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# Liquid Ammonia Injection in Internal Combustion Engines: droplet sizing

Utkarsha SONAWAME<sup>1</sup>, Camille HESPEL<sup>1</sup>, Christine Mounaïm-Rousselle<sup>1, 2</sup>,  
Keito HONDA<sup>3, 4</sup>, Akihiro HAWAKAWA<sup>3</sup>

<sup>1</sup>PRISME, University of Orléans, France

<sup>2</sup>Institut Universitaire de France, IUF, Paris, France

<sup>3</sup>Institute of Fluid Science, Tohoku University

2-1-1, Katahira, Aoba-ku, Sendai, Miyagi, 980-8577, Japan

<sup>4</sup>Department of Aerospace Engineering, Tohoku University

6-6-01 Aramaki, Aoba, Aoba-ku, Sendai, Miyagi, 980-8579, Japan

## ABSTRACT

Flash-boiling ammonia sprays exhibit complex plume dynamics and multiple scattering effects, posing serious challenges for optical diagnostics. This study explores advanced techniques, such as SLIPI and intensity ratio methods, to characterize ammonia spray structure and droplet sizing, overcoming measurement limitations near the nozzle region.

### 1. Introduction

The characterization of ammonia spray is critical for optimizing ammonia-fuelled combustion systems and particularly in the case of liquid direct injection of ammonia in Internal Combustion Engine. However, due to ammonia's distinct thermophysical properties and high susceptibility to flash boiling, conventional optical techniques face limitations, particularly due to dense spray-induced multiple scattering. In this context, techniques like Structured Laser Illumination Planar Imaging (SLIPI), and intensity-ratio-based diagnostics, offer improved resolution and accuracy by minimizing multiple scattering.

### 2. Optical Challenges in Ammonia Spray Diagnostics

Optical Challenges in Ammonia Spray Diagnostics  
Resolving fine spray structures and accurately determining droplet size distributions is particularly difficult for ammonia due to its markedly different physical properties compared to hydrocarbons. In multi-hole injector configurations, the high volatility of ammonia often leads to flash boiling, causing the spray plumes to expand, interact, and ultimately collapse. While mild collapse results in broader radial dispersion and shorter penetration, severe collapse can produce a denser central core with extended axial penetration and a reduced spray angle. Under such intense flash boiling, localized cooling induces liquid fuel accumulation between interacting plumes, increasing droplet density at the spray center. This leads to enhanced optical depth (OD), which quantifies the average number of scattering events photons experience while traversing the spray.

Multiple scattering from densely packed droplets and the surrounding vapor phase introduces significant noise in optical measurements, degrading spatial resolution and signal integrity. Du et al. [1] reported elevated light intensity at the spray core, confirming the presence of multiple scattering. Although laser tomography can visualize the internal spray structure, its effectiveness is compromised by these scattering effects.

Sonawane et al. [2] studied ammonia sprays using a multi-hole gasoline direct injector (ECN SPRAY G -

<https://ecn.sandia.gov/gasoline-spray-combustion/>) at an injection pressure of 75 bar while varying fuel temperatures from -10°C to 50°C and ambient pressures of 1 and 3 bar. Their analysis (Figure 1) showed high optical density near the nozzle at the beginning of injection, which diminished as the spray evolved. For a low superheat ratio ( $R_p = 0.97$ ), the plumes remained distinct, indicating non-flash boiling behavior with minimal interaction or collapse.

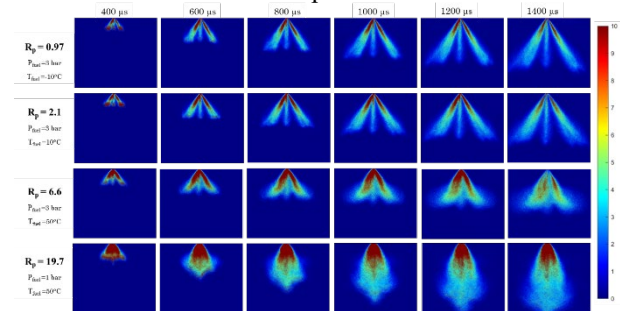


Fig. 1 OD analysis for multi-hole ammonia sprays under various  $R_p$ .

At a high superheat ratio ( $R_p = 19.7$ ), strong flash boiling was evident. Even 1400  $\mu$ s after the start of injection, OD near the nozzle remained high. The plumes merged centrally with no visible gaps, creating a dense spray core conducive to multiple scattering. As fuel temperature increased, the reduced pressure within the plume encouraged convergence toward the axis, forming a closed spray region impervious to external airflow. Continued downstream evolution created a pressure imbalance between the center and edges, further driving the collapse. A higher fuel temperature of 50°C facilitated enhanced evaporation away from the nozzle, yielding a more dilute downstream spray and reduced OD. However, near-nozzle regions remained highly opaque, making them unsuitable for conventional optical diagnostics.

### 3. Methodology: SLIPI and Intensity-Ratio Approaches

#### 3.1 Structured Laser Illumination Planar Imaging (SLIPI)

SLIPI utilizes modulated laser illumination to isolate singly scattered light. By capturing phase-shifted images (1p, 2p, or 3p SLIPI), it removes up to 44% of multiply scattered light, thereby improving contrast from 55% to 80%. For example, 2-phase SLIPI has demonstrated optimal trade-offs between resolution and practicality in spray visualization (Berroual et al. [3]). Using SLIPI instead of a conventional laser sheet looks promising to get reliable and accurate data measurement. Hence, our suggestion is to combine the intensity ratio technique and SLIPI for suppressing the unwanted intensity due to multiple scattering as highlighted in Figure 2 Intensity ratio-based techniques include polarization ratio, LIF/Mie ratio and Raman/Mie ratio are proportional to the mean diameter.

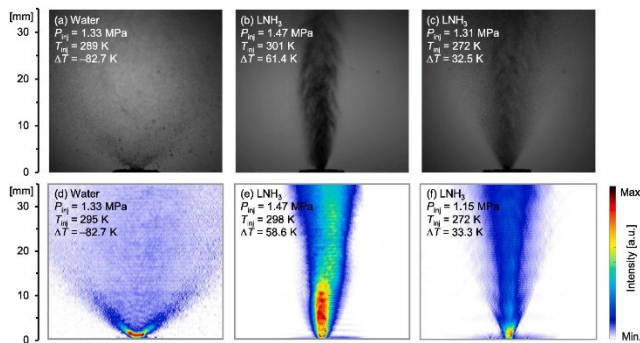


Fig. 2 Comparison of instantaneous images of water and liquid ammonia sprays at atmospheric  $P_{amb}$  [4]

### 3.2 SLIPI-Enhanced LIF/Mie Ratio Technique

This technique captures Laser Induced Fluorescence (LIF) and Mie scattering images from dye-doped sprays. LIF reflects droplet volume, while Mie scattering indicates surface area. The LIF/Mie ratio relates to Sauter Mean Diameter (SMD). SLIPI further enhances signal clarity by eliminating multiple scattering artifacts. However, the LIF method is limited to non-evaporative environments due to dye concentration variation during evaporation.

### 3.3 SLIPI-Polarization Ratio Technique

Polarization ratio imaging compares perpendicular (S-pol) and parallel (P-pol) scattered light, providing D21-based droplet sizing. Unlike LIF/Mie, it doesn't require dye, making it suitable for evaporative and flash boiling sprays. Calibration and incident polarization angle are crucial for measurement accuracy. Figure 3 represents the example of the experimental setup of SLIPI-Polarization ratio technique developed at University of Orléans.

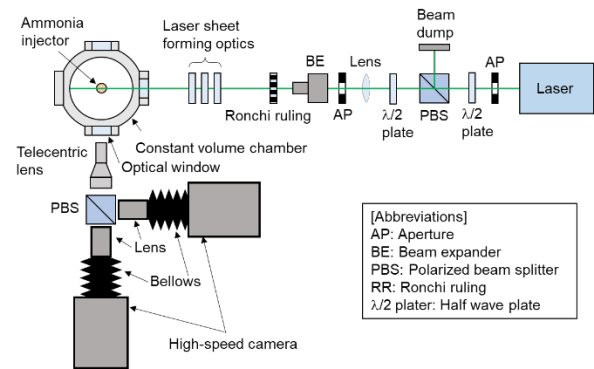


Fig. 3 Example of the SLIPI-Polarization ratio technique developed at University of Orléans.

## 4. Examples of results from SLIPI-polarisation ratio for GDI injectors

The Engine Combustion Network (ECN) spray G 8-hole injector (<https://ecn.sandia.gov/gasoline-spray-combustion/computational-method/mesh-and-geometry/>) is mounted on the stainless-steel spherical vessel of 4.2 L. Ammonia is pressurized up to 120 bar by helium and injected in liquid state at 75 bar FIP. The injection duration of 1000  $\mu$ s was controlled with an injector power driver (EFS 8427). The ammonia spray is injected into spray vessel. A National Instrument CRIO 9024 was used to trigger the fuel injection and cameras recording system simultaneously.

First experimental studies on ammonia sprays with multi-hole injectors at  $T_{fuel} = 28^\circ\text{C}$  and  $P_{inj} = 75$  bar showed significant plume collapse and central densification, verified via OD and polarization ratio techniques. SLIPI imaging clearly differentiated hollow-cone and collapsed spray regions. The polarization ratio technique identified secondary breakup and droplet coalescence zones, which conventional imaging failed to resolve. In strong flash boiling, high OD near the nozzle limited the utility of traditional planar imaging but validated the robustness of SLIPI-enhanced diagnostics.

Figure 4 shows an example of droplet density and droplet sizing distribution obtained with this injector, presented in Sonawane et al. [5]. The intensity peak indicated the spray region with the secondary break-up occurs, inducing a higher droplet density. The region near the nozzle was also dense and consisted of larger liquid ligaments and droplets 'Grey print'. Results showed plume-to-plume interaction and spray collapse, leading to coarser droplets at the spray centre, especially during the start of injection. The drag forces at the spray front led to droplet collision and coalescence, forming coarser droplets at the spray front.

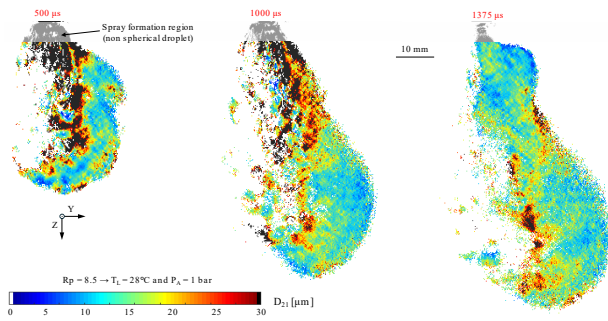


Figure 4 Example of droplet sizing distribution [5]

## 5. Concluding Remarks

Advanced optical diagnostics such as SLIPI, LIF/Mie, and polarization ratio methods can significantly improve ammonia spray visualization and droplet sizing under flash-boiling conditions. These techniques mitigate the influence of multiple scattering and enable accurate characterization of plume collapse and dense spray cores. Future studies should focus on expanding SLIPI applications to reactive and high-pressure ammonia sprays.

## Acknowledgements

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