF,  $\Phi=1$ , T = 932 K

It is interesting to note that for inhomogeneous ignition at low temperatures first ignition spots are visible significant earlier in the Schlieren images than they can be detected by the photodiode (Figs. 4-5), because the light intensity emitted by the first ignition spots is below the detection limit of the photodiode. For homogenous ignition with a faster energy release the signal from the photodiode and the time of appearance of ignition spots in the Schlieren images correlate well (Figs. 3, 6).

The different ignition modes can have an important impact on the performance of a combustion engine. For SI engines knocking can be a major problem. In the case of knocking a detonation like pressure waves can lead to significant damages. In this context the ignition behavior of ethanol or 2,5-DMF seems to be preferable since at engine relevant temperatures these fuels show no tendency of a transformation of the deflagration to detonation. For both fuels ignition at lower temperature starts randomly distributed in the observation area from local spots followed by a deflagration process consuming the whole fuel-air mixture. In the same temperature regime 2-MTHF ignites quasi homogenously resulting in a significant faster fuel consumption and energy release. This type of ignition is preferable for autoignition based engines (Diesel or HCCI) since a homogeneous combustion leads to higher engine performance and lower soot emissions. Recent engine investigations already mentioned in the introduction confirm the tendency of faster fuel combustion in comparison to standard fuels [11]. Furthermore, soot emissions are drastically reduced for 2-MTHF. Besides other effects, the homogenous ignition behavior of 2-MTHF may be one reason for this positive result.

### 4 Summary

In the present study shock tube ignition delay time measurements for three different biofuels, i.e. ethanol, 2-MTHF, and 2,5-DMF, are performed. Pressures have been varied from 5 to 13 bar and temperatures from 920 to 1300 K. High temperature ignition data have been correlated using Arrhenius approach. The focus of the present study lies on optical investigations of the ignition process. A rectangular shock tube in combination with a high speed Schlieren setup has been used to perform time resolved visualizations of the ignition. At high temperatures all investigated fuels behave similar. Homogenous ignition occurs near the end wall followed by a short deflagration stage and transformation to detonation. At low temperatures local spot ignition occurs for ethanol and 2,5-DMF followed by a deflagration of the whole fuel-air-mixture. In contrast 2-MTHF does not show spot ignition but homogenous ignition at low temperatures. In this case the combustion process is significantly faster than for the deflagration process of ethanol and 2,5-DMF. These different ignition modes can have a significant influence on combustion engine performances. For SI engines fuels are preferable that do not tend to detonate like ethanol and 2,5-DMF. Homogenous auto-ignition as observed for 2-MTHF is an important aspect for diesel engines or modern engine concepts like HCCI for improving performance and reducing emissions.

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