Dynamics of the Ammonia Spray Using High-Speed Schlieren Imaging

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Abstract

Ammonia (NH3), as a carbon-free fuel, has a higher optimization potential to power internal combustion engines (ICEs) compared to hydrogen due to its relatively high energy density (7.1MJ/L), with an established transportation network and high flexibility. However, the NH3 is still far underdeveloped as fuel for ICE application because of its completely different chemical and physical properties compared with hydrocarbon fuels. Among all uncertainties, the dynamics of the NH3 spray at engine conditions is one of the most important factors that should be clarified for optimizing the fuel-air mixing. To characterize the evolution and evaporation process of NH3 spray, a high-speed Z-type schlieren imaging technique is employed to estimate the spray characteristics under different injection pressure and air densities in a constant volume chamber. Three renewable fuels, including NH3, methanol and ethanol, are investigated to compare the differences in their spray behavior at engine-like conditions. The basic parameters of the spray geometry such as spray penetration, spray cone angle and cross-section area are quantified based on the schlieren images postprocessing. The results show that the spray geometry of NH3 differs from that of the other fuels, which exhibits a longer penetration, larger spray cone angle and cross-section area. Moreover, the NH3 also shows a faster evaporation rate than methanol and ethanol. To extract more information from the spray images, an optical flow algorithm is derived to visualize the velocity field based on the schlieren images. The results indicate that NH3 spray is driven to the spray axis under the effect of the vortices. The vortices are induced by the entrainment of the surrounding gas and act as the driving forces that push the spray plumes towards the axis at the same time. The two vortices of NH3 grow much bigger and stronger and move closer to the spray axis compared to the ethanol and methanol.

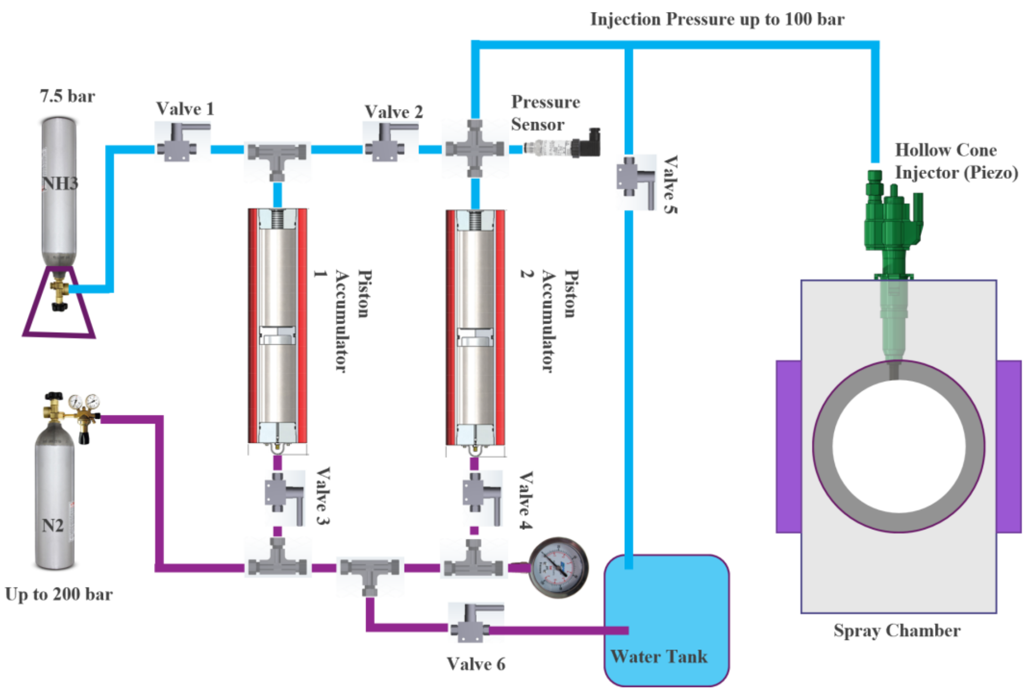
1. Introduction

In 2020, 24% of global CO2 emissions comes from transportation through fossil fuel combustion [1]. Road transportation powered by internal combustion engines (ICEs) was by far the main culprit, accounting for nearly 75% of emissions. To become the first climate-neutral continent by 2050, Europe must significantly reduce CO2 emissions from ICE-based transportation in the coming decades. The combustion system, at the heart of ICEs, has a higher optimization potential when powered by carbon-free fuels such as hydrogen (H2) and ammonia (NH3) to mitigate CO2 emissions. The energy vector H2 is a potential enabler of a carbon-free economy. However, issues associated with H2 storage, distribution, and low volumetric energy density (2.9MJ/L at 70MPa) are currently a barrier to its implementation [2]. NH3 offers high energy density (7.1MJ/L), with an established transportation network and high flexibility, which could provide a practical next-generation system for energy transportation, storage, and use for power generation [3], which also offers innovative solutions to sustainability problems within the energy industry.

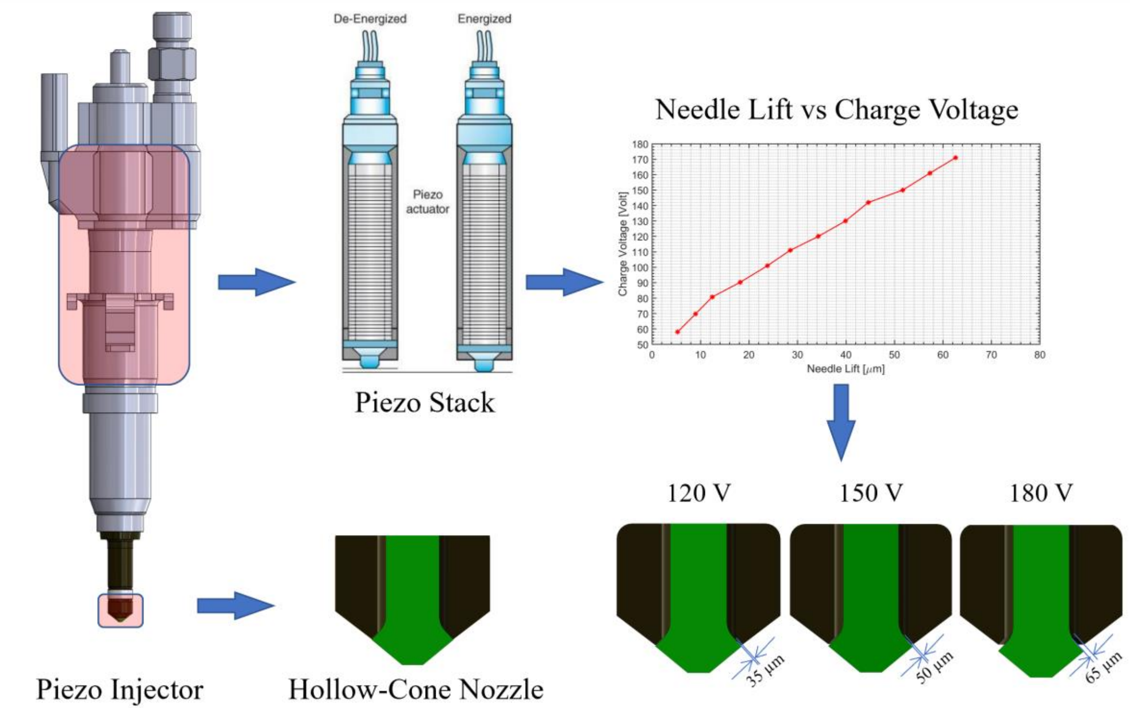
Reviewing all options of NH3 applications, covering ICE [3, 4, 5, 6], proton-exchange membrane fuel cells (PEMFC) [7, 8], alkaline fuel cell (AFC) [9, 10] and solid oxide fuel cell (SOFC) [11, 12] for power pulsations the ICE has high efficiency and is sufficiently practical [3, 13]. The SOFC scores better in efficiency than the ICE but lacks power density, load response capability and is still too expensive. The ICE is second in efficiency and therefore more efficient than the PEMFC and the AFC (in case these are operated close to maximum power). Furthermore, the ICE is less expensive, more robust with the acceptable power density and load response [14].

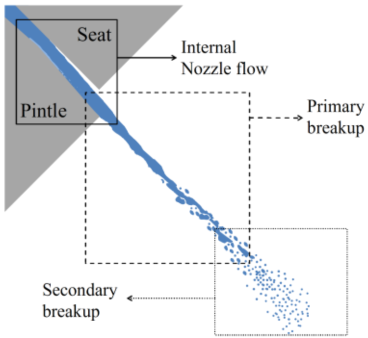
NH3 has been successfully operated in SI engine as a mono fuel in 1966 and 1967 by Starkman, et al. [15, 16]. The experiments were carried out in a single-cylinder SI engine with a compression ratio of 6-10 and an equivalence ratio of 0.8-1.4. They conclude that NH3 can be used successfully as

High-Pressure Ammonia System



Hollow-Cone Piezo Injector





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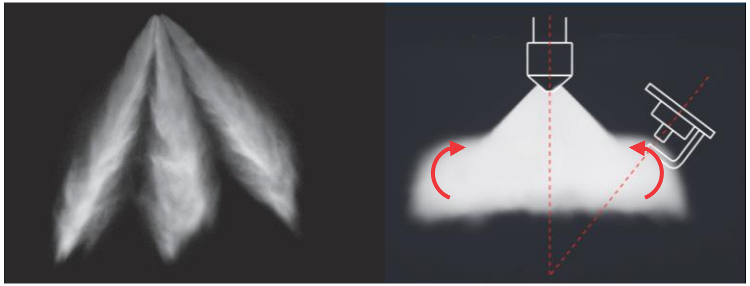
Multi-Hole GDI Injector

Hollow-Cone GDI Injector



- The injector has an annular nozzle which creates a hollow cone spray structure.
- The piezo module acts directly on the needle which results in a highly reproducible spray pattern.
- Due to momentum exchange between the droplets and the air, a strong vortex of the fuel droplets is being formed, see red arrows. This fuel droplet vortex is moving downstream with the moving of the vortex.
- Outward-opening units distribute the fuel via an annulus giving a largely uniform, hollow cone spray. This uniformity insures an even and largely predictable spray structure. Alternatively, the inward-opening unit is configured with multiple holes in a variety of configurations; typically arranged asymmetrically with 5-7 holes.

https://www.researchgate.net/publication/313899525_A_comparison_of_non_reactive_fuel_sprays_under_realistic_but_quiescent_engine_conditions_for_SGDI

Optical Setup

High-Speed Schlieren Imaging

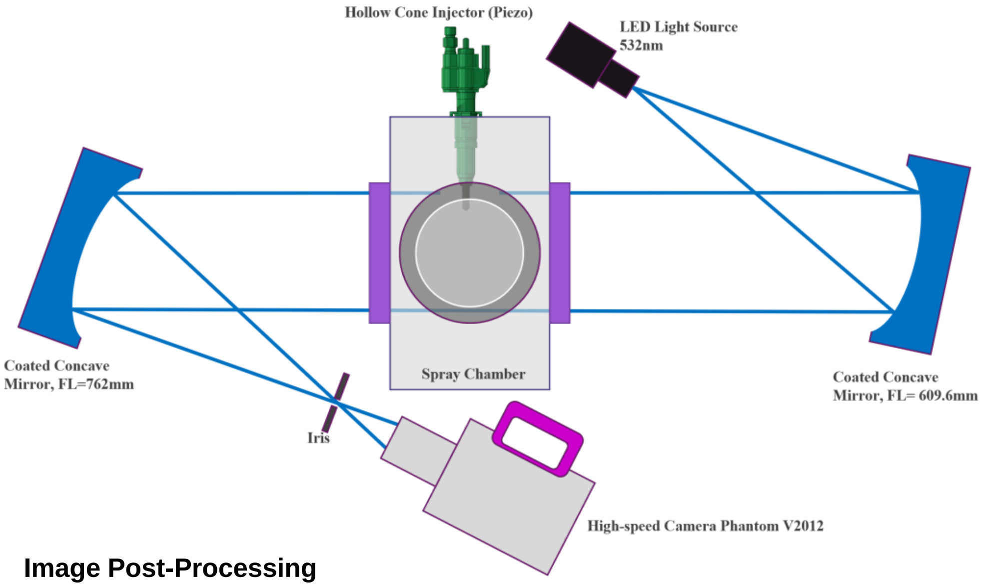
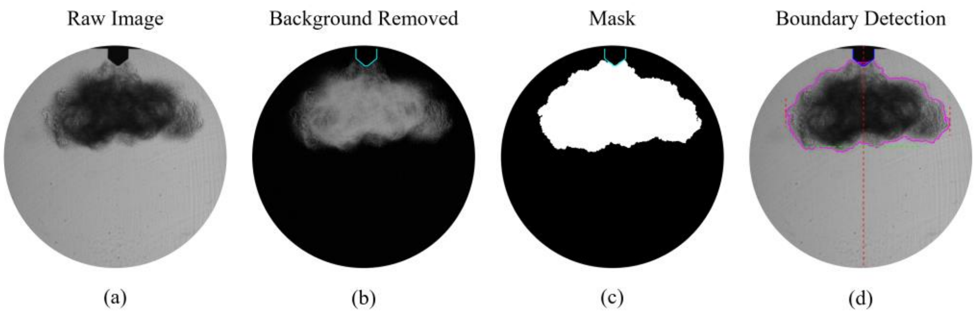
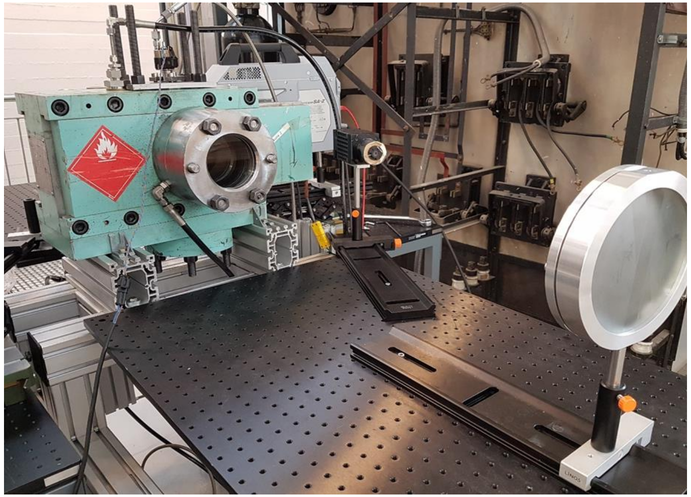
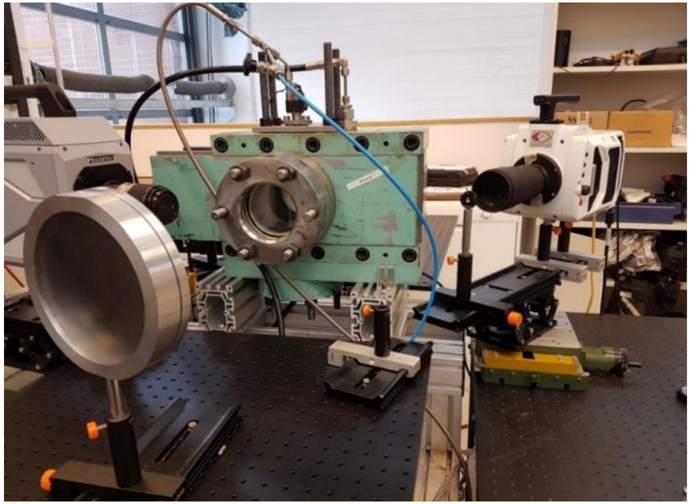


Image Post-Processing







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Optical Flow Velocimetry Method

- Optical flow is the name given to the machine-vision algorithm put forth in a seminal paper by Horn and Schunck. It is a variational calculus approach to determine the velocity field linking two images via energy minimization.
- The basis of Horn and Schunck's algorithm is a conservation of brightness, I (defined at image coordinates x and y, for time t1 and t2) which ensures that the same feature in both images maintain their intensity.

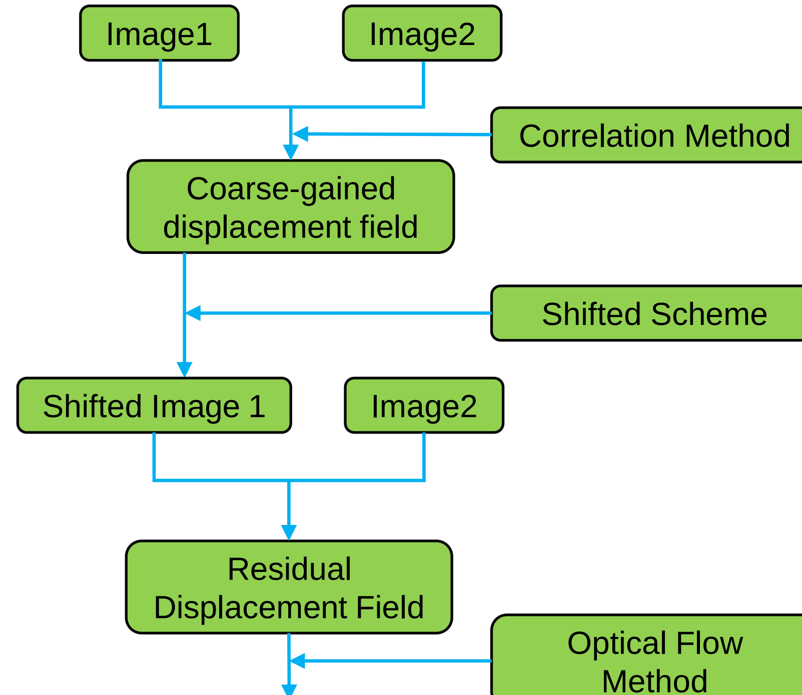
$$\frac{DI\,(x,y,t)}{Dt}=0$$

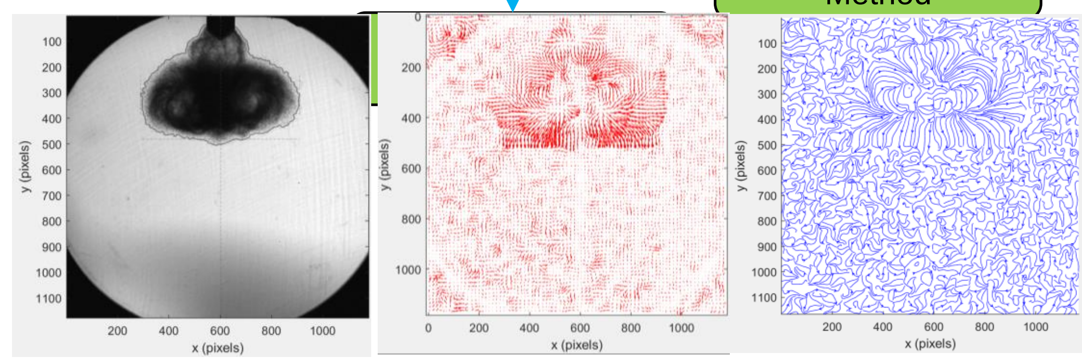
$$\frac{\partial I}{\partial x}\frac{\partial x}{\partial t}+\frac{\partial I}{\partial y}\frac{\partial y}{\partial t}+\frac{\partial I}{\partial t}=0$$

- The brightness constancy constraint equation (BCCE)

$$I_x u + I_y v + I_t = 0$$

Variables u and v are the x and y velocity components, respectively, and the I terms are derivatives of image intensity in the indicated direction.





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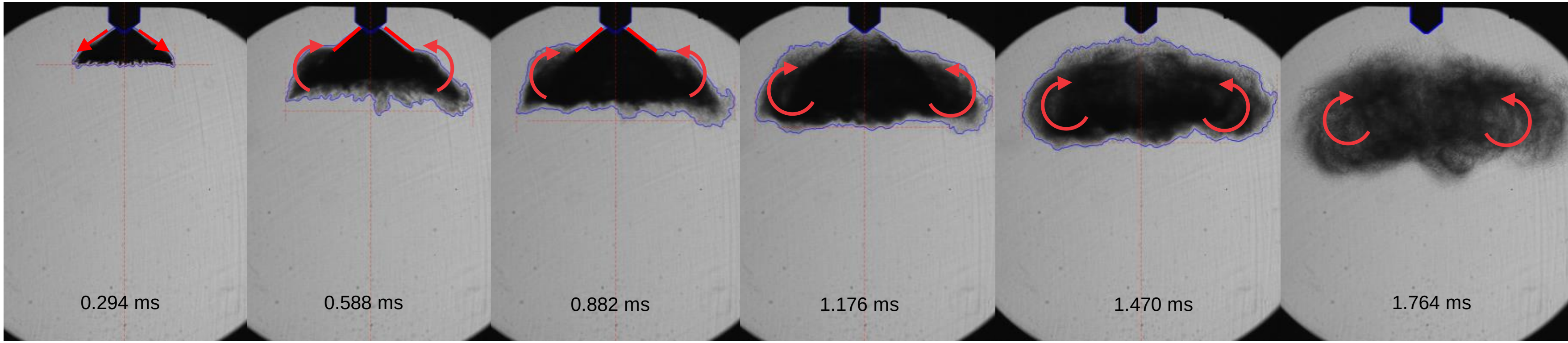
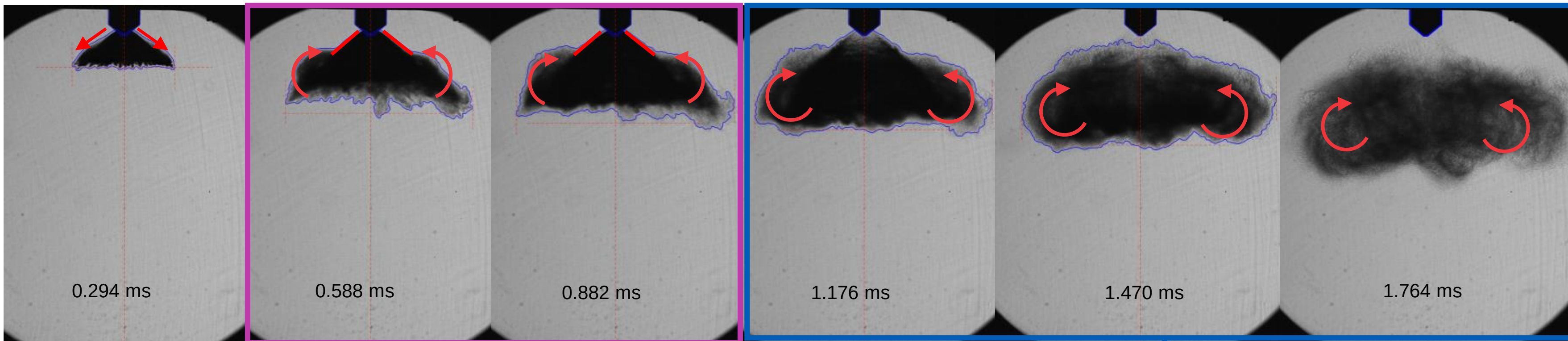
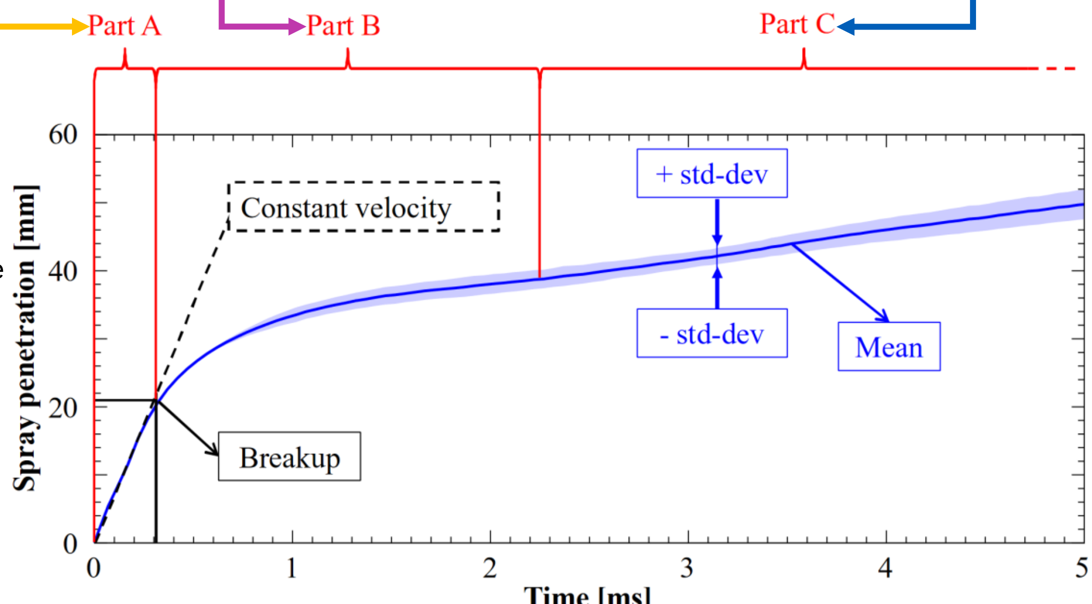
Hollow-Cone Spray Evolution



- The vortices start to form very early, close to the nozzle.
- The vortices travel along downwards the jet, driven by the liquid phase which is supplying the vortices with kinetic energy and – in case of non evaporating conditions – with liquid phase in the form of small droplets.
- During the injection the main vortex grows and gains strength, as the fast jet passes along its side and transfers its momentum to the vortex
- While the vortices grow, they gain influence until they are strong enough to have a noticeable influence on the spray.
- The main vortex grows and to builds up momentum and starts to bend the breakup region of the spray towards the inner side of the hollow cone.
- The spray propagates in the axial direction, transporting the droplets away from the nozzle. The radial component has been transferred, to a great extend, to the vortex.

Hollow-Cone Spray Evolution





- In part A, during the linear penetration before the liquid breakup, the tip is pushed by the liquid core, large ligaments and blobs.
- In part B the tip is formed by large groups of droplets which are slowed down by the surrounding gas in such a way that the curve of the tip penetration describes a square root-like shape.

- In part C, the tip seems to accelerate again and continues its propagation with constant velocity.
- As can easily be seen, the tip slows down its nominal expansion and starts becoming wider, while in the hollow cone a vortex travels further in axial direction.

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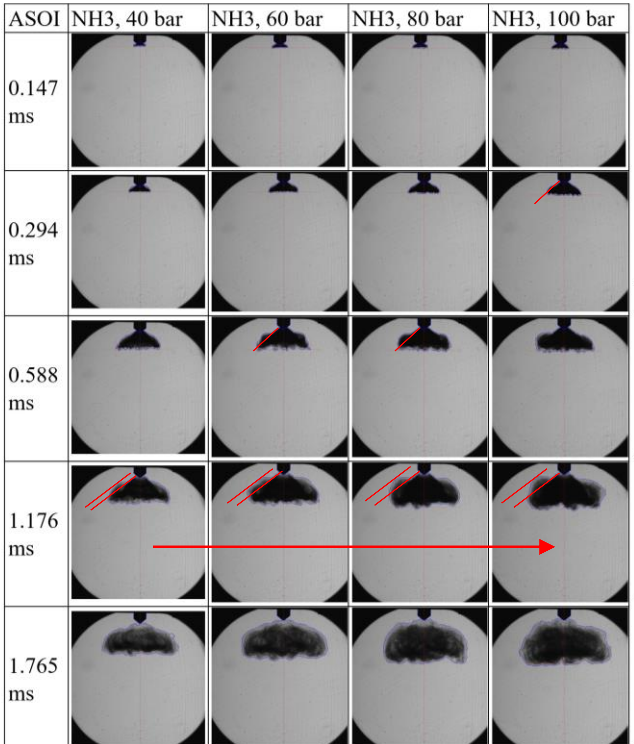
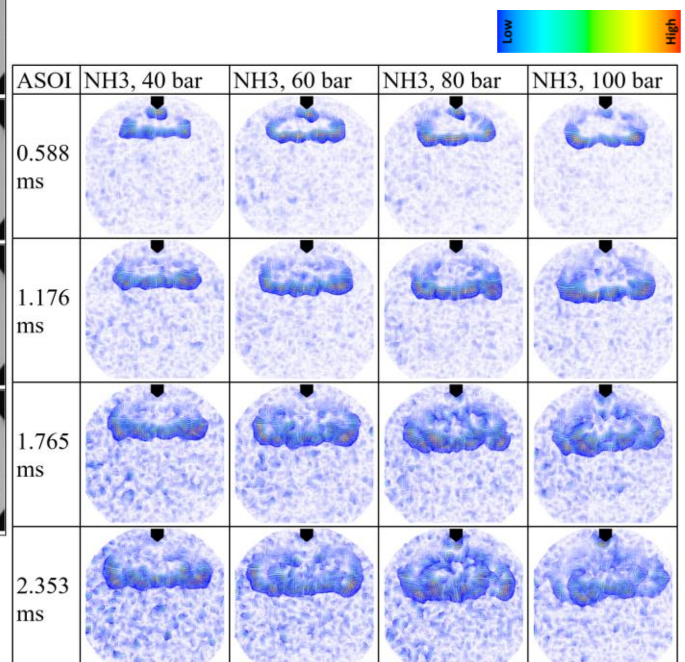
Effect of the Injection Pressure on the Ammonia Spray





- Larger recirculation zone for the higher injection pressure.
- Before breakup, the spray tip propagates faster with higher injection pressure.
- After the breakup, when the larger fragments have been broken up and only droplets are left, the spray is decelerated.
- Lower injection pressure cases decelerate faster

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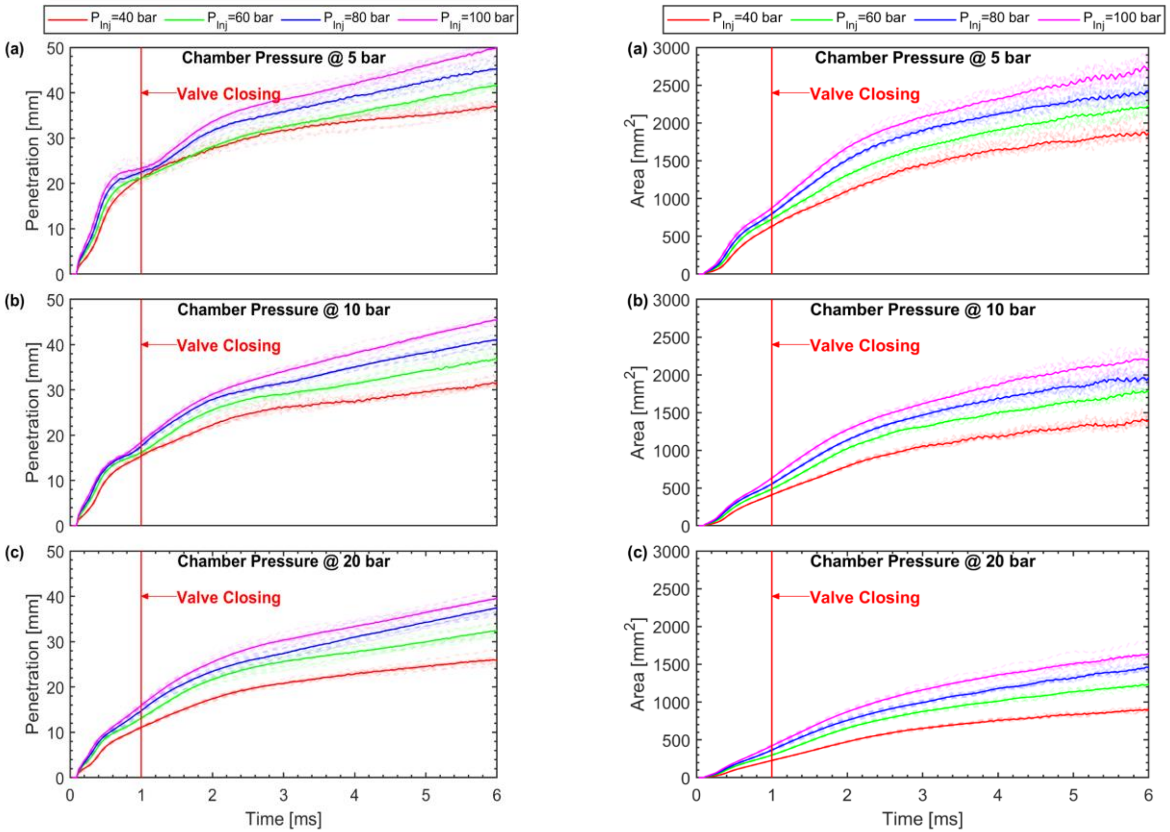
Effect of the Injection Pressure on the Ammonia Spray



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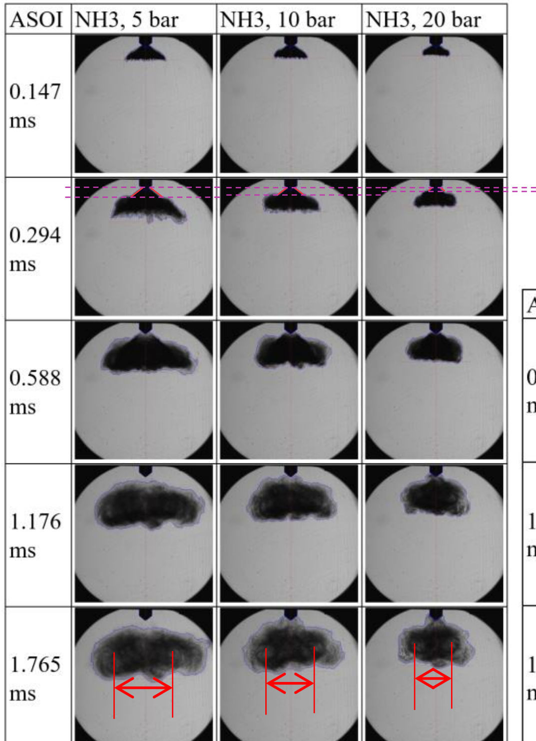
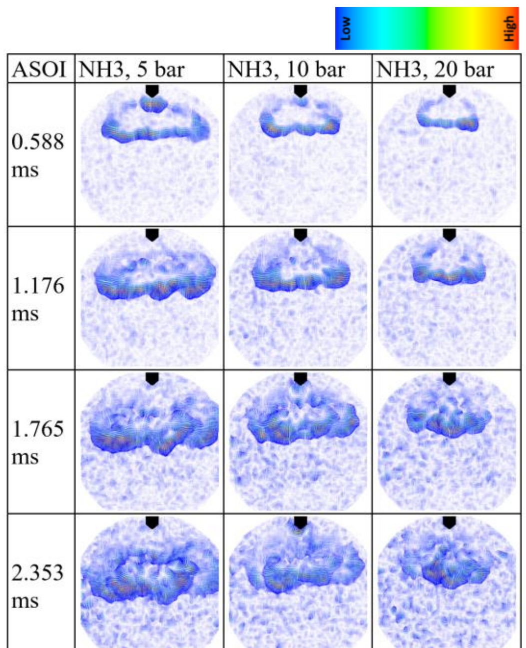
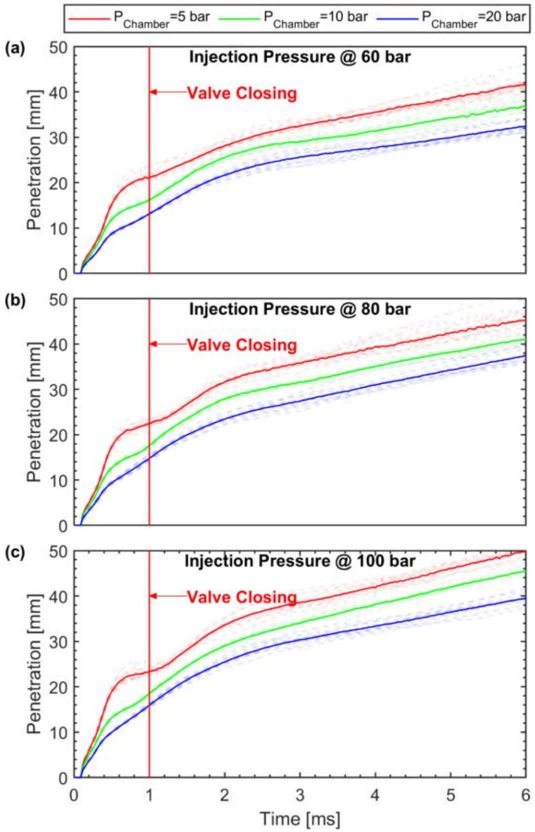
Effect of the Chamber Pressure on the Ammonia Spray

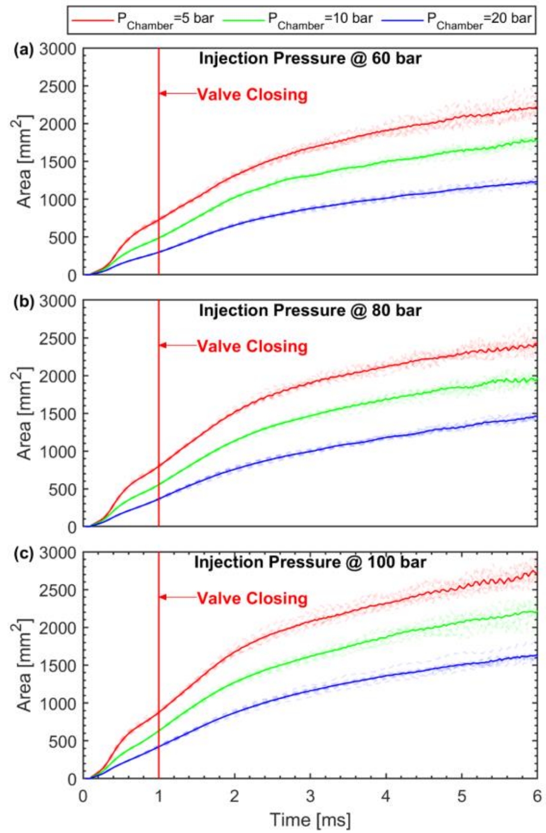




- Lower gas density is seen in higher spray penetration -→ less aerodynamic drag
- Lower gas density leads to ‘finger’ –like structures in the spray. These fingers are vanishing with increasing gas density.
- Higher gas density leads to more confined spray cloud (e.g. at t=1.765 ms)

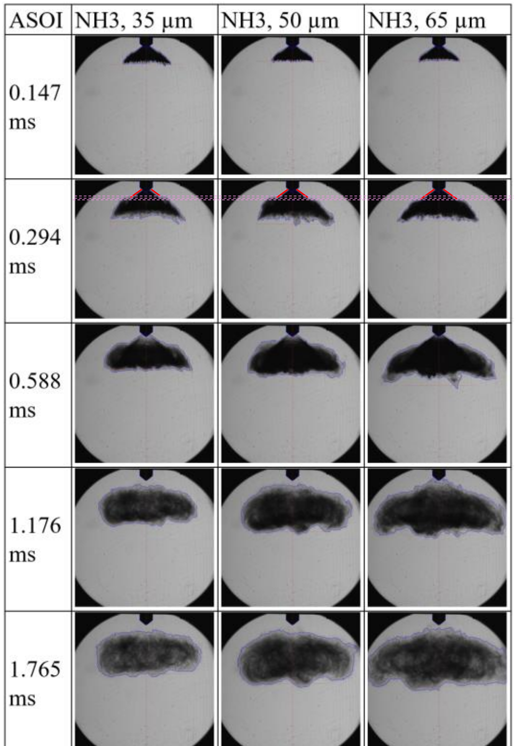
Effect of the Chamber Pressure on the Ammonia Spray

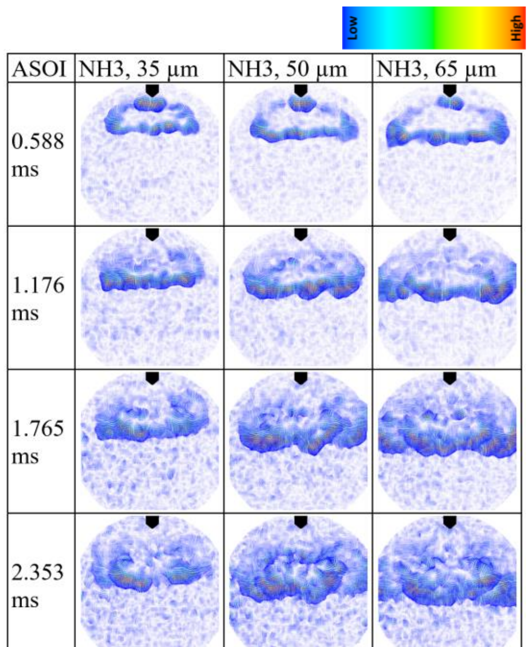




- With a low surrounding gas density, the spray tip penetrates much faster than under conditions with increased gas density.
- This behaviour would be expected, as the drag is a linear function of the gas density. This also affects the breakup process.
- Towards lower gas density, the forces which tear the liquid structures apart become weaker. Therefore, the core sustains longer and the larger structures in the spray can travel further until they break up.
- The Weber number is also linearly dependent on gas density. Higher Weber number implies faster droplet breakup. As soon as the spray is broken up, the surface is drastically increased and the spray faces a higher resistance.

Effect of the Needle Lift on the Ammonia Spray





- When the needle lift is low (35 µm), an evident two stage spray, the breakup and atomization can be observed. Meanwhile, increasing the needle lift leads to a longer breakup length and two stage is merged into one.
- Towards smaller needle lift, the mass flow is reduced and the spray becomes less dense.
- With bigger needle lift the spray is denser and has a higher momentum.

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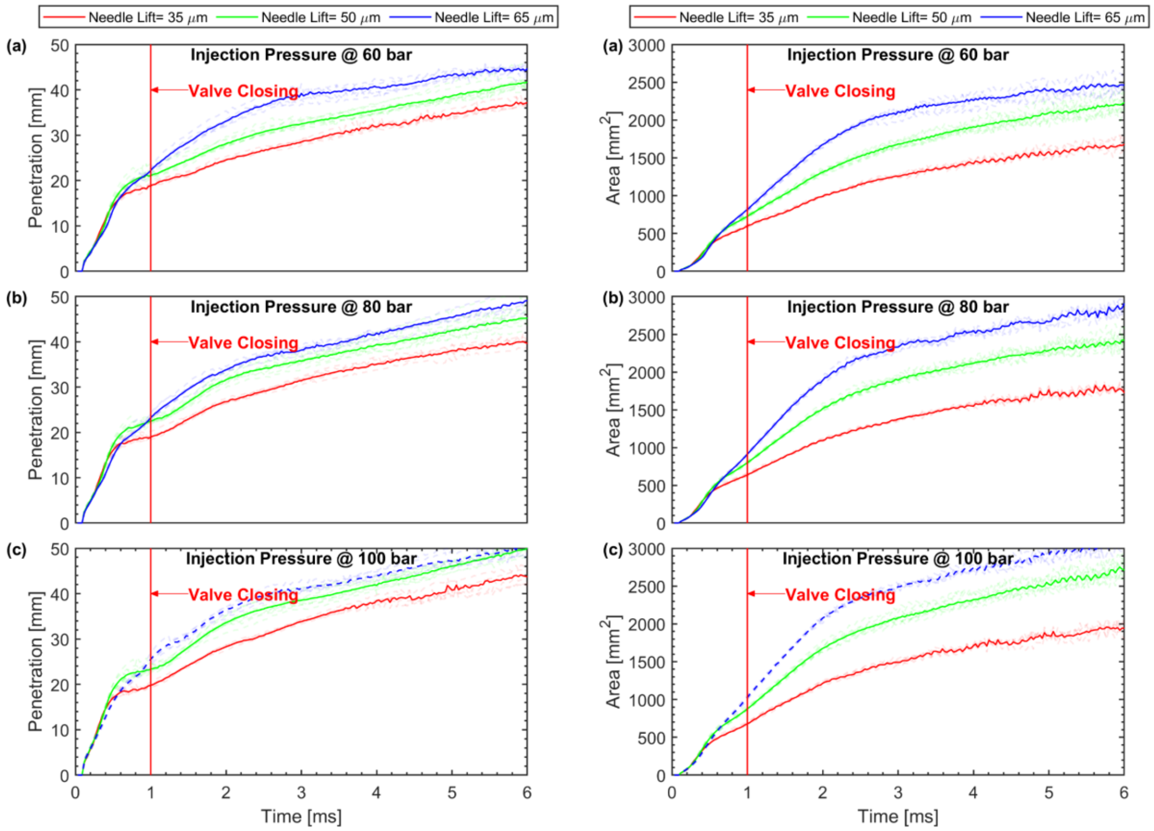
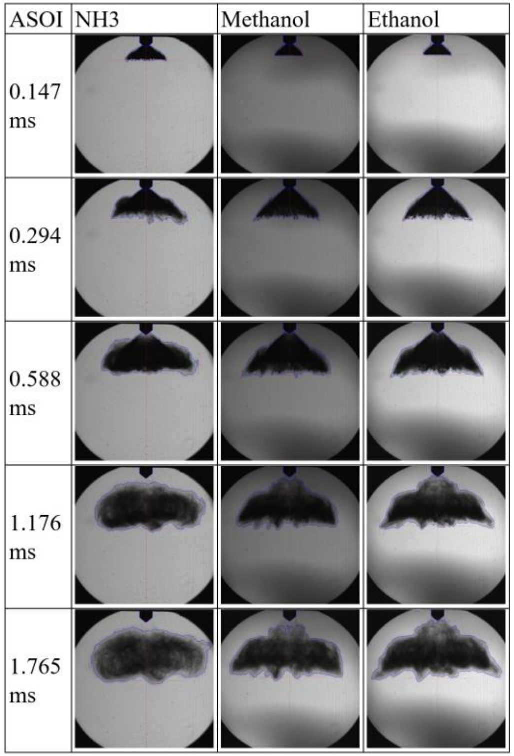
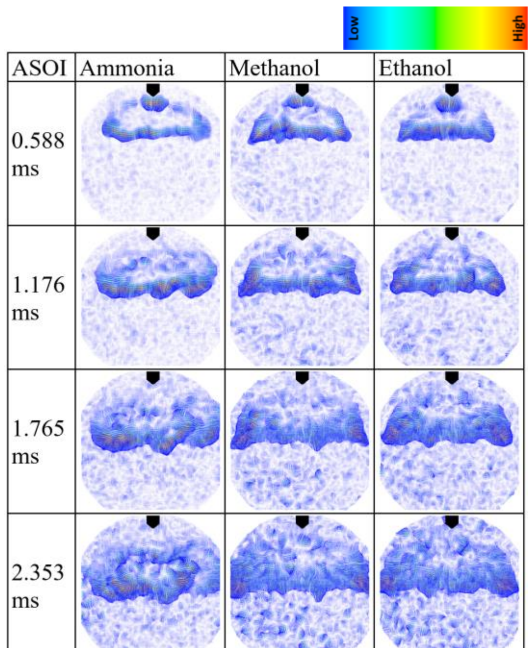
Effect of the Needle Lift on the Ammonia Spray



- Initially there is almost no difference in the spray penetration as a function of the needle lift
- Increased needle lift implies higher mass flow. This is seen in the higher spray penetration.

Effect of the Fuel Properties on Spray





- With ammonia as fuel, the cloud tends to widen towards the side. The spray shape becomes asymmetric. The strings are more pronounced at the beginning of injection.
- The appearance of the recirculation is earlier than methanol and ethanol due to the lower density and viscosity of ammonia, which results in a smaller droplet size.
- Since the higher saturated vapor pressure than ethanol and methanol, the vapor phase can be observed in the spray edge.
- The is no significant difference in spray geometry between ethanol and methanol due to their similar physical properties.

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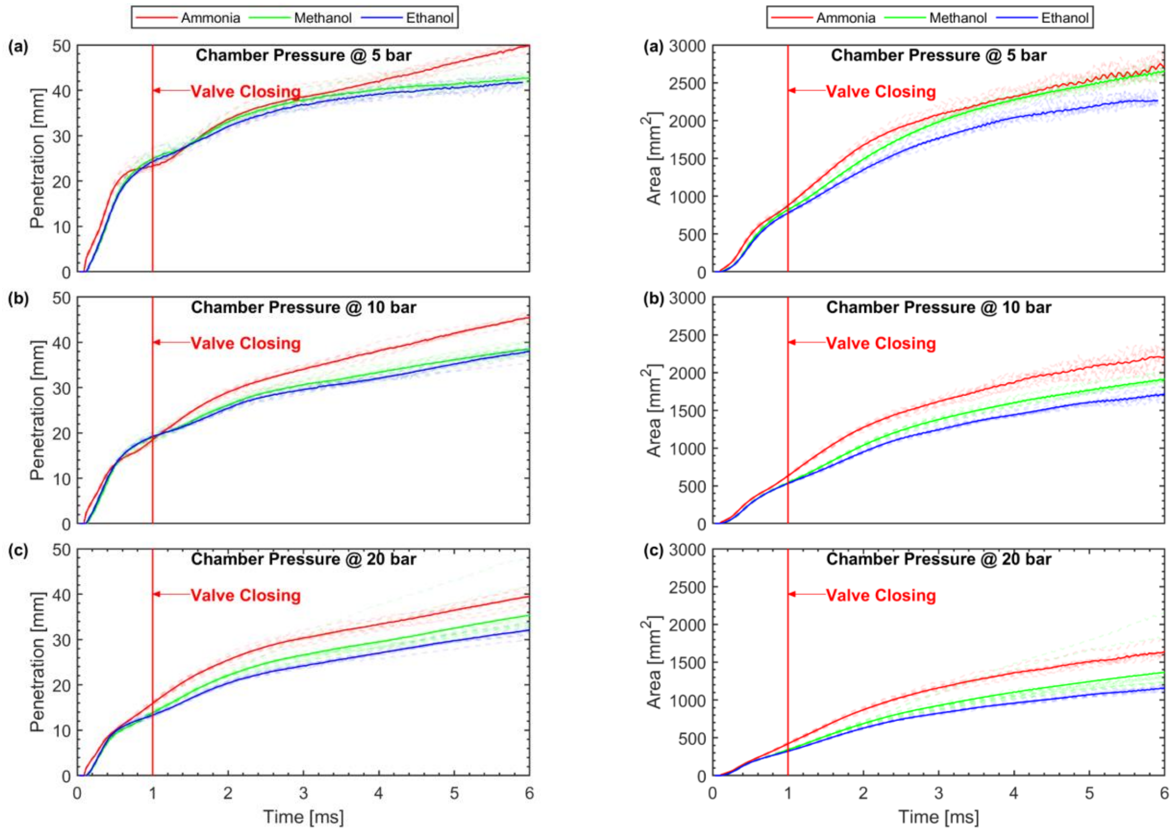
Effect of the Fuel Properties on Spray



Conclusion and Discussion

- Increasing the injection pressure leads to a longer spray penetration and larger spray area. The higher injection pressure also induces more turbulence in the spray.
- Increasing the chamber pressure results in a shorter spray penetration and smaller spray area. Since the increase of the chamber pressure leads to a higher chamber density and larger air drag force, which obstruct the spray propagation.
- The needle lift of the injector also shows dramatical effects on the ammonia spray characteristics. Since the increase of the needle lift leads to a larger injection rate and higher momentum. Therefore, increasing the needle lift results in a longer spray penetration and larger spray area.
- The comparison of the spray characteristics of ammonia, methanol and ethanol indicates that the spray penetration and area of ammonia is larger than those of methanol and ethanol due to its lower density and viscosity. Moreover, since the higher vapor pressure of the ammonia, it shows faster evaporation rate than methanol and ethanol. This implies that the ammonia spray has more effective fuel-air mixing process compared to methanol and ethanol.
- Ammonia has some properties that need to be taken seriously, e.g. reacts with copper, not compatible with all rubber types and ammonia is poisonous in rather small amounts