

An Experimental Investigation on the Evaporation Characteristics of a Two-Component Fuel in Diesel-Like Sprays

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ABSTRACT

Tailor-made multi-component fuels are currently being developed for advanced Diesel engines. Accordingly, there is renewed interest in the detailed evaporation characteristics of such multi-component fuels, in particular because soot formation in reacting Diesel sprays generally depends on the mixture formation upstream of the lift-off location. It is also well established that fuel components with different volatility are generally not coevaporative due to fractional distillation in the mixture formation process of spark-ignition engines, but it is not clear if this holds for Diesel-like sprays, in which evaporation and mixing are expected to be more rapid. Unfortunately, little work has been done in this field, and some of the previous results appear to be contradictory.

This paper presents a new laser diagnostic approach, which yields the vapor-phase concentrations of two fuel components simultaneously in Diesel-like sprays. Thus, preferential evaporation of different fuel components can be studied for two-component fuels, namely mixtures of an alkane and an alcohol (without any additives). This technique is first applied to a mixture of ethanol and isooctane, because the evaporation of these two components was found to be significantly different in Diesel-like single-component fuel sprays previously. Thus, preferential evaporation might be expected particularly for the isooctane-ethanol blend. However, the results show that these components are essentially coevaporative in the investigated Diesel-like sprays.

The new diagnostic approach is based on 1-d spontaneous Raman scattering. It is described in detail in the paper. This technique also yields the total stoichiometric ratio and the

temperature in the vapor phase, so that the air-fuel mixture can be characterized more completely. The measurements are conducted in a high-temperature, high-pressure vessel under approximately engine-relevant conditions. The investigated Diesel-like sprays are emanating from a state-of-the-art piezo injector. The fuel-rail pressure and injection duration are varied. The results also lead to conclusions on soot formation in Diesel-like sprays.

INTRODUCTION

The evaporation of Diesel-like sprays was previously investigated by modern experimental and numerical methods, e.g. in Ref. [1]. However, single-component model fuels were used in most of these detailed studies. Tailor-made multi-component fuels are currently being developed for advanced Diesel engines, as discussed in Refs. [2,3] and the references therein. Accordingly, there is renewed interest in the detailed evaporation characteristics of such multi-component fuels, in particular because soot formation in reacting Diesel sprays generally depends on the mixture formation upstream of the lift-off location [3, 4, 5].

It is also well established that fuel components with different volatility are generally not coevaporative due to fractional distillation in the mixture formation process of spark-ignition engines [6, 7, 8, 9, 10, 11], but it is not clear if this holds for Diesel-like sprays, in which evaporation and mixing are expected to be more rapid. Unfortunately, little work has been done in this field, and some of the previous results appear to be contradictory. On the one hand, time-averaged measurements of the quasi-steady liquid-phase penetration length of multi-component fuels showed that it is controlled by its lower volatility fractions, suggesting that evaporation occurs in a batch distillation mode [12]. On the other hand,

ensemble-averaged visualization of a number of fuel components with significantly different volatility in the unsteady vapor phase indicated that the components were coevaporative, because their distributions appeared to be very similar [13]. However, the measurements of the liquid-phase fuel by imaging of Mie-scattered light described in Ref. [12], and qualitative visualization of fuel components by PLIF (planar laser-induced fluorescence) as demonstrated in Ref. [13] essentially only yield the outer boundary of the distributions of the liquid-phase, or vapor-phase fuel, respectively. Quantitative measurements of the fuel-air ratio by PLIF are generally very difficult in the Diesel environment as discussed in Ref. [13] and the references therein. Thus, the quantitative concentrations of different fuel components in the vapor phase could not be determined in these previous experiments.

This paper presents a new diagnostic approach, which is based on spontaneous Raman scattering (SRS). It yields the quantitative concentrations of both fuel components in the vapor phase for alkane-alcohol blends. Nonideal behavior in the liquid phase is generally expected for evaporating mixtures of a nonpolar and a polar component [15, 16, 17] and references therein.

Quantitative fuel concentration measurements by SRS in Diesel-like, single-component fuel sprays were previously presented in Refs. [1, 13, 14] and the references therein. Simultaneous measurements of two fuel components are achieved in the current work by exploiting the CH- and the OH-stretching SRS lines. The CH line arises from both molecular species, whereas the OH line represents the alcohol only. The stoichiometric ratio is quantified by simultaneously recording the N₂-SRS line. The vapor-phase temperature can also be determined simultaneously by this diagnostic via the total density of fuel and air, without assuming adiabatic mixing [13]. The OH-SRS signals of alcohols were previously exploited for vapor concentration measurements in the vicinity of droplets and droplet thermometry in single-component droplet streams and sprays [1, 14, 18].

The new diagnostic approach is first applied to a fuel mixture of 50% isooctane and 50% ethanol by volume. This blend is chosen because it was demonstrated by liquid length measurements that the evaporation of comparable neat isooctane sprays is significantly more rapid as compared to ethanol sprays [19]. This can be basically explained by the significantly higher heat of vaporization of ethanol [19, 20]. Thus, one might expect preferential evaporation of isooctane in the two-component spray [12, 20]. The fuel injection system and the engine-like conditions of the surrounding air in the current work are very similar to those applied in Ref. [19]. The present measurements can also be compared to a comprehensive study on similar neat-ethanol sprays, which were investigated partly under the same ambient conditions

as in the current work [1] (it should be noted that the current mixture of 50% ethanol and 50% isooctane by volume contains 73.9% alcohol and 26.1% isooctane by the number of molecules).

EXPERIMENTAL

Non-reacting sprays are investigated under ambient-air conditions of 700 K and 43.8 bar in a vessel. The temperature inside the chamber is measured using two thermocouples. The temperature variability without injection is about ± 5 K. The Diesel-like sprays are emanating from a state-of-the-art piezo injector (Bosch, third generation), which is equipped with a three-hole nozzle (orifice diameter 99 μm , k-factor 1.5, degree of HE grinding 10.5%, hydraulic flow 93 cm³/30 s/100 bar). The fuel-rail pressure is set to 600 or 900 bar, and the energizing time of the injector is 400 μs , or 1400 μs , respectively. The optically-accessible vessel is described in detail elsewhere [21].

The measurement system is very similar to the one used for SRS measurements in Diesel-like n-decane sprays [13]. It is illustrated in Fig. 1. The rectangular laser beam of a KrF excimer laser is focused by a spherical lens ($f = 2$ m) and a cylindrical lens ($f = 1$ m). The laser axis is directed perpendicularly through the spray axis. The focus is located several centimeters behind the vessel to avoid ignition and gas breakdown in the probe area as well as damage of the windows. Since the vessel is mounted on a moveable table every spatial position of the spray can be investigated without realigning optics. A 36 mm long section of the focused laser beam in the spray is imaged onto the entrance slit of an imaging spectrograph (aperture $f/4$, resolution 0.1 nm) by two spherical lenses ($f = 300$ mm and $f = 150$ mm) with a demagnification of about 2:1. The scattered light passes a liquid, long-pass butyl-acetate filter in front of the spectrometer with a thickness of 10 mm to reduce the Rayleigh signal. An image-intensified CCD-camera (Lavisision, 1280 $\times$ 1024 pixels without hardware binning) is mounted in the exit plane of the spectrograph. One dimension of the CCD-chip (1024 rows) corresponds to the spectral axis while the other one (1280 columns) yields spatial resolution along the imaged section. For the stoichiometric ratio calibration the relative SRS cross-sections of ethanol and isooctane in relation to the SRS cross-section of N₂ are measured by recording a SRS-spectrum of a saturated nitrogen / hydrocarbon mixture in a stabilized calibration cell, which can be mounted inside the vessel. Thus, the calibration data are acquired without any changes of the measurement system. The spatial resolution in the direction of observation is limited by the 2 mm depth, y , of the laser beam. The spatial resolution along the laser beam axis is determined empirically to be at least about 0.5 mm by analyzing the intensity change along this direction associated with an illuminated very small object in the focal plane. The height of the probe volume (1 mm) is determined by the demagnification and the entrance

slit of the spectrometer (500 μm). A typical ICCD-image, that is averaged over 25 injections ($p_{\text{rail}} = 600$ bar at $t_{\text{aci}} = 700$ μs), is shown in Fig. 2. It is measured at a nozzle distance of $z = 20$ mm. The measurement is conducted in the droplet-free region. The liquid length is discussed below. The horizontal axis of the image corresponds to the horizontal extension of the probe volume. Its vertical axis corresponds to the emission wavelength. The region of the fuel jet is characterized basically by increased Rayleigh scattering and hydrocarbon SRS. Basically two lines arise from hydrocarbon SRS in the present work as shown in Fig. 2. The CH-stretching line (at about 268 nm) represents both hydrocarbons, whereas the OH-stretching line (at about 273 nm) arises from ethanol only. The concentrations of both hydrocarbons can be measured simultaneously, because the intensity ratio of the CH and OH lines is determined for neat ethanol in the calibration procedure described previously.

Fig. 2 also shows that some of the ambient air is probed on both sides of the jet. It is used for calibration of the temperature measurements. A vertical profile of the image in Fig. 2 averaged over 1.0 mm around the spray axis yields an emission spectrum, which shows the SRS lines in more detail. It is depicted in Fig. 3. The spectrum shows that the ensemble-averaged measurements are essentially shot-noise free [13]. (Recall that the relative error induced by shot-noise is $1/\sqrt{N}$, where N is the number of photoelectrons generated in the image intensifier. Thus, it is negligible for very strong signals.) However, Fig. 3 also shows that there is some cross-talk of the N_2 - and CH-stretching lines, which is taken into account in the data reduction procedure.

Fig. 2 and Fig. 3 also show that some laser-induced predissociative fluorescence (LIPF) of oxygen is detected in the present experiment, which is discussed in detail elsewhere [13]. It can hardly be avoided due to the broadband portion of the laser light. Thus, there is also an O_2 -LIPF line at an emission wavelength of 267 nm, which interferes with the CH-SRS line. However, the intensity of this LIPF line at 267 nm is very similar to the interference-free line at 277 nm, [13] and references therein. Thus, the interference of the LIPF line at 267 nm and the CH-SRS line is negligible, as illustrated in Fig. 3.

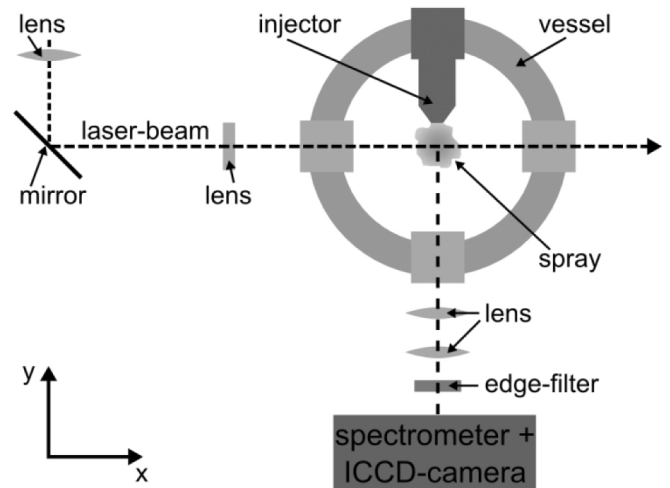


Fig. 1. Optical set-up for acquisition of the 1-d SRS spectra. The injector is equipped with a 3-hole nozzle. The axis of the investigated spray (z) is perpendicular to the paper.

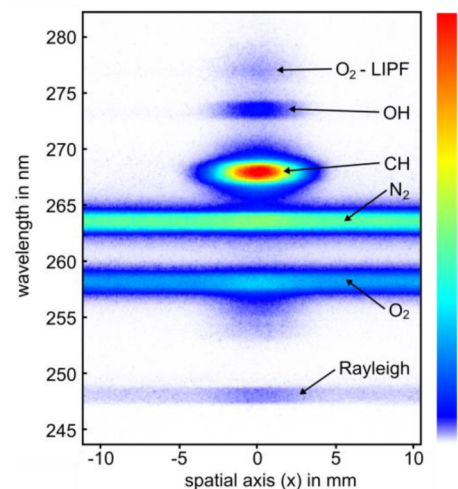


Fig. 2. Typical raw ICCD-image, averaged over 25 injections ($p_{\text{rail}} = 600$ bar, $t_{\text{aci}} = 700$ μs , $h = 20$ mm, ET 400 μs). The “CH”-SRS signal arises from the CH groups of isooctane and ethanol, whereas the “OH”-SRS signal arises solely from ethanol.

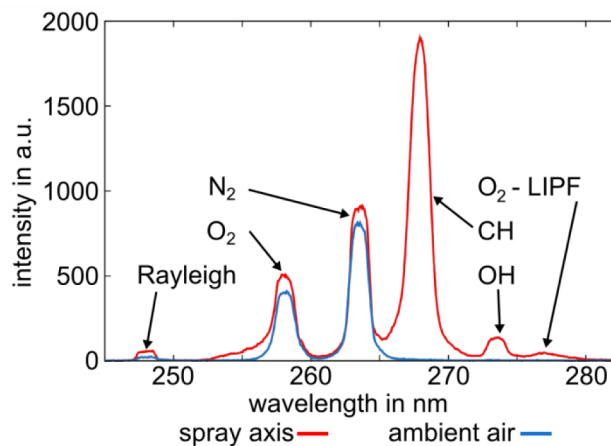


Fig. 3. Spectra of the raw image in Fig. 1. The graph shows a spectrum on the spray axis (red, averaged over 1 mm) and one outside the spray, containing only signals from ambient air (blue, averaged over 1 mm).

DATA REDUCTION AND MEASUREMENT UNCERTAINTIES

The local air density is determined by exploiting the intensity of the N₂-SRS line, because the O₂-SRS line is affected by interfering hydrocarbon-SRS and O₂-LIPF emissions [13]. The intensities of the N₂-, CH- stretching and OH-stretching SRS lines are determined by essentially integrating over the full line widths, in order to reduce the shot noise of the single-shot measurements. For the same reason the SRS signals are averaged over spatial elements with a length of 1 mm along the axis of the 1-d probe volume. The spatial resolution of these measurements is therefore different in the three dimensions (x, y, z): 1 mm × 2 mm × 1 mm. The temperature and the other desired quantities, which are described in the following, are determined for each single-shot measurement before averaging in order to avoid averaging errors [22]. Knowing the condition of the ambient air of the spray, a single-shot based self-calibration is possible, and so the data are not affected by laser fluctuations. The total air density inside the spray is calculated via the relative N₂ changes as compared to the ambient air. Then the temperature is determined via the total density of fuel and air and the ideal gas law as noted previously [13].

The total stoichiometric ratio, λ , is defined as follows:

$$\lambda = \frac{[O_2]}{[O_2]_{sto}} \quad (1)$$

Where $[O_2]$ is the local oxygen concentration, and $[O_2]_{sto}$ is the oxygen concentration required for stoichiometric combustion of the local fuel concentration according to

$$[O_2]_{sto} = [O_2]_{eth} + [O_2]_{iso} \quad (2)$$

where $[O_2]_{eth}$ and $[O_2]_{iso}$ are the oxygen concentrations required for stoichiometric combustion of the local concentrations of ethanol and isooctane, respectively.

Any preferential evaporation is characterized by the following coefficient:

$$C = \frac{[iso.]_l}{[eth.]_l} * \frac{[eth.]_l}{[iso.]_l} \quad (3)$$

where $[iso.]$ and $[eth.]$ are the local concentrations of isooctane and ethanol, respectively, and $[eth.]_l$ and $[iso.]_l$ are the concentrations of the two components in the liquid fuel before injection (by the number of molecules). Hence, C equals unity for coevaporative fuel components.

The shot-to-shot variability in the measured stoichiometric ratio is found to be in the range $\pm 5\%$ - $\pm 10\%$ on the spray axis close to the liquid length under quasi-steady spray conditions. Note that this variability is the result of true spray fluctuations *and* the single-shot measurement precision. This implies that the precision (relative error) of the single-shot λ measurements is in the same range there. A comparable λ variability was previously found on the axis of n-decane sprays in Ref. [13]. In principle, the accuracy (absolute error) of the ensemble-averaged λ measurements may be better due to the reduction of shot noise, but it also depends on the calibration procedure. Overall, the uncertainty in the averaged λ measurements can be estimated to be in the range $\pm 5\%$ - $\pm 10\%$.

The shot-to-shot variability in the measured temperature on the spray axis is about $\pm 3\%$ in the vicinity of the liquid length for quasi-steady sprays. Slightly higher variations were found under comparable conditions in n-decane sprays due to an interfering laser-induced fluorescence (LIF) background from low-temperature flame products [13]. In the present work, the precision of the single-shot measurements on the spray axis can therefore be estimated to be at least $\pm 3\%$, too. However, the precision of the ensemble-averaged temperature measurements is higher because shot noise is negligible and due to the calibration in the surrounding air outside the spray. Overall, the precision is estimated to be about $\pm 1\%$. This is confirmed by ensemble-averaged measurements in the vessel without fuel injection. It is noteworthy that very high measurement precision can be attained by the SRS technique under suitable conditions, if shot noise is suppressed by averaging, as demonstrated, for instance, in Ref. [18]. In the present application, acceptable precision is also found for single-shot measurements, basically due to the high particle density in the vessel. Accordingly, it was demonstrated