

# Influence of In-Cylinder Air Flow on Spray Propagation

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## ABSTRACT

The influence of in-cylinder flow on the propagation of 2-Butanone and Ethanol sprays is studied. To solely evaluate the interaction of air flow and fuel, high-speed Mie-Scattering Imaging of hollow cone sprays is conducted both in a single-cylinder optical engine with tumble movement and in a pressure vessel with negligible air flow. The direct comparison reveals an improved spray propagation of 2-Butanone due to the engine's air flow. The lower viscosity of 2-Butanone causes an enhanced jet breakup compared to Ethanol such that the spray consists of more and smaller droplets. Small droplets possess a lower momentum, which allows the droplets to be more efficiently transported by the air flow. Consequently, the fuel distribution across the cylinder is enhanced. As the liquid fuel is distributed to a larger volume, improved convection accelerates evaporation. Finally, 2-Butanone is more volatile compared to Ethanol, which further improves evaporation, such that, 2-Butanone is considered a promising surrogate fuel for Ethanol and Gasoline.

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## INTRODUCTION

Modern biofuels allow sustainable energy consumption and an improved combustion process with low emissions [1, 2, 3]. While combustion of conventional fuels is accompanied by a significant amount of CO<sub>2</sub> emission, biofuels are designed with a high amount of molecular bonded oxygen that allows emission reduction [4]. In addition, biofuels possess a different behavior that allows a higher degree of freedom in controlling mixture formation and start of ignition [1, 5].

Several experimental studies available have investigated spray propagation and mixture formation of bio-fuels under gasoline direct injection conditions. While experiments in engines typically focus on performance and emissions [1, 2, 5, 6], experiments in less complex pressure vessels aim for an isolated study of the spray breakup and mixture formation [7, 8]. The latter type of experiments also allows detailed insight in the relationship of the physical fuel properties and spray propagation<sup>1</sup>. However, findings from pressure vessel experiments are not necessarily transferable to engine applications. While pressure flow vessels are almost free of air movement [9], engine air flow due to piston movement, valve movement, and supercharging is assumed to have a non-negligible influence on spray propagation.

Until now, only limited information on the interaction of in-cylinder air flow and biofuels under gasoline direct injection (GDI) conditions and the influence on the mixture formation is available. A previous study [10] indicates that fuel injection dominates the flow close to the nozzle outlet. However, the impact decays downstream of the nozzle,

where the tumble vortex, which is imprinted by the intake air flow, determines the spray distribution. Close to the nozzle outlet, high spray momentum of large liquid structures accelerates nearby air and causes subsequent air entrainment [7]. Further downstream of the nozzle outlet, the jet's momentum is reduced since the jet breaks up into droplets. Hence, in-cylinder air flow, i.e., the tumble movement, becomes a more effective transport mechanism. Since spray momentum and droplet size distribution are also predetermined by the physical fuel properties, the fuel influences air movement and spray propagation.

In this study, the fuel influence on liquid spray propagation with regard to the tumble movement of a GDI engine is studied in detail. The work is based on our previous investigations [10]. For an isolated consideration of the influence of in-cylinder air flow, high-speed Mie-Scattering Imaging (MSI) is conducted in an optical engine with tumble air flow and in a constant-pressure flow (CPF) vessel with negligible air flow. In general, the tumble vortex is the predominant vortical structure in most DISI engines, while most CI engines feature a swirl vortex [11].

The spray penetration and spray-cone angle of the measurements, which were conducted with and without the influence of air flow, are compared to qualitatively evaluate the suitability of both fuels under realistic engine conditions. Findings can be used either to adapt the air flow of the engine to the special characteristics of the fuel or to alter the fuel composition to the given air flow. At any rate, the engine's in-cylinder air flow may be used as an additional parameter to achieve a more homogeneous and wider fuel distribution across the cylinder, such that the mixture formation is enhanced.

1. Most notable fuel influences on mixture formation result from dynamic viscosity and the boiling point.

## RESEARCH METHODOLOGY

### Fuel Selection

Two fuels are selected for the experiments. Ethanol is chosen as reference, since it is a well established bio-fuel with high efficiency in GDI engines and a high-yield production path [12, 13]. 2-Butanone<sup>2</sup> is selected as a novel, promising gasoline surrogate [1, 14]. In single-cylinder engine experiments, 2-Butanone has already proven superior characteristics compared to Ethanol and Gasoline [1, 12, 15], since 2-Butanone features a high knocking resistance, good combustion stability, high ignition delay times, improved engine efficiency, and significant reduction in particle emissions. Production pathways of 2-Butanone are known to be similarly efficient to Ethanol [16, 17, 18] and sustainable since production is based on conversion of lignocellulose. Therefore, there is no interference with the food chain [19].

Table 1 displays the liquid fuel properties of Ethanol and 2-Butanone at standard conditions. Both biofuels feature the typical high amount of molecular bonded oxygen that allows for a significant reduction in combustion emissions. Higher engine efficiency of 2-Butanone is indicated by a higher heating value, while preferable knocking resistance can be deduced by the octane number. The lower heat of vaporization of 2-Butanone is a drawback in comparison to Ethanol, since charge cooling due to evaporation increases the volumetric efficiency [20, 21]. However, 2-Butanone still has a preferable heat of vaporization compared to Gasoline. Although both fuels are from different chemical families, their fuel properties are similar in density, surface tension, and boiling point. This similarity concerning the physical properties makes it easier to relate differences in spray propagation to either viscosity or volatility effects.

Table 1. Physical properties of Ethanol and 2-Butanone at standard conditions [22]. Octane numbers according to [23, 24].

| physical fuel property | unit              | symbol           | Ethanol                         | 2-Butanone                      |
|------------------------|-------------------|------------------|---------------------------------|---------------------------------|
| empirical formula      | -                 | -                | C <sub>2</sub> H <sub>6</sub> O | C <sub>4</sub> H <sub>8</sub> O |
| oxygen content         | mass-%            | CO <sub>2</sub>  | 34.7                            | 22.2                            |
| lower heating value    | MJ/kg             | LHN              | 26.84                           | 31.45                           |
| octane number          | -                 | RON              | 109                             | 117                             |
| density                | kg/m <sup>3</sup> | $\rho$           | 787                             | 799                             |
| dynamic viscosity      | mPas              | $\eta$           | 1.07                            | 0.40                            |
| surface tension        | mN/m              | $\sigma$         | 22.1                            | 23.9                            |
| boiling temperature    | K                 | T <sub>b</sub>   | 351                             | 353                             |
| heat of vaporization   | kJ/kg             | $\Delta H_{vap}$ | 920                             | 480                             |
| vapor pressure         | kPa               | P <sub>v</sub>   | 5.8                             | 10.8                            |

### Experimental Facilities

#### Chamber Test Rig without Air Flow

Investigations with negligible air flow are conducted in a constant-pressure flow (CPF) vessel (figure 1). The air moves constantly in the chamber from top to bottom with a flow velocity of less than 0.1 m/s.

The air can be heated and pressurized to simulate gasoline-like engine conditions. The temperature drop across the chamber remains below 10 K for all experiments<sup>3</sup>. Four optical accesses allow measurements in the CPF chamber. The injector is placed on the rotational axis in the chamber head such that the view through the optical access is identical from all sides. An outwardly opening piezo-injector is chosen for the experiments. The design half-cone angle accounts for 94°, maximum needle lift for 35  $\mu$ m, and the length of the annular channel between seat and needle is approximately 311  $\mu$ m. Mathieu et al. [7] showed that the maximum needle lift is reached after approximately 200  $\mu$ s. The injector is temperature controlled by a water circuit<sup>4</sup>. Since the injector features a small delay between signal output and nozzle opening, the two terms SOI and SOE are introduced. SOE describes the start of energizing, i.e., the output of the signal that initiates the start of injection, and SOI denotes the point in time when fuel starts leaving the nozzle. Nozzle exit velocity measurements have been conducted by Mathieu et al. [25] for Ethanol and other fuels, using the same injector.

Figure 1 shows the optical setup to visualize the hollow cone spray. In accordance with previous experiments that were conducted with this setup, Mie-Scattering Imaging (MSI) is chosen as the measurement technique to visualize solely the liquid spray phase. The continuous wave (CW) light beam of a diode laser with a wavelength of 532 nm is reshaped to a flat-top light sheet with a measured thickness of 0.3 mm and a height of 50 mm. The output power of the laser (90 mW, or rather 6 W/cm<sup>2</sup>) remains constant throughout the experiments. Since the injector is placed centrally in the chamber, the light sheet propagates through one optical access directly underneath the nozzle. The illuminated cut section of the spray shows two cross-section areas. Since the spray is assumed to be axisymmetric, just one half of the cut section is studied. Therefore, only the liquid spray phase close to the laser is collected by a high speed camera (Photron Fastcam SAX). Laser light sheet and camera are orientated perpendicular to each other. The camera is operated at a frame rate of 40 kfps and a shutter time of 15  $\mu$ s. Each recorded injection consists of 160 images, in total 4 ms. The optical resolution accounts for 11.52 px/mm, whereas the measurement volume is limited by the optical access to a height of 43 mm and a width of 45 mm.

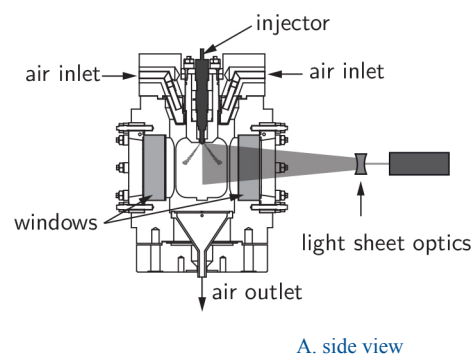


Figure 1. Constant-pressure flow (CPF) chamber with the Mie-Scattering Imaging setup. The chamber allows spray investigations with negligible air flow. High-speed MSI is performed for only the half of the spray section that is illuminated by a laser light sheet.

3. For an ambient temperature of 300 K, the temperature drop is negligible.

4. Assuming almost identical temperatures of water, injector, and fuel in the injector allows temperature control of the liquid.

2. Also known as Methyl Ethyl Ketone.

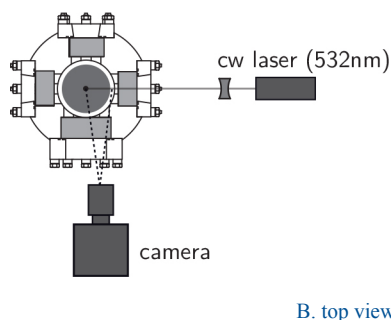


Figure 1. (cont.) Constant-pressure flow (CPF) chamber with the Mie-Scattering Imaging setup. The chamber allows spray investigations with negligible air flow. High-speed MSI is performed for only the half of the spray section that is illuminated by a laser light sheet.

### Engine Test Rig with Tumble Air Flow

The spray measurements in the internal combustion engine are conducted in an optical accessible direct injection spark ignition (DISI) engine<sup>5</sup>. The engine is a one-cylinder four-stroke internal combustion engine with a pent roof combustion chamber, two intake valves, and two exhaust ports. The tumble port features tumble numbers of approximately 2 to 4 relative to the crank angle [26]. Adomeit et al. [27] measured a flow coefficient of 0.11. Therefore, increased combustion stability for tailor-made fuels is enabled [28]. The engine's geometrical and mechanical parameters are given in table 2.

The optical engine is driven externally by a 30 kW electrical engine to circumvent the necessity of fuel combustion inside the combustion chamber, such that no combustion residues or soot influence the optical access. The combustion chamber consists of a quartz glass liner that provides a viewing angle of 360° around the cylinder axis and covers the complete piston stroke.

Table 2. Parameters of the optical DISI engine [26].

| engine parameter                 | value               |
|----------------------------------|---------------------|
| bore                             | 75 mm               |
| stroke                           | 82.5 mm             |
| displacement Volume              | 364 cm <sup>3</sup> |
| compression ratio                | 7.4:1               |
| number of valves                 | 4                   |
| valve lift                       | 9 mm                |
| valve diameter intake            | 27.1 mm             |
| valve diameter exhaust           | 23 mm               |
| exhaust valves open (1 mm lift)  | 154° btdc           |
| exhaust valves close (1 mm lift) | 20° btdc            |
| intake valves open (1 mm lift)   | 10° atdc            |
| intake valves close (1 mm lift)  | 196° atdc           |
| connecting rod length            | 146 mm              |
| crank radius                     | 42.2 mm             |

However, the viewing angle is limited by the supporting pillars. Additional optical access is possible through a 45° mirror placed in the elongated, slotted, hollow piston, which is equipped with a piston top made out of quartz glass. Both optical accesses are illustrated in figure 2.

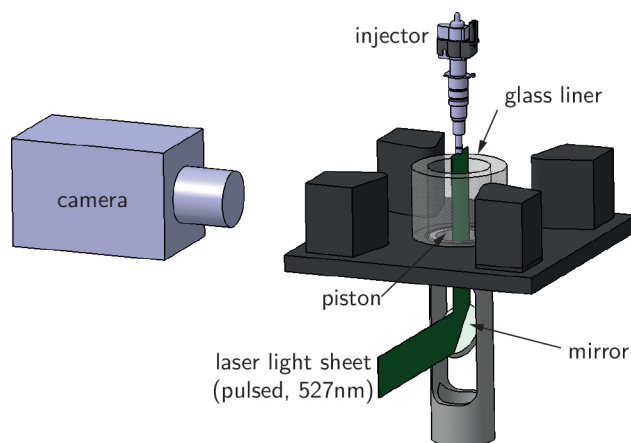


Figure 2. Electrically powered optical engine test rig with the Mie-Scattering Imaging (MSI) setup. A laser light sheet enters the cylinder from bottom to top, allowing homogeneous illumination of a center section of the hollow cone spray. Recorded images must be corrected due to optical refraction that are caused by the glass liner.

To control the engine temperature and to preheat the engine oil to operation conditions, the engine is equipped with a custom made oil conditioning system. The minimum temperature to start the engine is 313 K and the optimal engine temperature is between 333 and 343 K [10]. Furthermore, a custom made intake air conditioning system is used to control the intake air pressure in a range of 70 to 150 kPa. Therefore, the mass flow rate into a pressure reservoir is regulated by two magnetic valves. An infrared temperature sensor measures the engine temperature at the upper iron piston liner. Further information on the engine is given in [10, 26, 28].

Kastengren et al. [29] reported that injectors with identical design specifications still possess slight differences in exit diameter and global nozzle geometry. These differences affect the internal flow and the spray development [9, 30]. Hence, fuel injection inside the research engine is realized by the exact same injector that is used in the experiments inside the pressure chamber. The injector is integrated into the engine head such that its nozzle is positioned in the pent roof of the combustion chamber. The injector nozzle is located in the symmetry plane with a 6 mm distance off the cylinder axis towards the intake valves. Furthermore, the injector is inclined in the symmetry plane by 6° to the cylinder axis.

Similar to the experiments in the CPF vessel, spray visualizations are carried out using MSI (figure 2). A pulsed Nd:YLF laser (Darwin Duo 100) is used to illuminate the hollow cone spray at a frequency of 12 kHz, which corresponds to 1° of the crank shaft at 2,000 rpm. The light beam with a wavelength of 527 nm is directed into the

5. The engine is custom made by FEV GmbH, Aachen, Germany.

cylinder through the piston. The beam is reshaped into a light sheet with a thickness of approximately 1 mm and a width of 59 mm. Each light pulse of the laser has a length of  $\sim 210$  ns and an energy of  $\sim 8$  mJ, which leads to an illumination intensity of  $64.5$  kW/cm<sup>2</sup>. The light sheet is positioned in the symmetry plane of the combustion chamber, such that reflections are reduced as much as possible. A high-speed camera (Photron Fastcam SA5) is synchronized to the frame rate of the laser and collects the scattered light at an angle of  $90^\circ$  towards the light sheet. The camera's shutter time accounts for  $80$   $\mu$ s and the spatial resolution of  $[x, z] = 896 \times 704$  px<sup>2</sup> leads to an optical resolution of  $\sim 13.2$  px/mm. For each injection 40 images are recorded, resulting in a recording duration of 3.33 ms. Unlike the optical setup of the CPF vessel, both spray plums of the hollow cone spray's illuminated cut section are recorded and evaluated. The spray propagation is not expected to be axisymmetric due to the air flow that is strongly determined by the intake and exhaust valves.

The results of the chamber and engine MSI setups can be only compared in a certain range due to the angle and intensity dependence of the light scattering process [9, 31]. That is, spray dimensions can be qualitatively juxtaposed.

### Experimental Operating Conditions

All measurements inside the CPF chamber are conducted for Ethanol and 2-Butanone. Injection pressures ( $p_i$ ) of 10, 15, and 20 MPa are investigated for each set of measurement conditions. To analyze the influence of prolonged injections, injection durations ( $\Delta t_i$ ) of 0.5, 1, and 2 ms are selected. Most measurements are conducted at an ambient temperature ( $T_a$ ) of 300 K to simulate the optical engine's cold operating conditions, where evaporation is negligible. The ambient pressure ( $p_a$ ) includes 0.1, 0.2, 0.3, 0.5, and 1.0 MPa. A constant-flow water cooling system is used to guarantee a fuel temperature of 313 K.

In the CPF chamber, additional experiments are conducted at higher ambient temperatures of 400 and 500 K to facilitate a more general spray investigation with evaporation effects. However, the focus of this work is the investigation of the influences of an engine flow field and the fuel characteristics on spray propagation. Furthermore, measurements at evaporation conditions are not possible on the engine rig. Therefore, the investigation of the temperature depending evaporation aims to just determine the different tendencies in the evaporation behavior of both fuels.

For the engine test rig, the start of energizing (SOE) of the injector requires adjustment to achieve ambient pressures comparable to the CPF vessel. SOE timings of  $60$ ,  $277$ , and  $297^\circ$  atdc correspond to ambient pressures of 0.1, 0.2, and 0.3 MPa. The engine's oil conditioning system is used to keep the temperature of the engine block at approximately 333 K. Since the fuel temperature cannot be measured it is estimated to about 313 K - the temperature that is also regulated in the CPF system. The temperature of the intake air remains constant for all experiments at 300 K. The number of injections per measurement point is 30 in the CPF vessel experiments and 100 in the engine experiments<sup>6</sup>.

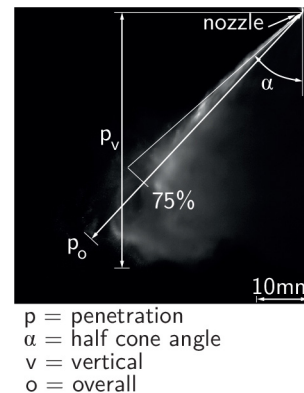
Since both setups use the identical injector, the measurements of injected fuel mass are conducted only once per fuel. Table 3 displays the amount of injected fuel depending on the injection pressure for an injection duration of 0.5 ms. The amount of injected fuel mass increases at higher injection pressure. Differences between fuels are found to be negligible.

Table 3. Mass of injected fuel at varying injection pressure ( $p_i$ ). Mass flow measurements are performed at standard ambient conditions for both fuels. Values are given for an injection duration of 0.5 ms [10].

| $p_i$<br>MPa | Ethanol<br>mg | 2-Butanone<br>mg |
|--------------|---------------|------------------|
| 10           | 10.2          | 10.3             |
| 15           | 10.6          | 10.6             |
| 20           | 10.9          | 10.9             |

### Image Processing

Figure 3 shows raw Mie-Scattering images of both setups. As mentioned before, the images of the CPF vessel show only half of the spray, since axisymmetric spray propagation is assumed. The results of the engine, however, contain the entire hollow cone cut section. It is evident that the spray propagation is influenced differently by the air flow at the inlet and exhaust valves. The images also indicate that results from the engine experiments are more affected by multiple scattered light. Multiple light scattering is enhanced due to a thicker light sheet<sup>7</sup> and a higher amount of reflections caused by the engine's glass liner and pent roof. Moreover, only images taken in the CPF vessel allow a view on the nozzle outlet since in the optical engine the pent roof prohibits a direct line of sight.



A. CPF-vessel

Figure 3. The raw images of both experimental setups only show a central cut section of the liquid spray phase. The images include the values of post processing, most importantly spray penetration and half-cone angle. The processing of the engine images differs slightly from the CPF vessel since no axisymmetric spray propagation can be assumed and spray values must be determined for both spray sides individually.

6. In engine experiments, liquid that impinges on the liner decreases image quality. Thus, cleaning cycles are required after 15-20 injections.

7. Light sheet thickness is limited by the  $M^2$  value of the pulse laser. The CPF vessel allows more precise laser focusing and thus a smaller light sheet that reduces multiple scattering effects.