Ignition delay times of single kerosene droplets based on formaldehyde LIF detection
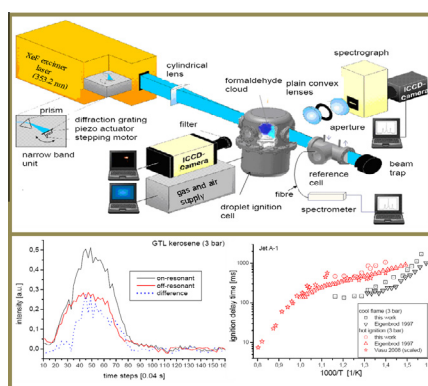
A. Burkert *, W. Paa

Leibniz Institute of Photonic Technology (IPHT), Albert-Einstein-Straße 9, Jena, Germany

HIGHLIGHTS

- Measurement of ignition delay times of single fuel droplets.
- Fuels: Jet A-1, GTL kerosene, Exxsol D80.
- Background corrected LIF images.
- Cold and hot ignition start by formaldehyde LIF appearance and depletion.
- Ignition delay times of cold and hot ignition.

GRAPHICAL ABSTRACT

ABSTRACT

Single droplet ignition experiments were performed with GTL kerosene, Jet A-1, and Exxsol D80 (reduced aromatics) in the temperature range from 550 to 900 K in air at 3 bar. The laser-induced fluorescence (LIF) intensities of liquid GTL kerosene and Exxsol D80 are on a lower level than that of Jet A-1. Formaldehyde LIF and background emission were measured with pulse-to-pulse wavelength switching at closely spaced excitation wavelengths (353.373 and 353.386 nm). Typically, formaldehyde LIF and background emission were observed simultaneously. However, in some droplet ignition sequences background emission was observed first followed by formaldehyde LIF after a time delay. Therefore, in the case of kerosene background subtraction has to be performed carefully to derive correct ignition delay times based on formaldehyde LIF (cool flame). A pulsating combustion was observed in several kerosene droplet ignition experiments. The cool flame ignition was found to appear significantly earlier for the synthetic GTL kerosene compared to Exxsol D80 and conventional Jet A-1 kerosenes. For GTL kerosene we found a cool flame ignition delay time of 624 ms, while corresponding values for Exxsol D80 and Jet A-1 amount to 1467 and 1699 ms, respectively. The differences for the starting time of hot ignition (around 1050 ms) and ignition temperatures (near 700 K) are comparatively small under the conditions of our experiments.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

The air pollution by airplanes includes among others the emission of CO_2, unburned hydrocarbons, water vapor and carbon-particulate matter which cause negative effects on the ozone layer.

The contribution of air traffic to the total environmental pollution is only on the order of three percent. However, with an annual growth rate of about 5% the air traffic becomes more and more important concerning air pollution prevention. Consequently its contribution is now also included into the emission trading [1].

One approach to reduce exhaust emission of airplanes is the use of synthetic fuels such as GTL (gas to liquid) and BTL (biomass to liquid) fuels. GTL [2,3] and BTL fuels are synthesized using the 'Fischer–Tropsch process'. To produce GTL kerosene natural gas is converted first into a synthetic gas. Then liquid hydrocarbons are built by adding oxygen and water vapor to this synthetic gas.

All kerosene fuels have to fulfill various requirements as, e.g., defined auto-ignition delay times. According to the review article of Aggarwal [4], presently there is a lack of measured auto-ignition delay data for real fuels. Auto-ignition delay times can be obtained with different techniques such as chemiluminescence detection [5], high-speed photography [6], Michelson interferometry [7,8], laser induced fluorescence formaldehyde measurements (LIF) of formaldehyde [9] as well as measurements in different experimental environments such as rapid compression engines [10], shock tubes [11] and combustion chambers [9]. Detailed information about experiments concerning auto-ignition delay times can be found in [12].

These measurement techniques are based on different physical/chemical processes. Auto-ignition delay times originating from chemiluminescence measurements (OH*, CH*) [5,13] are sensitive only to hot ignition. They typically give different values than measurements based on cool flame ignition. Formaldehyde LIF measurements show the start of the cool flame and, in a two stage ignition process with a strong intensity increase which is related e.g. to OH*, also that of the hot ignition [14,15]. Formaldehyde LIF disappears at the beginning of the hot ignition [15]. This characteristic was used for detection of knocking centers in internal combustion engines [16].

Additionally, we have to mention, that ignition delay times based on ground based droplet ignition measurements (formaldehyde LIF, Michelson interferometry) differ from micro-gravity experiments [8,15,27]. In ground based measurements higher local concentrations of gaseous fuel and consecutively also of formaldehyde were found below the fuel droplet at the beginning of the cool flame ignition. This often leads to slightly reduced ignition delay times [15] and is one reason for micro-gravity experiments. Additionally, formaldehyde LIF distributions under micro-gravity conditions are almost spherical symmetric which makes numerical simulations much easier. The comparison of measured formaldehyde-LIF distributions and ignition delay times with the results of simulations is a possibility to develop/verify reduced reaction kinetics. Consecutively this enables the simulation/optimization of complex combustion processes as e.g. internal combustion engines. In experiments often larger droplet diameters [7–9] are compared to technical sprays to make droplet ignition delay times experimentally measurable. This is justified, since scaling laws which relate ignition delay time to the inverse pressure [17,18] and droplet diameter [19] are available. The square of the droplet diameter is proportional to the fuel evaporation time. Increasing of the fuel temperature decreases the fuel evaporation time. The ignition delay time depends on pressure and temperature and can be expressed as an Arrhenius law. The ignition delay time is determined both by kinetics of the chemical reaction as well as physical processes as droplet heating and evaporation [20].

We investigated different types of kerosene (GTL kerosene from Shell, Jet A-1, and Exxsol D80) concerning their optical spectra and auto-ignition delay times. Exxsol D80 is a kerosene [21] with reduced aromatics which makes laser diagnostics easier due to less background emission. Here, we studied the ignition of single kerosene droplets in ground-based experiments using formaldehyde LIF with attention on background subtraction as well as the determination of ignition delay times.

2. Experimental

The experimental set-up for measurements of ignition delay times based on formaldehyde LIF is shown in Fig. 1. It consists of a double tube XeF excimer laser (Compex 150T from Lambda Physik, FWHM = 4 pm, 50 Hz, pulse length = 24 ns), a droplet ignition cell, a reference cell for wavelength control as well as two spectrometers [14,15]. The excimer laser which includes a narrow band and a pulse-to-pulse wavelength-switching unit was operated with 50 Hz pulse repetition rate. All droplet ignition experiments were performed with a fluence of 10 mJ/cm^2. Formaldehyde LIF was excited at 353.373 nm (vacuum wavelength). Measurements of the background emission were performed with 353.386 nm excitation. Due to pressure broadening a significant formaldehyde LIF contribution was also present at the background wavelength. This was corrected with a procedure which is described in [15]. This correction is based on reference measurements on pure formaldehyde/air. Several fused silica lenses (f_{total} = 1 m) were used to shape a laser light sheet of 40 mm height beside of the liquid fuel droplet in the droplet ignition cell. Additionally, the laser beam was guided through the reference cell. Gaseous formaldehyde which was created from para-formaldehyde [14,15] was pumped through this reference cell. Formaldehyde LIF spectra were measured in the reference cell using a HR2000 spectrometer (Ocean Optics).

The droplet ignition cell consisted of a lower fueling part which was kept at room temperature and above that an combustion chamber with a resist heater around it. This combustion chamber [22] has four optical windows for access of the laser beam and perpendicular to this for formaldehyde LIF detection with an ICCD camera (DALSA, CA-D1, 256 × 256 pixels, 8 bit dynamics; UV–VIS corrected optics f = 105 mm, UV-Nikkor, Barr 358 nm long-pass filter). The droplet holder (0.2 mm diameter sapphire sphere, see inset in Fig. 1 and [23]) was fueled in the lower part of the droplet ignition cell using a tiltable needle which was connected to the fuel reservoir (electrically moveable syringe). Starting an experiment, the droplet holder was moved up through a hole of 10 mm diameter in the bottom of the combustion chamber. In the combustion chamber the fuel heated up and evaporated. Formaldehyde was build as an combustion intermediate in the gas space around the droplet. The gaseous formaldehyde was excited close to the droplet in the laser light sheet (see inset in Fig. 1). The gas temperature
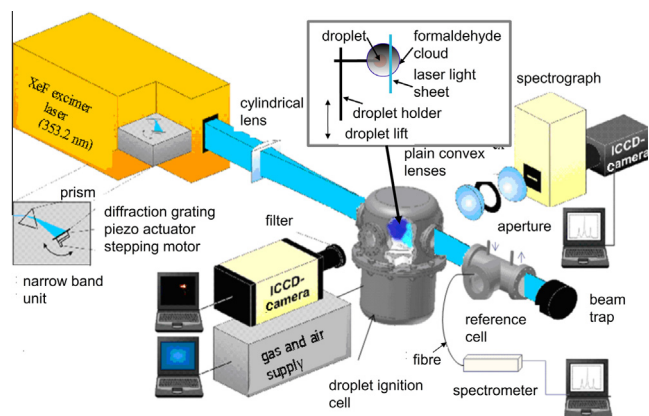

Fig. 1. Experimental set-up for formaldehyde LIF measurements around single igniting fuel droplets. The inset shows the droplet holder, the droplet, the formaldehyde cloud and the position of the laser light sheet.