Experimental Investigation of Spray Propagation and Mixture Formation of Tailor-Made Fuels under Engine-Relevant Conditions

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Abstract

The aim of this particular project is to specify the desired and tolerable values for the physical fuel properties that are necessary as input for the fuel development in the Cluster of Excellence "Tailor-Made Fuels from Biomass". Therefore this study characterizes the fuel influence on macroscopic and microscopic spray propagation and mixture formation, as there is little known about this influence for most of the fuels under consideration. For this purpose reference fuels of various substance classes have been defined whose physical and chemical properties cover a wide range of potential synthetic fuels. In detail Butanol, Ethanol, Dodecane, Iso-Octane and Tetrahydrofurfuryl Alcohol were analysed using scattering light visualisations and shadowgraphy methods. The investigation of the penetration length supplies information about the influence of the hydrodynamic and thermodynamic fuel properties on atomization and evaporation. The measurements are performed under diesel-engine relevant conditions in a heatable pressurized chamber with optical access. With exception of the ambient temperature the parameters of the measurement system are kept constant. In the case under consideration the wide range of physical properties of the potential tailor-made fuels has a significant influence on spray propagation.

Introduction

World-wide increasing carbon dioxide emissions, a rising energy demand and limited availability of fossil energy resources constitute major challenges today's societies are facing. In this context the Cluster of Excellence "Tailor-Made Fuels from Biomass" (TMFB) takes an interdisciplinary and inverse research approach towards new synthetic fuels based on biomass feedstock. In clustering expertise from natural and engineering sciences a model-based design procedure is pursued. A mixture of well-defined candidate fuel components with tailored properties will be derived from the requirements of the combustion process. The long-term objective is to describe the optimum combination of fuel components and related combustion behaviour. As a prerequisite to the engine combustion process, the injection system and strategy needs to be adapted to the potential fuel properties. Beside alkanes and alcohols, furans as potential chemicals from biomass provide a basis for the iterative and inverse development process.

Despite the fact that in the past a considerable number of successful engine experiments have been performed using alternative fuels, there is little knowledge about the influence of the different macroscopic properties (viscosity, density, surface tension etc.) of potential tailor-made fuels on the atomization process. From a theoretical analysis of these parameters Ahmed et al. [1] expect a considerable impact on spray formation. Higgins et al. [2] have investigated a number of alternative fuels and provide a correlation for the stationary liquid penetration length depending on the fuel/ambient density ratio and the latent heat of the fuel. Grimaldi and Postrioti [3] have compared the transient penetration of biodiesel with conventional Diesel fuel and noticed a faster penetration of the spray tip for biodiesel. They also found a fuel influence on spray tip penetration. Also Li [4] compared the spray propagation of biodiesel and Diesel and found a faster penetration and a smaller cone angle in the experiments with biodiesel. Chang and Farrell [5] and Desantes et al. [6] investigated various fuels and did not observe an influence of viscosity on the injection rate of a Diesel injector. However, the latter investigation found a significant influence of fuel density and reported increased Sauter mean diameters in the spray with higher viscosity. From this, the authors expect a significant influence on the combustion process. Also Yule et al. [7] and Stan et al. [8] studied the fuel influence on spray propagation but found only small influences for the investigated fuels. However, the general sensitivity of injection processes to fuel properties can be seen in investigations like those of Araneo et al. [9]. There the fuel temperature effect on the spray from a swirl injector was investigated and a strong impact on spray

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penetration and shape for a temperature increase of only 20 K was detected. To summarize, no systematic study covering all aspects of fuel influence on spray propagation is available. In order to determine desirable and tolerable properties of tailor-made fuels a systematic investigation of the fuel property influence on spray propagation is inevitable.

Materials and Methods

In this work the influence of the fuel parameters on spray propagation is investigated with the fuels Butanol, Ethanol, Dodecane, Iso-Octane and Tetrahydrofurfuryl alcohol (THFA) in order to cover a wide range of chemical properties (see Table 1).

Fuel Properties		Butanol	Dodecane	Ethanol	Iso-Octane	THFA
Density at 300 K	kg/m³	804.2	743.8	784.3	688.8	1048.07
Viscosity at 300 K	mPas	2.41	1.36	1.04	0.47	4.68
Surface Tension at 300 K	N/m	0.024	0.025	0.022	0.018	0.037
Liquid Heat Capacity at 300 K	J/kgK	2,415.8	2,223.3	2,454.2	2,039.4	1,796.1
Boiling Point	K	391.05	498.47	351.45	372.39	450.80
Heat of Vaporization at Boiling Point	kJ/kg	581.30	255.11	838.98	262.61	442.86

Table 1. Fuel properties according to Daubert and Danner [10].

The experimental set-up is composed of a spray visualization system, a pressurized chamber and a diesel common rail injection system. For basic investigations on fuel spray behaviour, optically accessible pressurized vessels are used as test facilities as shown in Figure 1.

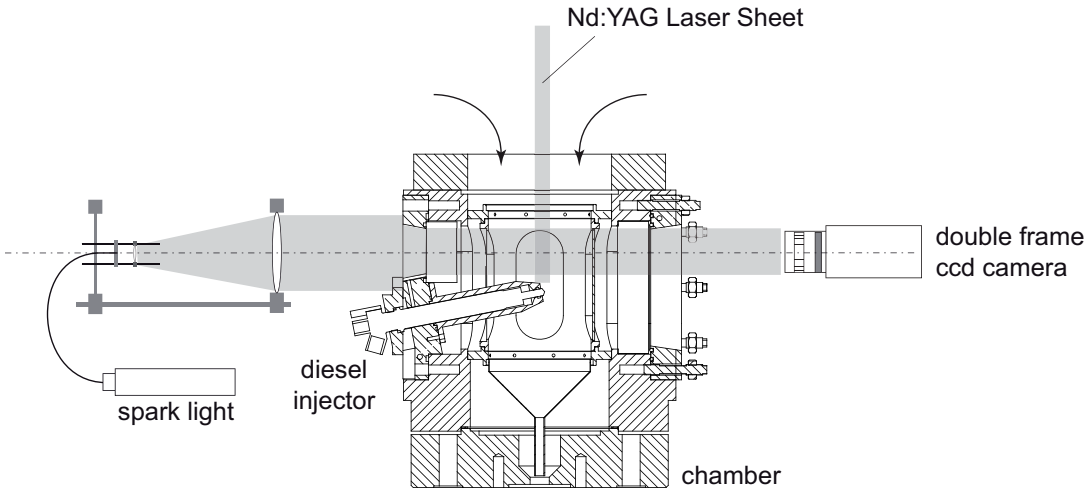

Figure 1. Experimental Apparatus.

This decoupling from the engine combustion processes ensures a detailed and repeatable investigation of the influence of specific parameters on fuel-mixture generation. The chamber can be configured according to the needs of the desired investigation. The ambient conditions in the pressurized chamber have been set to temperatures of 600K, 700K and 800K and a pressure of 5 MPa for all investigations. A continuous air flow of about 25 kg/h is delivered by a compressor and heated electrically to the desired temperature before entering the chamber. A diesel common-rail system is used with an injection pressure of 72 MPa and an energizing time of the injector of 400 µsec. The injector is orientated in the chamber so that one spray of the 8-hole piezo diesel injector penetrates in vertical direction. The nozzle orifice diameter is 109 µm. The chamber configuration for this investigation employs a test section with three window openings at a 90° spacing in the vertical layer. The liquid phase of this spray is investigated using scattering light visualisation. This technique is based on the scattering of a Nd:YAG laser sheet illuminating the spray from above. For this reason the chamber is equipped with an additional window at the head.

The scattered photons are collected by the first frame of a double frame CCD-camera. A backlight technique has been used to detect the envelope of the vapor phase. This technique detects the refractive index gradients caused by the presence of fuel and it requires the light source, the object and the detector to be aligned on a straight line. For this reason the injector configuration had to be mounted opposite to the camera, using a window in the injector holder for illumination in the front view. The Shadowgraph image is detected by the second frame of the camera. Typically, 20 images per time step are recorded. The image recording has been completely automated based on the DaVis software from LaVision GmbH. An automatic image processing tool based on Matlab has been developed to extract information about the spray width from the images.

Results and Discussion

Figure 2 shows scattering light visualisation images of the liquid phase for the five fuels 0.9 ms after energizing the injector and for the ambient conditions 800 K and 5 MPa. Larger differences of the liquid penetration length are shown. At the same time at the bottom of Figure 2 the penetration of both phases achieved with the shadowgraph imaging technique is presented. Unlike the liquid phase, the penetration of the vapor phase differs insignificantly.

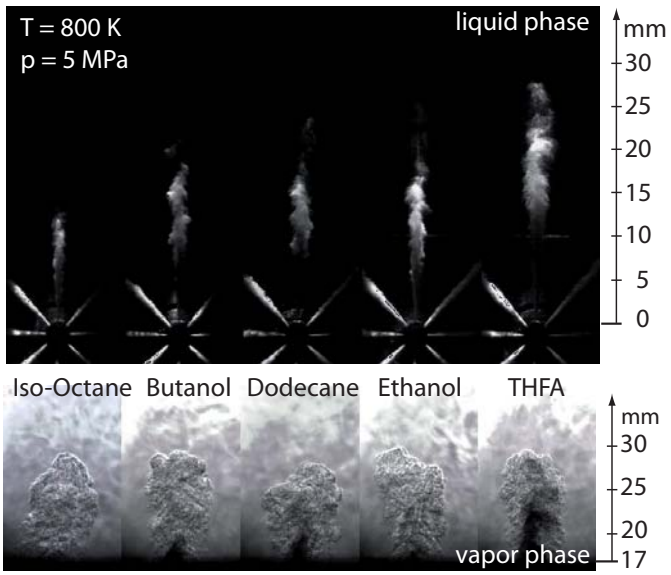

Figure 2. Penetration of the liquid and the vapor phase at 0.9 ms after energizing the injector.

The first phase of the spray propagation is characterized by the pressure difference and the primary and secondary breakup. In this region the hydrodynamic fuel properties density, viscosity and surface tension mainly affect the penetration.

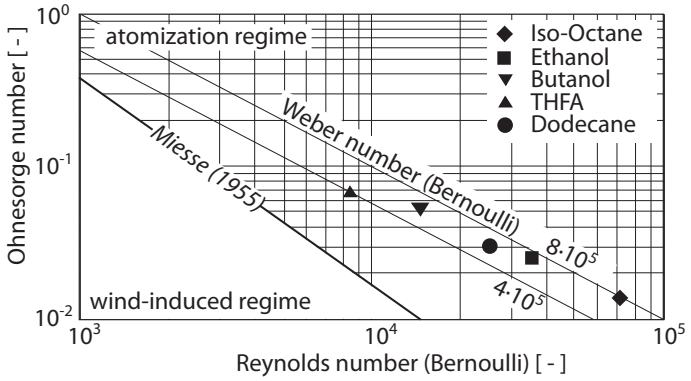

Figure 3. Ohnesorge diagram with referenced fuels according to Reitz [11].

In order to ensure an analysis which is independent from explicit material parameters dimensionless Reynolds (*Re*), Weber (*We*) and Ohnesorge numbers (*Oh*) and density ratio (ρ^*) are used to characterize the fuels. For this purpose the investigated fuels are plotted in the Ohnesorge diagram (see Figure 3). Due to lack of information about the spray velocity at the nozzle the calculation of Reynolds and Weber number is based on the theoretical Bernoulli velocity at 300 K. A high Weber number indicates a good and a low Weber number a worse atomization of the spray. The relation between Weber number and penetration length is supported by Figure 4: For the ambient temperature of 800 K the maximum penetration length is marked by THFA due to its low density ratio and low Weber number which stabilizes the surface against aerodynamic forces and decreases the breakup probability. The opposite conclusion can be made for Iso-Octane. The properties of any other investigated fuel are in the range between both and consequently, the penetration length data also are within the envelope marked by THFA and Iso-Octane.

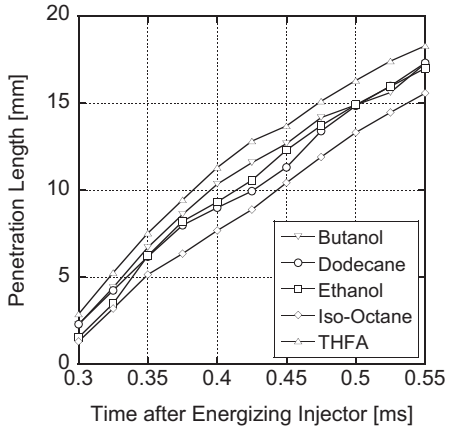

Figure 4. Penetration of the liquid phase.

The penetration of the vapor phase for different ambient temperatures is shown in Figure 5. The results correspond to the liquid phase penetration in the initial stage as mentioned before.

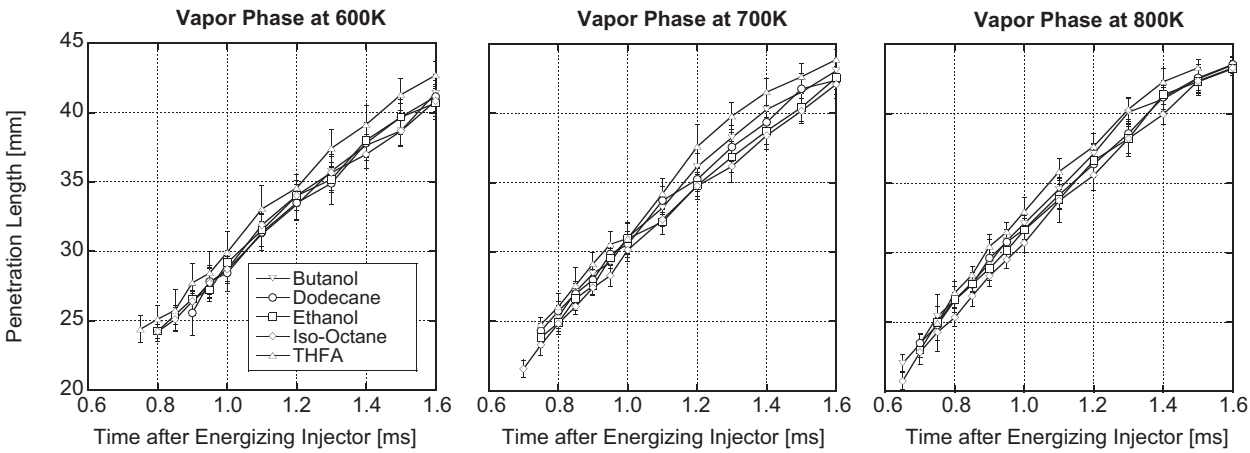

Figure 5. Penetration of the vapor phase for different ambient temperatures.

The vapor pressure of the fuel is a measure for the tendency of the fuel to cavitate in the nozzle hole. This phenomenon is described by the cavitation number. The graph of Figure 6 shows that the different fuels branch off from the initial horizontal curves when their vapour pressure approaches the ambient chamber pressure. For Ethanol the resulting pole in cavitation number is shown by the dotted line at around 500 K. On the one hand cavitation results in a lower mass flow rate but higher velocity due to the less effective cross section and wall friction in the nozzle hole and on the other hand imploding cavitation bubbles enhance the atomization process. It must be pointed

out that in comparison to the other fuels Ethanol has a higher tendency for cavitation. In the analysis of the liquid phase penetration this phenomenon must be taken into account.

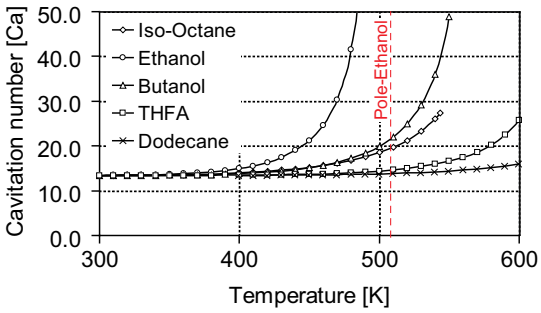

Figure 6. Influence of the temperature on the cavitation number (vapor pressures calculated according to Daubert and Danner [10]).

The second phase of the spray propagation is characterized by a rising influence of thermodynamic properties on spray propagation. The specific heat capacity, the enthalpy of vaporization and the boiling point of the fuel determine the amount of energy needed to evaporate a certain droplet with defined diameter. Figure 7 shows the spray penetration for all operating points. The evaporation of the fuel with simultaneous axial spray propagation results in a stationary penetration length. Based on different atomization behaviours Iso-Octane has a comparatively short and THFA a long stationary penetration length. Normally this length decreases with higher temperatures.

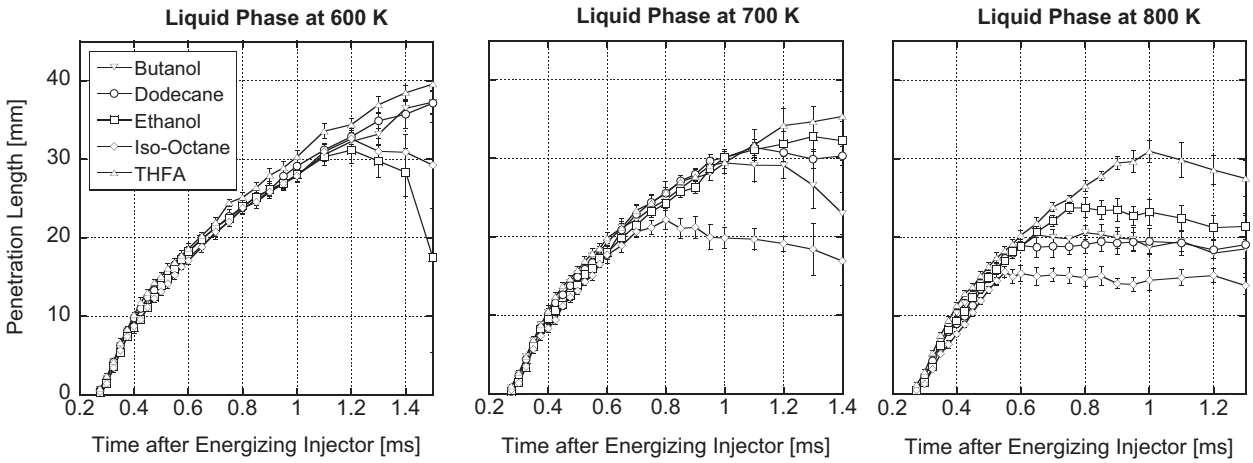

Figure 7. Penetration of the liquid phase for different ambient temperatures.

A comparison of the stationary penetration length between the two cases 600 and 700 K shows, that the penetration length of Ethanol rises with higher ambient temperature. As indicator for this phenomenon, the cavitation number may be used. From Figure 6 it can be seen, that especially Ethanol shows an increase of the cavitation number for fuel temperatures above 400 K. However, as the fuel temperature has not been measured in this study, this effect needs to be clarified in the future. In addition the measurements at 800 K show a significant influence of the heat of vaporization on the penetration length of Ethanol: Taking only the hydrodynamic properties into account Ethanol should have a shorter penetration length than Dodecane and Butanol because of its high Weber number. But due to its high heat of vaporization Ethanol has a longer stationary penetration length.

Summary

Especially the evaporation and the atomization behaviour and therefore the stationary penetration length of the liquid phase are affected by the variation of the fuel properties. The penetration length of the vapor phase remains

largely unaffected. Particularly the furan Tetrahydrofurfuryl Alcohol (THFA) shows a different characteristic in mixture formation as compared to conventional fuels. In the near future these conclusions will be verified by a complementary investigation using Phase Doppler Anemometry.

Acknowledgment

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Nomenclature

d	diameter	
p	pressure	
v	velocity	
η	viscosity	
ρ	density	
σ	surface tension	
We	Weber number	$We = \rho_l \cdot v^2 \cdot d_{noz} / \sigma_l$
Re	Reynolds number	$Re = \rho_l \cdot v \cdot d_{noz} / \eta_l$
Oh	Ohnesorge number	$Oh = \sqrt{We} / Re$
Ca	Cavitation number	$Ca = (p_{inj} - p_{ch}) / (p_{ch} - p_{vap})$
ρ^*	Density Ratio	$\rho^* = \rho_g / \rho_l$

Subscripts

ch	chamber
inj	injection
l	liquid
g	gas
vap	vapor

References

1. Ahmed, A., Ejim, C.E., Fleck, B. Amirfazli, A., *Effect of Biodiesel Fuel Properties and Its Blends on Atomization*, SAE paper 2006-01-0893 (2006).
2. Higgins, B. S., Mueller, C. J., Siebers, D. L., *Measurements of Fuel Effects on Liquid-Phase Penetration in Di Sprays*, SAE paper 1999-01-0519 (1999).
3. Grimaldi, C. N., Postrioti, L., *Experimental Comparison Between Conventional and Bio-Derived Fuels Sprays From a Common-Rail Injection System*, SAE paper 2000-01-1252 (2000).
4. Li, L., 2006, *Experimental Study of Biodiesel Spay and Combustion Characteristics*, SAE paper 2006-01-3250 (2006).
5. Chang, C., and Farrell, P., *A Study on the Effects of Fuel Viscosity and Nozzle Geometry on High Injection Pressure Diesel Spray Characteristics*, SAE paper 970353 (1997).
6. Desantes, J. M., Arregle, J., Pastor, J. V., Delage, A., *Influence of the Fuel Characteristics on the Injection Process in a D.I. Diesel Engine*, SAE paper 980802 (1998).
7. Yule, A. J., Akhtar P., Shrimpton, J. S., Wagner, T., Rickeard, D. J., Duff, J. L., *PDA Measurements of Fuel Effects on Atomization and Spray Structure From a Diesel Engine Injector*, SAE paper 982544 (1998).
8. Stan, C. C., Troeger, R., Grimaldi, C. N., Postrioti, L., *Direct Injection of Variable Gasoline/Methanol Mixtures: Injection and Spray Characteristics*, SAE paper 2001-01-0966 (2001).
9. Araneo, L., Coghe, A., Brunello, A., Donde, R., *Effects of Fuel Temperature and Ambient Pressure on a GDI Swirled Injector Spray*, SAE 2000-01-1901 (2000).
10. Daubert, T. E., Danner, R. P., *Physical and thermodynamic properties of pure chemicals*, Hemisphere Pub. Corp. New York (1994).
11. Reitz R. D., *Atomization and other breakup regimes of a liquid jet.* PhD thesis. Princeton Univ. (1978).