Schlieren/Mie-Scattering Images of a High-Volatility Fluid Impacting on a Heated Surface: Liquid/Vapor Phase Detection

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Abstract The paper reports the vapor and liquid phase evolutions of sprays impacting on an aluminum flat wall, controlled in temperatures in the range from 300 to 573 K. The fluid is iso-octane, injected at pressures up to 25.0 MPa by a Common Rail apparatus. The spray-wall interaction was characterized by means of high-speed imaging. Schlieren and Mie-scattering images of the sprays were acquired nearly simultaneously along the same line-of-sight. The technique is suitable to highlight fluid with inner density gradients, allowing to detect both the liquid and vapor phase of the evolving spray. The optical system, coupled with a high-speed C-Mos camera, permitted to acquire the evolution of the spray on the wall at a frequency of 25,000 frames/s with images of 640x464 pixels. A customized image-processing procedure was developed was used to batch processing and outlining the contours of the liquid and vapor phase.

Keywords: DISI engines, spray-wall interaction, Schlieren, Mie-Scattering, Image processing

1 Introduction

The direct injection in spark ignition (DISI) engines offers undoubtedly substantial advantages with respect to the traditional port fuel injection (PFI) configuration [1]. Respect to the last one, they can operate at higher compression ratios, higher thermal efficiencies and power outputs, adopting different injection strategies and operation modes, and allowing an accurate metering of the air fuel ratio. They can work under lean fuel conditions in stratified charge mode, approaching to efficiencies and emission indexes typical of compression ignition engines. However, the achievement of a proper air-fuel mixture inside the combustion chamber, varying the engine load and the strategy of fuel injection, remains a critical point [2].

The evolution of the fuel spray inside the cylinder is governed by the injector nozzle design, the fuel pressure, the injection timing and by its interaction with the cylinder/piston walls [3-5]. Spray droplets hitting on the surface may rebound, stick to form a film on the wall, or undergo heating and evaporation. In particular, wall wetting should be avoided, because of its strong impact on the mixture formation and emission of particulate and unburned hydrocarbons. As a result, the widespread of DISI engines has given new impetus to the study of fuel spray behavior [6-9]. The new generation of GDI injectors adopts a non-axisymmetric multi-hole architecture, and at present, their behavior does not have yet exhaustively investigated [10-12]. To overcome the complexities inherent to the study of the spray-wall, the jet-jet or jet-flow field interactions, and their impact on the combustion in the engine, simplified experimental configurations considering single-hole injectors and heated flat walls can be profitably investigated [13,14].

In this work, the behavior of an isooctane spray impinging on a flat metal surface, varying the fuel injection pressure and wall temperature, was investigated in an optically accessible quiescent vessel. A single-hole axially-disposed injector was used, 0.200 mm in diameter and L/d=1.0, while the injection pressure and the wall temperature ranged between 5.0 - 20.0 MPa and room to 573 K, respectively. The phenomenon was analyzed by means of high-speed imaging. Schlieren and Mie-scattering images of the spray were acquired alternatively and in a quasi-simultaneous way along the same line-of-sight, using a C-Mos high-speed camera. The tests were performed at atmospheric backpressure and room gas temperature. The images were processed through a customized algorithm to better outline the contours of the liquid phase and the vapor/atomized zone. Spatial and temporal evolutions were measured for both the phases in terms of width penetration and thickness growth.

2 Experimental and Procedures

The tests were performed in a high-pressure vessel, optically accessible through quartz windows 80 mm in diameter. The vessel was kept at ambient temperature and atmospheric backpressure. The fuel was injected through a single-hole axially-disposed electro-injector (IHP-279 Magneti Marelli), 0.200 mm in diameter and L/d=1. A pneumatic injection system pressurized the fluid at pressures up to 20.0 MPa and fed the injector, with an injection timing of 1000 µs. Iso-octane was used as fluid. An aluminum flat plate, 80 mm in diameter, was placed 22.5 mm downstream the injector tip and orthogonally to the spray axis. The plate was heated in the temperature range 295-573 K. A thoroughly description of the apparatus can be found elsewhere [15].

The spray-wall interaction was characterized by means of high-speed imaging technique. Schlieren and scattering images of the sprays were acquired nearly simultaneous along the same line-of-sight, through the optical configuration shown schematically in Figure 1. The Schlieren setup was realized according a traditional Z-folded configuration using two 15° off-axis parabolic mirrors (4-inches in diameter, 508 mm parent focal length). The razor blade was positioned horizontally. A pulsed LED (Omicron LEDMOD V2 - 455nm / 450mW) was used as the schlieren light source. A pulsed cool-white LED emitter (LZP-00CW00, LedEngin, Inc.), 5500 lm on a 40 mm² light emitting area (25 LED's matrix), was the source of the scattering setup. The scattered light was collected in the forward, at a scattering angle of about 5°, as imposed by setup geometric constraints. The images of the impinging spray were acquired using a high-speed C-Mos camera (Photron FASTCAM SA4), at a rate of 25,000 frame per second (fps) (40 µs per frame) with an image window of 640x224 pixels. The camera was equipped with a 90 mm objective, f 1:2.8, resulting the spatial resolution 0.118 mm/pixel.



Fig. 1 Optical setup realizing the near-simultaneous acquisition of schlieren and Mie-scattering images

Schlieren and scattering images were acquired alternatively and in a quasi-simultaneous fashion using the "frame straddling" procedure [16], according to the timing diagram of Figure 2. Synchronized to the "sync out" signal of the camera, the TTL pulses driving schlieren and scattering LED sources (8 μ s each) are positioned straddling consecutive frames, with a resulting time-shift between two images around 10 μ s and an acquisition period of 80 μ s.



Fig. 2 Timing diagram of the schlieren/Mie-scattering images acquisition

10th Pacific Symposium on Flow Visualization and Image Processing Naples, Italy, 15-18 June, 2015

Figure 3 shows a time sequence of coupled Schlieren (left) and Mie-scattering (right) images acquired quasisimultaneously at 160, 240, 400, and 640 μ s after the start of injection (ASOI). The fuel pressure was 15.0 MPa and the temperature of the aluminum plate was 573 K. The total fuel injected quantity, Q_{inj}, was 4.19 mg/stroke.

Schlieren images take account of both liquid and vapor fraction of the spray, while the scattered light is largely due to the liquid fraction. After the impact of the jet on the wall, about 240 µs ASOI, the fuel spreads radially outward along the plate in a quite symmetric fashion. Scattering images of the impinging spray show a dark central line, because of the strong light extinction from the dense liquid core. A dark region is clearly observable also on the plate later from the impact, when a multitude of fuel still lies on the wall. It is surrounded by regions of high luminosity, due to the light scattered by the presence of finely dispersed fuel droplets. The schlieren images at the described condition highlight huge width and thickness structures of the fluid on the wall. They are mainly due to both the fuel vapor and the strong rebounding of droplets experiencing the great temperature of the wall, higher than the Nukiyama and Leidenfrost ones for iso-octane [17, 18].



Fig. 3 Schlieren (left) and Mie-scattering images (right) of the impinging spray acquired at 160, 240, 400, and 640 µs after the start of injection, being 15.0 MPa the injection pressure and 573 K the wall temperature. The total injected was 4.19 mg/stroke

3 Image processing

A customized image-processing [19] procedure, developed in C#.Net [20], was used to process the batch and outline the contours of the images. Schlieren and Mie-scattering images were treated little differently due to their diverse intensity of the spray image. The procedure is schematically shown in the flow chart of Figure 4.

Each image of the spray, I_{spray} (grey level matrix of the image), must be firstly corrected respect to the background levels. In the investigated conditions, the background intensity does not change significantly between successive frames throughout the injection process, allowing to use the first picture (the one without fuel) of the sequence as background image, I_{bg} . We perform a Change Mask filtering, an unusual method that will make full transparent the specific pixels in the destination image. In other words, the pixels in the destination image are those matching the given source image, according to the current Fuzz Factor setting [21]. Then, the resulting images undergo a gamma factor correction (2.3 for schlieren, 1.4 for elastic scattering), a Gaussian smoothing (11, 4) and a morphology filtering (dilatation for schlieren, erosion for scattering). The next step consists in a thresholding of the images. Schlieren images are subjected to an iterative threshold filtering [22], whereas the Otsu filtering [23] was applied to the Mie-scattering images.

After, a fill hole operation was adopted for filling the holes in the major feature and a contour detection allowed to identify the perimeters of the figures. The last step was the determination of the width and thickness of the liquid and vapor phases of the impinged figures.



Fig.4 Flow chart of the image processing adopted in the paper

A result of the above procedure is shown in Figure 5 as a sample. In the figure, the width and thickness outline overlaid on Mie-scattering and schlieren original I_{spray} images are shown. The example is referred to the condition shown in Figure 3 at 640 μ s after the impact, and reports the steps of the processing algorithm applied on schlieren (left) and Mie-scattering (right) images.

In the rows "a" and "b" of the Figure 5, the background and the raw images are reported. The background correspond to the images acquired immediately before the fuel injection. The Mie-scattering image on the right has a low brightness; nevertheless, the silhouette of the spray is clearly recognizable. In the figure, a core of the spray, both for the free-evolving side than for the impacted one, shows a dark area indicative of total extinction of the incident light due to the presence of a high density and strong atomization of the fuel. The row "c" shows the effects of the background subtraction for both the techniques. The goodness of the choice is in the quality of the results where alone the distribution of the impacting fuel appears clearly visible superimposed to a complete dark background. The threshold filter and the morphological operations previously described lead to the row "d" where a complete binarization of the figure is represented to permit a calculation of the maximum values of width and thickness of the spreading fuel after the impact. Finally, vertical and horizontal bars, indicative of the widths and thickness of the impact are reported in the row "e" of Figure 5.

10th Pacific Symposium on Flow Visualization and Image Processing Naples, Italy, 15-18 June, 2015



Fig. 5 Results of the image processing for schlieren (left) and elastic scattering (right). (a) background; (b) raw images; (c) results after the background subtraction; (d) threshold filter and morphological operations; (e) I_{spray} width and thickness outlines

In Figure 6 the results of the processing procedure have been overlapped the raw images of the impinging fuel. In fact, the blue line is the contour of the liquid part of the fuel recognized by the elastic-scattering technique and the blue bars indicate the maximum width and height. The red line, instead, indicates the contour of atomized/vapor phase and is the results of the schlieren techniques. The red bars indicate the elongation and thickness of the vapor. In Figure 6 these contours and bars are applied both to the schlieren (left) and elastic-scattered images (right). It appears evident that the profile contours do not fully catch the sprinkled droplets such as, on the contrary, some holes appear inside the silhouette. It is due to the threshold choices that loose some part of the fuel but these results are fully acceptable considering the complexity of the event.



Fig. 6 Overlay of width and thickness outlines on schlieren (left) and Mie-scattering (right) images

4 Results and Discussion

In this section, we will show some selected results regarding the effect of wall temperature on the behavior of the impinging spray.

Figure 7 illustrates the procedure used to determine the spray width and thickness, according the automatized procedure of contour shaping previously described and shown at the top of the figure. Per each image, the distance of the farthest point of the rebound fuel from the impact site (intersection of the spray-axis with the wall) in radial direction is considered as width value and the highest one, with respect to the plate, as thickness one for both the liquid (in blue color) and vapor (in red) parts. The analysis was carried out on both the "wings" of the figure while the graphs report the mean value for clarity of reading. The results were further averaged on five consecutive injections for an analysis of the spread to highlight the cycle variability.

At the bottom of the Figure 7, the graphs of width and thickness are reported having displayed the time after the impact on the x-axis. Concerning the width, bottom row on the left, the curves of the liquid and vapor rebound start from a coincident value of 2.12 mm and go on very close up to 240 μ s meaning a poor fraction of vaporization in the early stages of the impact. At later time, the curves split the trend and the vapor phase overcome the liquid one as result of the vaporization due to the heat exchange with the plate, which temperature was at a value highest that of the iso-octane boiling point. The width curves assume different slopes up to 480 μ s indicating a further growth of the vapor phase. Then, the development proceed increasing in a parallel fashion up to the field-of-view limit of the test section, resulted at around 30 mm. The increase of the widths shows linear vs. the time. The view-field limits are reached at 880 and 960 μ s for the vapor and the liquid, respectively. Indeterminations on the measures are reported in the graphs, too. They are calculated on five consecutive repetitions carried out at the same experimental conditions and show a quite reduced spread of the width all along the impact duration, indicative of a good repetitiveness of the process.

The thickness measurements, reported on the bottom-right of the Figure 7, indicate the spreading of the fuel in a direction orthogonal to the plate after the impact. Both the curves show an increasing trend during the impact but develop in a different way and point out an increasing gap versus the time from the start of impact.



Fig. 7 Width and thickness measurement procedure of the impact (top) and the graphs describing their behavior vs. the time from the impingement (bottom)

Figure 8 reports the widths (top) and thickness (bottom) of the liquid (left) and vapor fraction (right) versus the time after jet impact, for a fuel injection pressure of 15.0 MPa and plate temperatures of 295 K and 573 K. At the impact time, the liquid width is about 2 mm for both temperatures, and practically coincides with the vapor ones. After that, the displacement along the surface increases linearly versus the time from the impact up to 30 mm (maximum line-of-sight), and the slip along the wall of both liquid and vapor is faster at the higher temperature. The trend of the curves of thickness is still increasing versus the time from the impact with a tendency to saturate at long period. With respect to the width curves, a higher scattering of the results has been observed for the thickness ones. This is likely inherent to the complexity of the impingement and vapor ization processes, which is reflected in the difficulty of precisely defining the contours of liquid and vapor phase and the difficulty to define the image processing algorithm.

10th Pacific Symposium on Flow Visualization and Image Processing Naples, Italy, 15-18 June, 2015



Fig. 8 Width (top) and thickness (bottom) behavior of the liquid (left) and vapor (right) phases of the impinging spray at $p_{inj} = 15.0$ MPa and $T_W = 295-573$ K

5 Final Remarks

In this work, the characterization of the impact of a fuel jet on a heated aluminum flat plate was carried out. The fuel was iso-octane and the jet was generated by an axially-disposed single-hole GDI injector. The fuel injection pressure was15.0 MPa and the wall temperatures ranged between 295 and 573 K. The tests were performed in air at atmospheric backpressure and room temperature.

The phenomenon was analyzed by high-speed imaging technique. Schlieren and Mie-scattering images of the spray were acquired alternatively and in a quasi-simultaneous way along the same line-of-sight, using a C-Mos high-speed camera. The images were processed through a customized algorithm to outline the contours of the liquid and the vapor/atomized phases. Spatial and temporal evolutions were measured for both the phases in terms of width penetration and thickness growth.

The results seem substantiate the goodness of the image processing procedure, which allows automatically processing the schlieren and scattering images and outlining the slipping and rebounding figures of the fuel such as the liquid and vapor fraction produced through the heat exchange with the plate.

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Paper ID:095

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