

## The Influence of Fuel Properties on Spray Propagation, Atomization and Evaporation

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### Abstract

Understanding the relationship between physical properties and spray behavior is essential for the development of future synthetic diesel fuels. Therefore, in the present work the fuel influence on the spatial and temporal spray structure is studied experimentally using multiple methods. The macroscopic spray propagation is investigated by means of visualization measurements. Additionally, a two component PDA is used for a simultaneous study of the velocity field and the particle size distribution at different axial and radial positions inside the spray. A parametric study is conducted on the effects of fuel properties. Specific fuels of various substance classes were chosen to represent a wide range of potential synthetic fuels. In detail, Butanol, Ethanol, Dodecane, Iso-Octane and Tetrahydrofurfuryl Alcohol are analyzed. In order to quantify the influence of evaporation on the droplet size reduction the investigations are performed under different ambient conditions. A significant influence of the hydrodynamic and thermodynamic properties on the macroscopic and microscopic spray structure is detectable. As previously known, close to the nozzle the droplet size is mainly controlled by surface tension, density ratio and viscosity through primary and secondary breakup. It was found that further downstream the fuel properties relevant for evaporation are the main factors for further droplet size reduction.

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### Introduction

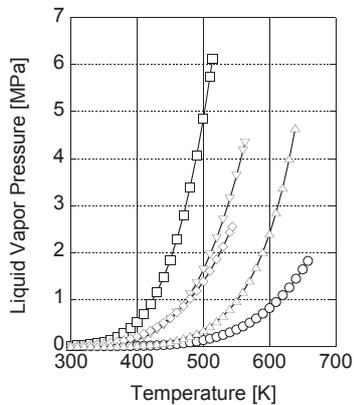
World-wide increasing carbon dioxide emissions, a rising energy demand and limited availability of fossil energy resources constitute major challenges today's societies are facing. In this context the project 'Tailor Made Fuels from Biomass' takes an interdisciplinary and inverse research approach towards 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 behavior. As a prerequisite to the engine combustion process, the injection system and the related strategy need to be adapted to the potential fuel properties. Besides 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 fuel properties 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 Postriotti [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 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.

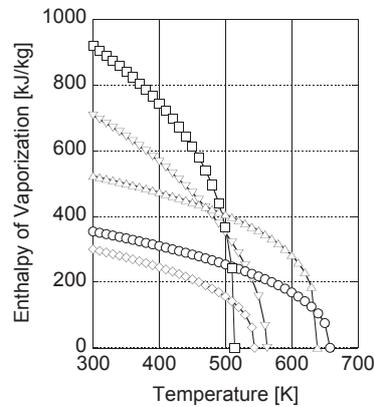
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## Materials and Methods

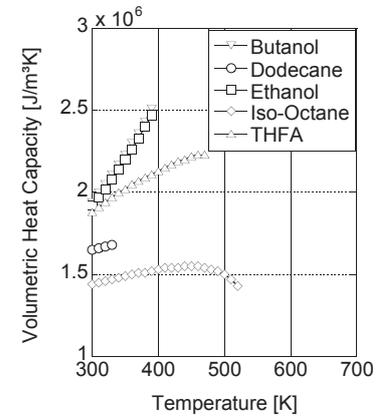
In this work the influence of fuel parameters on spray propagation, atomization and evaporation is investigated using Butanol, Ethanol, Dodecane, Iso-Octane and Tetrahydrofurfuryl Alcohol (THFA) as fuels for covering a wide range of chemical properties, see figures 1 to 6. The corresponding sprays are investigated with complementary



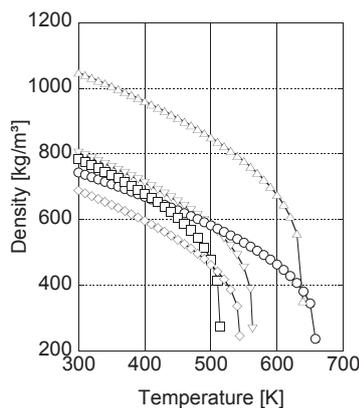
**Figure 1.** Vapor pressure, see Daubert and Danner [10].



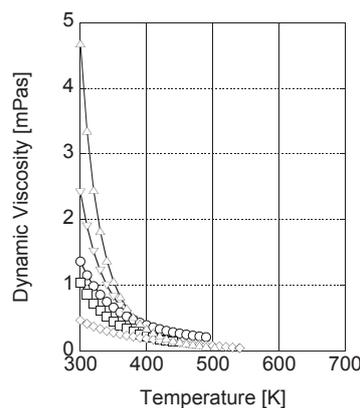
**Figure 2.** Heat of vaporization, see Daubert and Danner [10].



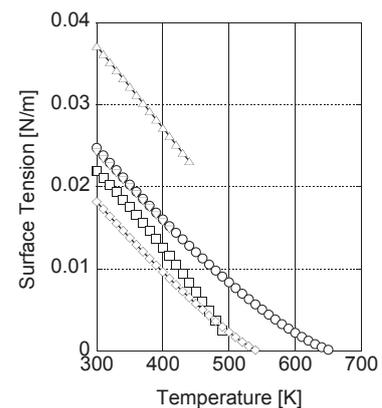
**Figure 3.** Volumetric heat capacity, see Daubert and Danner [10].



**Figure 4.** Density, see Daubert and Danner [10].



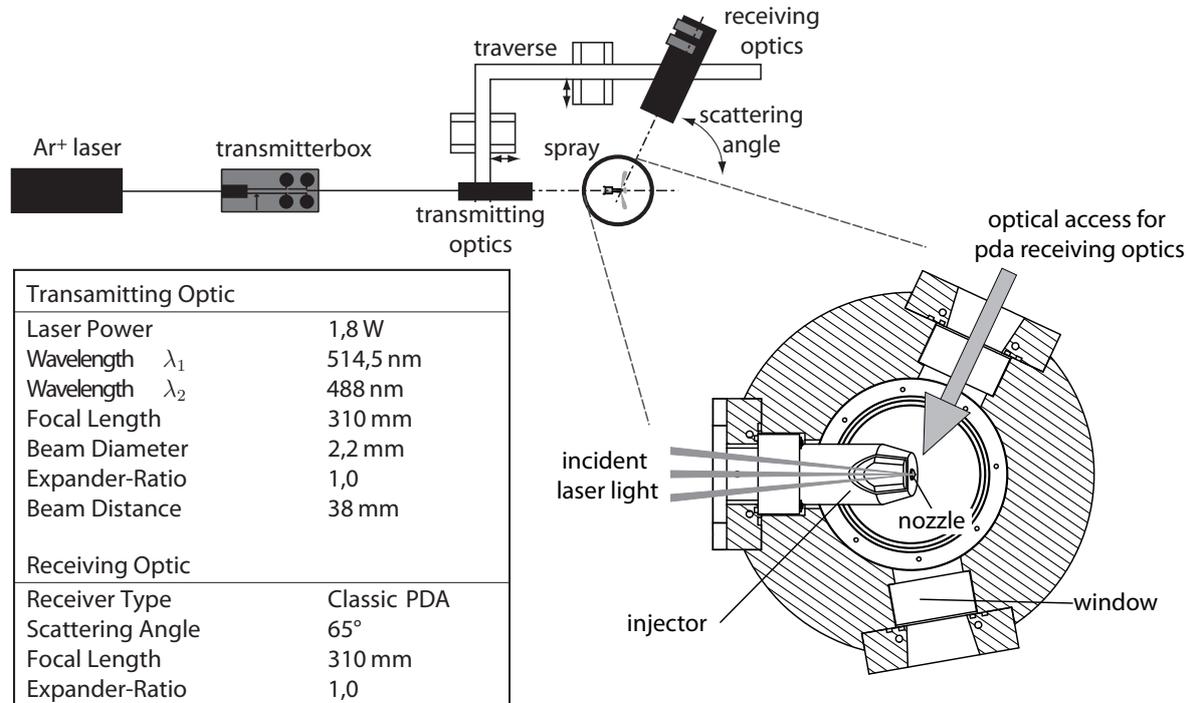
**Figure 5.** Dynamic viscosity, see Daubert and Danner [10].



**Figure 6.** Surface tension, see Daubert and Danner [10].

measurement systems. In detail, visualization measurements and phase doppler measurements provide macroscopical and microscopical information. The diesel set-up is composed of a pressurized chamber and a diesel common rail injection system. For basic investigations on fuel spray behavior, optically accessible pressurized vessels are used as test facilities as shown in Figure 7. 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 600 and 800 K and a pressure of 3 and 5 MPa. A continuous air flow of about 20 m<sup>3</sup>/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 μs. The injector is orientated in the chamber so that one spray of the 8-hole piezo diesel injector (Bosch) penetrates in vertical direction. The nozzle orifice diameter is 109 μm. Two different chamber configurations are used. For visualization measurements the chamber configuration 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 defocused 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 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. For additional information, see Reddemann et al. [11].



**Figure 7.** Experimental set-up for pda measurements.

Measurements of the droplet diameters and their velocities are conducted by PDA as shown in Figure 7. The transmitting and receiving optics are mounted on an automated traverse which allows for accurately positioning the measurement volume. Different planes can be measured by adjusting the chamber elevation. The data rate (counts per second) is responsible for the effective measurement range in sprays. Only a high data rate ensures a sufficient statistical accuracy for PDA measurements. In order to achieve an adequate data rate and therefore comparability for all investigated fuels the measurement planes have been set to 20 mm, 24 mm and 28 mm axial distance. However, in some cases the measurements are not possible due to a low data rate, hence the results for this fuel and operation point won't show up in the diagrams.

## Results and Discussion

In the following the measured penetration lengths, droplet size and velocity distributions are used to understand the fuel dependence of spray phenomena in detail. It must be pointed out that spray phenomena are coupled to each other. Considering conditions relevant for a diesel engine, the droplet size distribution depends on both vaporization and liquid breakup. On the one hand fuel properties relevant for vaporization affect the mean droplet temperature and on the other hand fuel properties relevant for breakup are temperature dependent. Neglecting this effect leads to misinterpretations with regards to measurement values. Unfortunately, only few quantitative experimental data on the liquid phase temperature field for engine related diesel sprays can be found in literature (see Megahed [12] and Wolff et al. [13]).

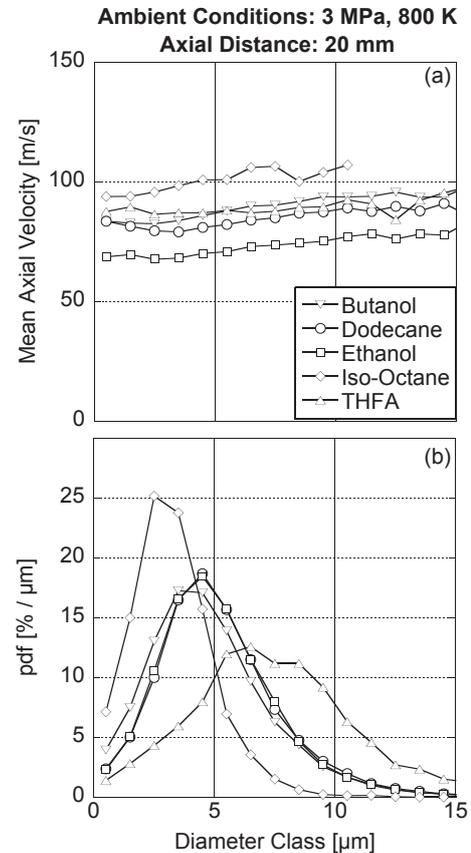
The PDA principle relies on single particles passing through the measurement volume in order to avoid falsifications of the scattered light. Overlapped scattering signals due to multiple droplets in the measurement volume are refused by the PDA processor which leads to reduced data rates in regions with high droplet concentration and strong optical density. To ensure a sufficient data rate for all investigated fuels the measurements are performed far from the nozzle. For this spray region figure 8 (a) shows the velocity change over diameter on the spray axis exemplarily for one operation point. The mean velocity variation of each fuel in this diameter range

is below 15 %. This low variation is detectable in the whole measurement region for every operation point, even at the spray edge. However, depending on the fuel dependent droplet size distributions, as indicated in figure 8 (b), one would expect a stronger change of velocity with droplet diameter. Instead, the momentum exchange of droplets seems to be mainly completed for every fuel. An explanation could be based upon two approaches: (1) Assuming that the mean velocity of the ambient air is represented by the mean velocity of the smallest droplets due to their small response time to disturbances, see Sánchez et al. [14] a conclusion follows: The relative velocity and therefore the mean droplet Weber number  $We = \rho_G du_{rel}^2 / \sigma$  is small for all droplet sizes and therefore the breakup probability is small. (2) It can be assumed that the strong droplet interaction leads to a harmonization of the droplet velocities due to deformation, oscillation, breakup or coalescence. The higher the ambient pressure the more relevant is the bouncing regime, see Quian and Law [15]. Typically, the liquid breakup due to aerodynamic forces takes place at the edge and the tip of the spray. Inside the spray the droplet interaction predominates. For the PDA measurements one can conclude that in the spray region under consideration the liquid breakup due to aerodynamic forces is largely completed and further droplet size reduction depends mainly on vaporization and droplet interaction.

The vaporization process is based on evaporation or (flash) boiling. Boiling occurs when the ambient pressure is smaller than the droplet temperature dependent liquid vapor pressure. In this context the boiling probability for short-chain alcohols (e.g. Ethanol) is higher than for alkanes as shown in figure 1. However, usually diesel evaporation is determined by the surrounded pressure and temperature fields. Therefore, the behavior of the investigated fuels will be analysed in the following with respect to evaporation. Even though combustion chambers are operated at ambient conditions which may be above the critical point with respect to the injected fluid, fuels usually don't reach their critical point: On the one hand the low spray entrance temperature and its subsequent evaporation causes a cooling of the entrained air in the boundary layer of droplets and on the other hand the fuel vapor concentration in the region of strong evaporation (at the spray edge) is small.

The evaporation of droplets is characterized by a heating process leading to an equilibrium temperature, where the same amount of energy is delivered through convection as is needed for vaporization. However, the concentration field around a single droplet changes temporally and spatially over its lifetime and therefore the droplet temperature changes, too. The heating process of a droplet with constant diameter and therefore the change of its internal energy depends on its volumetric heat capacity, shown in figure 3 for the investigated fuels. Figure 3 leads to the conclusion, that a given variation of the internal energy causes a higher temperature change for the n-alkanes than for the alcohols. In other words, more energy is needed to heat up alcohols to a certain temperature than alkanes. The temporal relevance of the heating process for the whole evaporation process depends on the ambient conditions. However, the equilibrium temperature is the main indicator for the evaporation behavior of a fuel. It depends on the ambient conditions and on the fuel parameters. Its value is mostly influenced by the enthalpy of vaporization, shown in figure 2. Especially the alcohols (e.g. Ethanol) show high enthalpies of vaporization and therefore a comparatively low equilibrium temperature can be expected. It may be concluded that the relevance of the heating process for the whole evaporation is larger for Dodecane and Iso-Octane than for Ethanol.

Besides the thermodynamic properties the evaporation time is mainly influenced by the initial droplet diameter. Smaller droplets lead to an increased heat and mass transfer due to a larger effective surface. Thus, the fuel properties relevant for liquid breakup have to be considered: density, viscosity and surface tension. The liquid breakup due to turbulence and aerodynamic forces can be subdivided in the primary and secondary breakup. The relevance of the fuel properties for the primary breakup close to the nozzle decreases with increased turbulence, therefore the influence of the primary breakup on the droplet size distribution is not considered in this work. Over



**Figure 8.** Mean axial Velocity on the spray axis depending on diameter class (a) and droplet size distribution (b).

a wide range of Ohnesorge numbers ( $Oh < 0.1$ ) the liquid viscosity has little influence on the secondary breakup of droplets, see Hsiang and Faeth [16]. Only close to the critical point, the Ohnesorge number increases rapidly as the surface tension approaches zero. However, the stabilizing effect of the surface tension (as part of the Weber number) seems to be the most important fuel parameter for the secondary breakup.

Figure 9 shows the influence of ambient conditions and fuel properties on the radial velocity distribution in the quasistationary region of the spray 20 mm downstream the nozzle. As expected, the mean axial droplet velocity increases with decreasing ambient density because of less aerodynamic forces and a higher outlet velocity. Additionally the influence of the fuel properties on the velocity variation reduces with increased ambient density (the curves move together). Both Iso-Octane and THFA are characterized by a high axial velocity even though

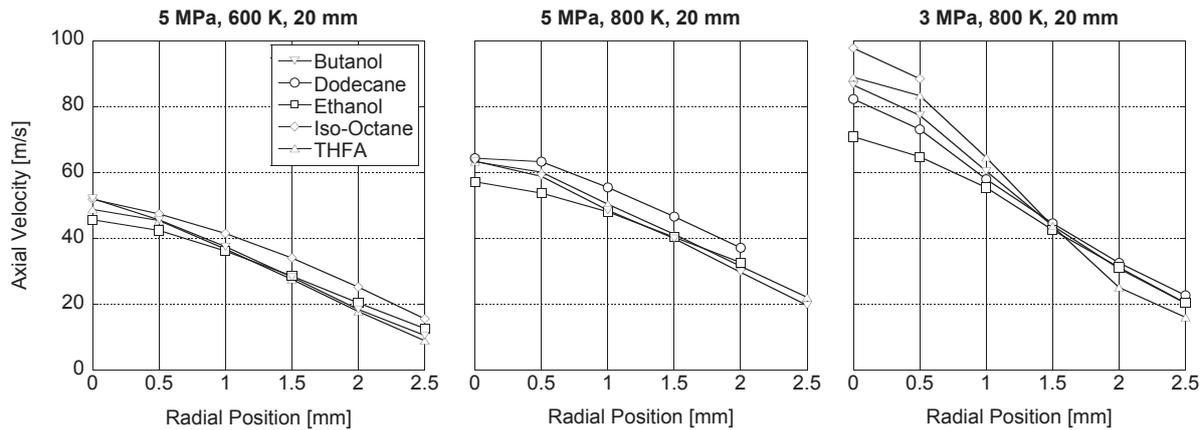


Figure 9. Axial Velocity for different ambient conditions.

they have oppositional fuel properties. Iso-Octane has the lowest and THFA the highest density of all investigated fuels, see figure 4. On the one hand a low density leads to a high outlet velocity (following the Bernoulli law) and on the other hand to a strong deceleration of the droplets due to aerodynamic forces. Following the assumption that aerodynamic forces affect the spray core by means of droplet interaction both effects neutralize each other depending on the axial position. Ethanol always shows the smallest axial velocity of all investigated fuels. Besides the liquid density a reason could be cavitation in the nozzle hole due to its high vapor pressure, which leads to a smaller effective flow cross section and therefore a lower effective mass flow rate and momentum transfer. This needs to be clarified in the future.

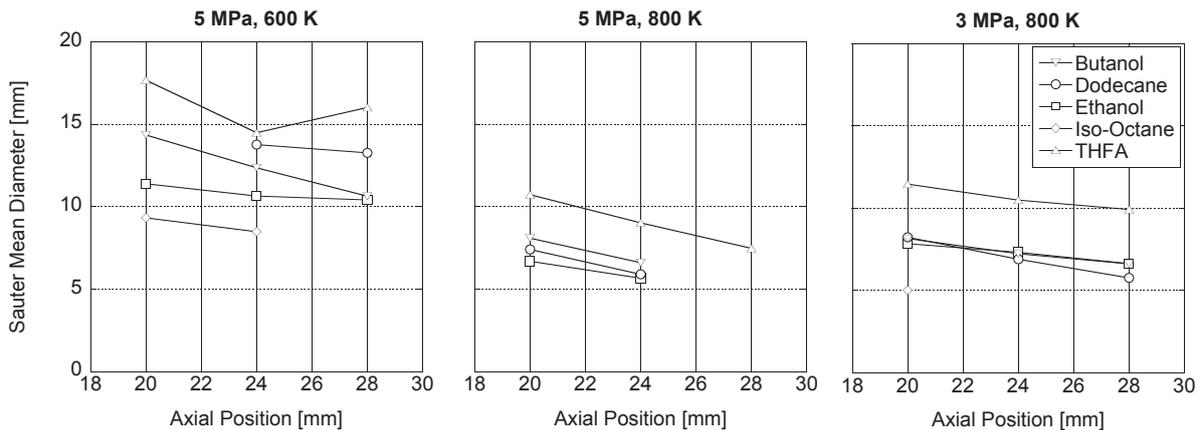


Figure 10. Sauter mean diameter on the spray axis for different ambient conditions.

Figure 10 shows the mean Sauter diameter on the spray axis. For THFA the combination of less-pronounced atomization due to a high surface tension and slow evaporation (due to a high density) leads to the biggest droplets compared to the other fuels. For 600 K THFA shows an increase in mean droplet diameter with axial distance. A reason could be coalescence due to the high surface tension of this fuel. On the other hand Ethanol has the smallest droplets by reason of its small surface tension. One can conclude that the surface tension is the most relevant

parameter for the initial droplet diameter whereas further diameter reduction mainly depends on the thermodynamic properties. Especially for Ethanol the reduction of the droplet diameter is lower than for the other fuels due to its high enthalpy of vaporization. The low evaporation rate leads to a comparatively long penetration length of the spray tip, as shown in figure 11. The change of the ambient temperature from 600 to 800 K results in a significant effect. Especially for Dodecane the temperature change induces a strong droplet diameter change. For lower temperatures Dodecane is characterized by a slow evaporation due to its small vapor pressure. With the change of the ambient temperature to 800 K, on the basis of the fuel parameters one would expect a strong droplet temperature change for Dodecane. Assuming the evaporation rate is mainly influenced by the temperature difference between critical point and droplet temperature of the fuel this temperature change results in an increased evaporation. Contrary to Dodecane, the temperature change of Ethanol is smaller because of its strong change of enthalpy of vaporization with temperature, see figure 2. There is only a slight change of the vapor pressure and therefore of the evaporation time.

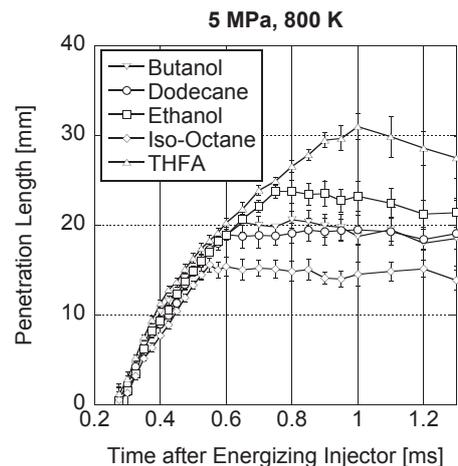


Figure 11. Liquid penetration length.

## Conclusion

For the interpretation of the fuel spray behavior the temperature dependence of the fuel properties respectively the fuel dependence of the droplet temperature have to be considered. The fuel parameter variation at room temperature doesn't necessarily give information about the variation in sprays. Additionally, the liquid spray temperature is the most important boundary condition to be known. This temperature strongly influences the Weber and Ohnesorge number relevant for breakup and the evaporation behavior. It has been shown, that different fuel temperatures due to variable ambient conditions could lead to oppositional evaporation and breakup effects. Thus, the determination of the fuel temperature in engine related diesel sprays is an important task for the future.

## Acknowledgement

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