

An Experimental and Numerical Study of Diesel Spray Impingement on a Flat Plate

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ABSTRACT

Combustion systems with advanced injection strategies have been extensively studied, but there still exists a significant fundamental knowledge gap on fuel spray interactions with the piston surface and chamber walls. This paper is meant to provide detailed data on spray-wall impingement physics and support the spray-wall model development. The experimental work of spray-wall impingement with non-vaporizing spray characterization, was carried out in a high pressure-temperature constant-volume combustion vessel. The simultaneous Mie scattering of liquid spray and schlieren of liquid and vapor spray were carried out. Diesel fuel was injected at a pressure of 1500 bar into ambient gas at a density of 22.8 kg/m³ with isothermal conditions (fuel, ambient, and plate temperatures of 423 K). A Lagrangian-Eulerian modeling approach was employed to characterize the spray-gas and spray-wall interactions in the CONVERGE™ framework by means of a Reynolds-Averaged Navier-Stokes (RANS) formulation. A set of turbulence and spray break-up model constants was identified to properly match the aforementioned measurements of liquid penetration within their experimental confidence intervals. An accuracy study on varying the minimum mesh size was also performed to ensure the grid convergence of the numerical results. Experimentally validated computational fluid dynamics (CFD) simulations were then used to investigate the local spray characteristics in the vicinity of the wall with a particular focus on Sauter Mean Diameter (SMD) and Reynolds and Weber numbers. The analysis was performed by considering before- and after-impingement conditions in order to take in account the influence of the impinged wall on the spray morphology.

CITATION: Zhao, L., Torelli, R., Zhu, X., Scarcelli, R. et al., "An Experimental and Numerical Study of Diesel Spray Impingement on a Flat Plate," *SAE Int. J. Fuels Lubr.* 10(2):2017, doi:10.4271/2017-01-0854.

INTRODUCTION

Internal combustion engines (ICEs) have seen a great evolution over the last few decades by the way of reduction in exhaust NOX and soot emissions through high pressure injection, multiple injections, and exhaust gas recirculation. Although combustion systems with advanced injection strategies have been studied extensively, there still exists a significant fundamental knowledge gap on fuel spray interactions with the piston surface and chamber walls. Studying soot generation is one of the major challenges for the combustion community [1, 2].

In particular, film formation in spray-wall interaction regions, which is caused by impinging spray and condensation of vapor, plays a critical role in engine performance and emissions. During transient operations, the deposition or discharge of fuel from the wall film may lead to deviations of the required air-fuel ratio [3]. In addition, in port fuel injection (PFI) Spark Ignited (SI) engines, some of the fuel does not vaporize completely in the port and is deposited on the walls of the combustion chamber, where it can escape combustion. This behavior that occurs predominantly under cold-start and warm-up conditions is generally referred to as wall-wetting [4]. Therefore, wall-wetting is a concern for the

engines, as well as direction injection (DI) engines due to spray-piston interactions. Fuel-wall wetting has been shown to significantly affect the mixture formation and combustion for low temperature combustion concepts such as Premixed Charge Compression Ignition and Reactivity Controlled Compression Ignition (PCCI/RCCI) [5] engines with poor efficiency and increased pollutant emissions.

The techniques for measuring details of spray-wall interaction and the resultant droplet sizes and wall-film characteristics have been carried out since the inception of the engines. However, with engine studies limited to the visualization access and unclear boundary conditions, much of the work on spray-wall interaction took support from atmospheric or constant volume chamber measurements. One of the early work from Akop et al. [6, 7] performed a series of studies on fuel impingement on a plate under atmospheric pressure conditions. In ref. [6], they performed the high-speed shadowgraphy and a mass measurement scale was used to weight the impingement fuel mass to begin the experimental campaign. Later the influence of plate angle and area was explored with a mass measurement scale which was used to weigh the film. Subsequently, high speed images were also taken capturing the entire injection event [7]. Further studies have been performed to measure the Weber number and Sauter Mean Diameter (SMD) of the impinging droplets using empirical relations and combining with film mass measurements [8]. A correlation with ambient pressure variation was later derived and Weber number correlations were subsequently revisited [9]. Since the spray impinging on the wall causes surface cooling, the temperature of the wall can be taken as an index to measure how much the temperature drops down along with getting an estimate of the film spread. This can be done with an infrared camera. One such study was performed in a recent work by Schulz et al. [10] where along with measuring the film area and temperature on the plate, a Phase Doppler Anemometry (PDA) system was used to measure the droplet size combined with high speed shadowgraphy to visualize the spray development.

Senda et al. [11] investigated the effects of wall films arising from spray-wall interactions in the SI engine port fuel injection where a 355 nm Laser Induced Fluorescence (LIF) technique was employed to measure the film thickness of a spray impinging on a glass plate in a constant volume combustion vessel. Later, LIF technique was employed by Lindgren et al. [12] in an open atmospheric condition along with a photomultiplier tube to detect light from Mie scattering of droplets in an effort to obtain a wall film thickness measuring device. Due to the highly turbulent nature of the engine in-cylinder flow field, efforts were made to replicate this and check if the cross flows have an effect on the spray-wall interaction. One such study was performed by Pano et al. [13] using Argon-Ion laser combined with a schlieren setup. The physics of impingement was sought and thickness of vapor layer (on a plate) was obtained. The use of PDA to measure spray droplet sizes has been long in use in various applications of sprays. It has been used by Lindgren et al. [14] to investigate the effect of wall characteristics on a gasoline spray after impingement from a wall. Argon-Ion laser was used for LIF to measure the film thickness and high-speed image for spray visualization was obtained coupled with PDA measurements for post-impingement droplet distribution

measurements. Refractive Index Matching (RIM) technique has been used to characterize spray deposit wetted area, and film thickness which is able to provide the quantitative temporal and spatial measure of film under vaporization conditions [15, 16]. It was found that the fuel thickness is in the range of 1 to 3 μm in the GDI application [16]. Montanaro et al. [17] experimentally studied the effects of wall temperature and injection pressure on atomization and vaporization of impinging spray on a heated surface by using a single-hole GDI injector in a quiescent vessel. They used Mie-scattering and schlieren diagnostics to simultaneously predict the liquid and vapor of spray and measured the liquid and vapor width penetration and thickness growth after spray impinging on the wall. In ref. [17], the liquid width is defined as the maximum radial elongation of an intact liquid core coming from the nozzle and flowing along the surface of the wall. The maximum height of the liquid on the plate is defined as liquid thickness. The liquid core is surrounded by an area composed of fuel vapor mixed with liquid ligaments, where the vapor phase is considered and the vapor width and vapor thickness are defined as the similar way with liquid width and thickness. The authors found that the liquid and vapor width penetrations increase proportionally with respect to the increasing of the wall temperature at the fixed injection pressure, and the liquid and vapor thicknesses increase with time but no proportional correlation with the wall temperature; they also concluded that at the fixed wall temperature of 573 K, the effect of the injection pressure highlighted a linear increasing of the liquid and vapor width vs. time and showed a proportional increasing with respect to the increasing of injection pressure, and the liquid and vapor thicknesses were directly proportional to the injection pressure with a conduct tending to a saturation at longer time.

Nevertheless, measuring the film thickness using laser techniques is still a challenge due to the very small scale of the film thickness. PDA measurements for higher injection and ambient pressures result in very small droplet sizes and often require careful calibration and pushing the limit of the measurement system. For near-term and long-term study on spray-wall interaction test at Michigan Technological University (MTU), the experimental validation effort is made by utilizing the high pressure-temperature constant volume vessel to match a wide range of engine conditions. Optical access to the vessel is provided by involving various high-tech non-intrusive diagnostics. These diagnostics include LIF, Laser Induced Exciplex Fluorescence (LIEF) for characterizing the fuel-air mixing formation and the evaporation phenomenon, and high-speed camera imaging with highly-zoomed lenses to gain an in-depth understanding of the film growth and droplet interaction process. This information will be used to characterize wall film formation from impinging sprays at different injection conditions and to investigate the applicability of different optical techniques. The experimental measurements will aid the CFD campaign in future wall-film sub-model development with inclusion of post-impingement droplet dynamics to increase the usability and prediction of the code in ICE applications.

Spray-wall interactions and fuel film formation and evaporation have been shown to play an important role in accurately simulating engine combustion processes by many researchers in the past two decades. Montorsi et al. [18] investigated diesel fuel spray impingement on

the cylinder walls through simulations using STAR-CD, KIVA-3v, and compared the simulation results against experimental measurements. Although the spray-wall interaction sub-models were different between the two codes, they concluded that spray-wall interactions are significantly sensitive to the temperature and pressure conditions and consequently affect heat release rate and emissions formation. The authors found that the heat transfer models between the spray and wall would be more accurate by considering the effect of the remaining liquid film and different kinds of evaporation that can occur during spray-wall interaction. The same group continued to explore the wall film formation in diesel sprays [19] and showed that heat transfer is significantly affected by the film thickness. Habchi et al. [20] employed a Lagrangian-Eulerian method until the spray hits the piston wall to study the effect of piston temperature on mixture preparation under stratified charge operating conditions in a DI gasoline engine. As the droplets interact with the wall and form a film, this liquid film mass is tracked in a Volume of Fluid (VOF) framework. The main film formation affecting physical mechanisms depends on the impingement wall conditions on a dry surface. The impingement characteristics of a liquid droplet on a dry surface include stick, bounce, spread, boiling-induced break-up, rebound with break-up, aerodynamic break-up, and splash as seen in Figure 1. All these processes are strong functions of the droplet Weber number which is the ratio of the kinetic energy on impact to the surface energy [20, 21].

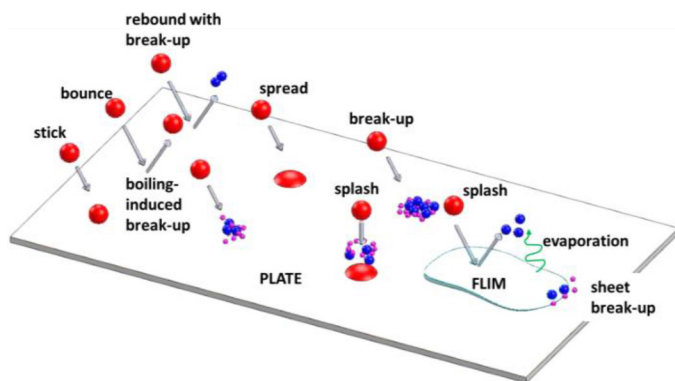


Figure 1. A schematic of the drop impinging on the dry and wetted surface.

In engine-spray applications, multi-component fuel droplet interaction with wall and film formation were performed using probability density function in the Lagrangian-Eulerian framework to capture the vaporization trends by Lippert et al. [22]. It was found that during cold start in diesel engine applications, varying spray impingement angle results in more secondary atomization (splashing) of the film after spray hits the film and enhances vaporization. O'Rourke and Amsden [23] implemented film formation and dynamics information based on a balance of mass, momentum, and energy in the KIVA-3v code. They implemented a projection method of droplets on the cylinder walls to start the inception of the fuel film in an ad-hoc manner. Thorough validation of these droplet and film models are lacking due to the lack of high-fidelity experimental data. Micro-scale analysis with a single droplet's normal impingement on a wetted-wall was performed to observe and correlate with the empirical 'splashing' equation results as done by Cole et al. [24]. They reported that the crown formation after droplet splash ejects the liquid and the subsequent crater collapse lacks the energy to

overcome surface tension and ejects a droplet. As the film is thickened, the crown lacks the energy to eject fluid, but the subsequent fountain created by the collapse ejects the liquid. Such micro-scale studies were implemented in macroscale model of spray-wall interaction using the Lagrangian-Eulerian model. When the representative parcel hits the wall, the behavior is replicated based on the results of the microscale study. Low Weber numbers cause the particles to stick, while high ones cause them to splash with more outbound reflected mass.

The wealth of the literature relies on spray models utilizing Lagrangian framework of modeling, which is a statistical technique of modeling droplets (parcels) ejecting from an injector, and lacks important considerations of physics relating to drop interaction. Most of the available spray-combustion CFD codes perform simulations which are in need of validations from experiments. In general, experimental data is used to further tune the model constants for the Lagrangian approach and the overall goal is to reduce the extent of this tuning. The main objective of the current study is to provide detailed data on spray-wall impingement physics from experiment and characterize the spray-gas and spray-wall interactions based on a Lagrangian-Eulerian modeling approach.

The paper is organized as follows: (1) Introduction; (2) Experimental apparatus and optical setup, a heated plate was employed in a constant volume combustion vessel to conduct a rigorous experiments to study spray-wall impingement and provide the available experimental data; (3) Simulation methodology: model selection, grid study, and structure of CFD work are provided in this section; (4) Results and discussions, starting from schematic of spray-wall impingement, the available CFD models are evaluated against the experimental results of high pressure spray impinging on a flat plate; (5) Major conclusions of this study.

EXPERIMENT APPARATUS AND CONDITIONS

Experimental Setup

An experimental study for testing spray impingement on a flat plate is carried out in an optically accessible constant volume Combustion Vessel (CV) as shown in Figure 2 (top). This vessel is a 1.1 L constant volume combustion chamber. The chamber is cubical with an interior of ~100 mm per side. On each of the six faces of the cube are ports. In three of these ports windows were installed providing unobstructed orthogonal optical access to the combustion chamber. Optical windows provide access for high-speed imaging to study spray development. The top face port houses the spark plug assembly and two fans in order to create turbulence inside the vessel as shown in Figure 2 (top). A face port houses the injector assembly. On the eight vertices of the combustion chamber there are instruments located with actuator access ports. In four of these ports are an intake and two exhaust ports and a dynamic pressure transducer. The latter is a Kistler 6001 piezo-electric dynamic pressure transducer that is coupled to a Kistler 5044a charge amplifier to measure the CV pressure [25].

Figure 2 (bottom) shows the photos of impingement and injector windows including the diesel injector mounted in the combustion vessel. The metal impingement window houses six heaters, seven thermocouples, and three heat flux transducers. The injector window has been mounted in CV and the 7-hole diesel injector has been tested for the preliminary spray-wall interaction validation. The current setup for the injector shows the longest distance between the injector tip and impinging window.

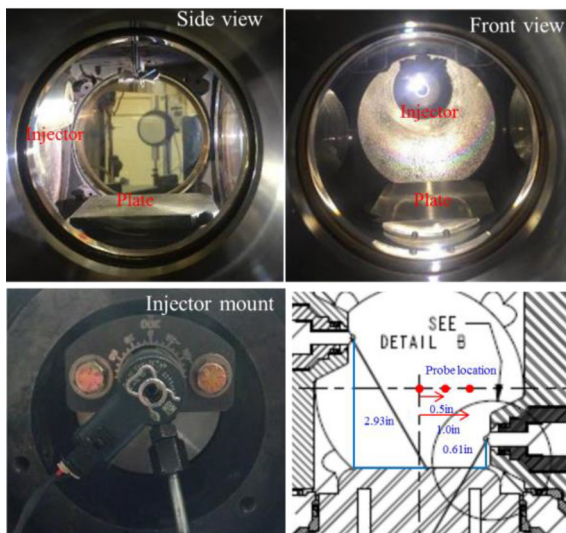
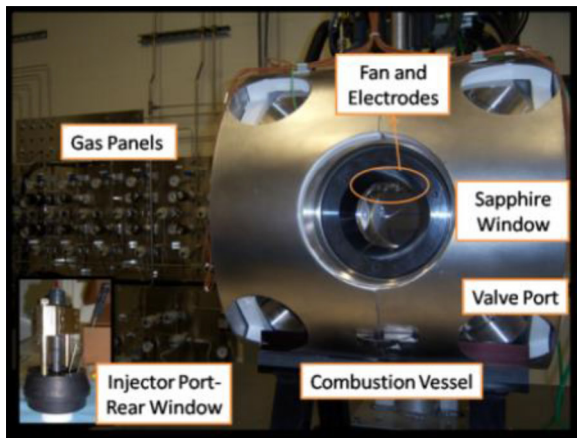


Figure 2. Combustion vessel (top) and the view of injector window mount in the combustion vessel (bottom).

Two views, including the front view and side view as given in the top right corner of Figure 3, are used in this study to visualize the spray characteristics. The optical setup of simultaneous Mie scattering and schlieren was used for the spray-wall interaction test, and Figure 3 shows the optical setup with side view. The schlieren diagnostics is based on density gradients to visualize vapor phase fuel spray behavior, which is enabled by changing in refractive indices. A high intensity pulsed LED with a pin-hole aperture is applied as the light source. One schlieren mirror is used to generate a collimated beam which is directed passing through the optical vessel and it is placed where its focal point coincides with the light source. Another schlieren mirror collects the beam and makes it converge on a negative bi-convex focusing lens where it is finally captured by a high-speed

camera. Unlike schlieren imaging system, the LED which is used for Mie scattering imaging is located in front of the side optical access of the combustion chamber [26]. Photron Fastcam SA 1.1 high-speed camera was used to acquire the liquid/vapor fuel spray at 30000 fps with an exposure time of 32.67 μ s. The camera lens is a Nikon Nikkor 85 mm lens with f-stop 1.4. The front view of the spray is captured when a high-speed camera is placed facing the injector window.

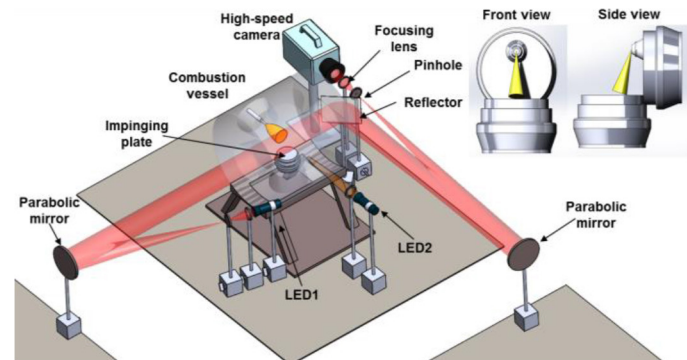


Figure 3. Optical setup for Mie and schlieren diagnostics with side view.

Bosch rate of injection (ROI) meter is adopted to obtain the injection rate shape by measuring the pressure wave generated when the injector injects fuel [27]. ROI profiles for the energizing injection time of 1 ms, 2 ms, and 4 ms at the injection pressure of 1500 bar are shown in Figure 4. The corresponding injection durations are approximately 1.6 ms, 2.9 ms and 4.8 ms. Figure 4 shows that the ROI profile is repeatable for different injection durations. ROI profile at energizing injection time of 2 ms was selected as the baseline condition for experimental and numerical evaluations. The total injected mass measured at ambient temperature is 114.5 mg, subsequently, this ROI measurement was scaled based on fuel temperature for the CV tests and then used in simulations.

The test condition for spray wall interaction is listed in Table 1. The 7-hole diesel nozzle was tested in the current work. The nozzle is characterized by a 139 μ m diameter, a K factor of 1.5 and an included angle of 148°. The ultra-low sulfur diesel (ULSD) is used as the fuel and its detailed properties listed in Table 2.

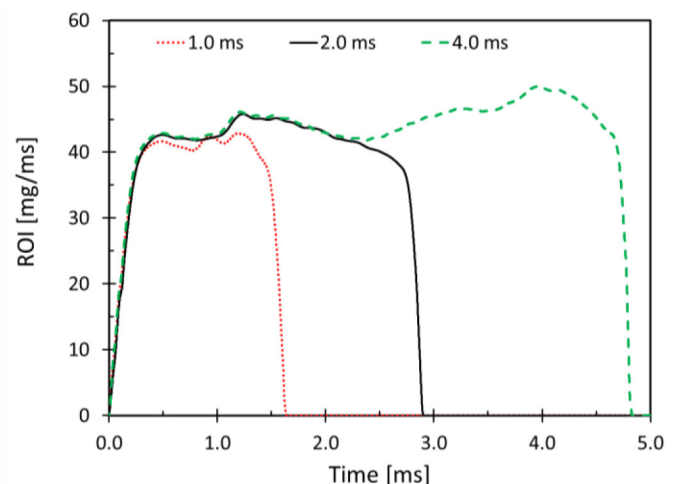


Figure 4. Rate of injection profiles for injection pressure of 1500 bar and 1-2-4 ms energizing injection time.

Table 1. Test conditions.

Parameter	Values
Ambient gas temperature	423 K
Ambient gas density	Varied
Ambient gas composition	100% N ₂ (non-vapor)
Ambient gas velocity	~0 m/s
Nominal nozzle outlet diameter	139 μ m
Nozzle K factor	1.5
Number of holes	7 (multi-hole)
Orifice orientation relative to injector axis	$\psi = 74^\circ$ (included angle: 148°)
Fuel injection pressure	150 MPa
Fuel	ULSD
Fuel temperature at nozzle	423 K (150°C)
Energizing injection time	2.0 ms
Distance between injector tip to impinging surface	65 mm

Table 2. Fuel (ULSD) properties.

Parameter	Values
Density	848 kg/m ³
Distillation	Initial boiling point: 344 K
	10%: 418 K
	50%: 514 K
	90%: 599 K
	Final boiling point: 656 K
Viscosity	2.6 cSt
Carbon (wt %)	86.8
Hydrogen (wt %)	13.2
Sulfur	8
Cetane Index	47.2
Net heating content	42.83 MJ/kg

Image Processing

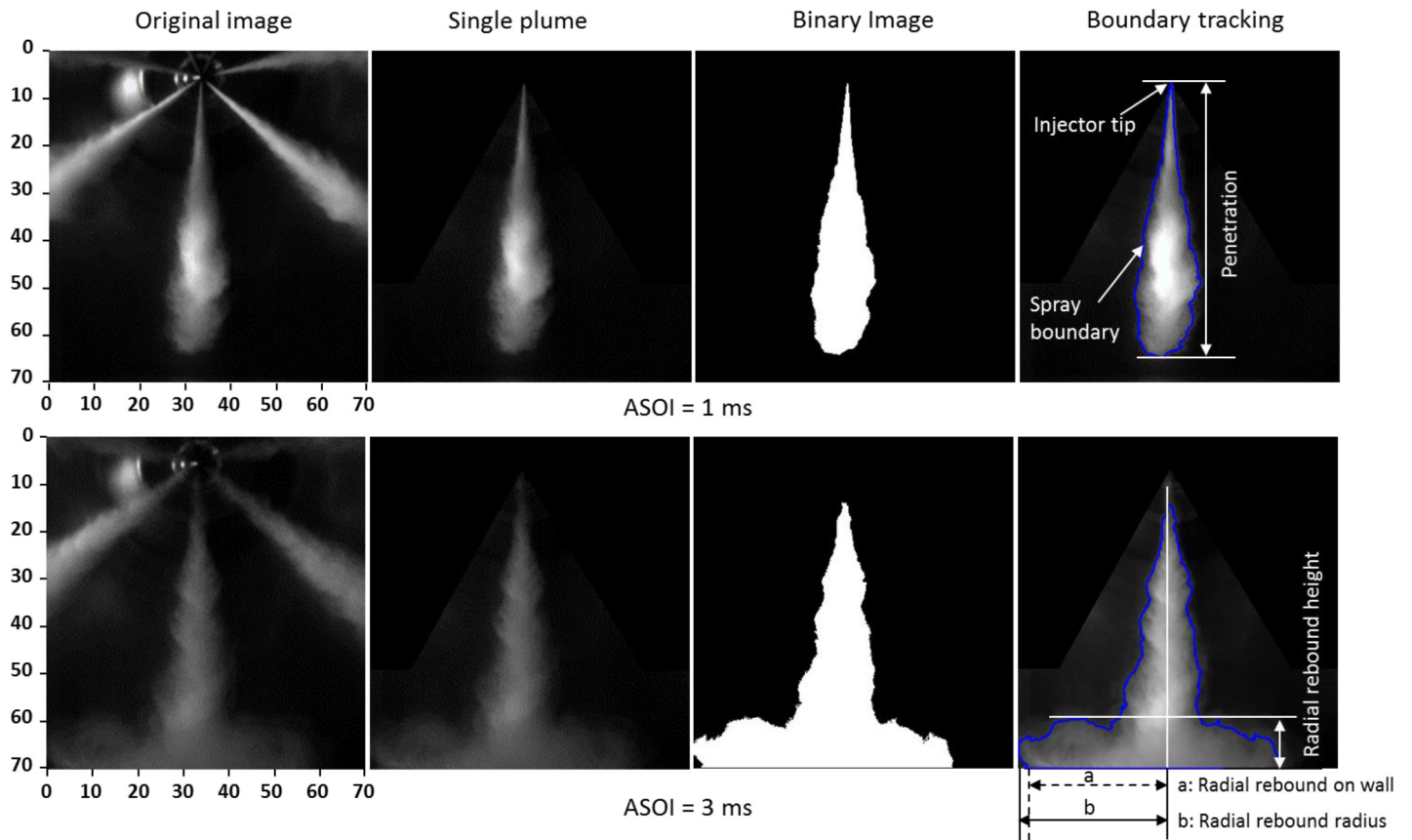


Figure 5. Results of image processing from Mie scattering images, liquid penetration (top) and radial properties (bottom).