Droplet Sizing in the Spray of a Fuel Injector Using Wavelet Analysis

R Stepanov *, V Batalov, A Sukhanovskii

Institute of Continuous Media Mechanics
Academic Korolyov, 1, Perm, 614013, Russia

E-mail: *rodion@icmm.ru

Abstract. The paper discusses the applied methods for studying the structure of the two-phase flow. Measurements of the size of liquid droplets in a spray of fuel injector were carried out using two methods: Interferometric Particle Imaging (IPI) and Glare Point Technique (GPT). The combined use of these methods allows to significantly expand the range of measured droplet sizes, and also provides an opportunity for cross-validation of methods and determining the level of errors. In this paper, we tested the IPI method using wavelet processing of interference drop images. As a result, it was shown that IPI images can have a highly inhomogeneous structure. This leads to a considerable variation in the period of the IPI-image and, as a consequence, to an increase of the error in determining the drop size. The proposed error estimation algorithm allows one to introduce an additional selection criterion and obtain statistically comparable results obtained by the IPI and GPT methods.

1. Introduction
Measurement of distribution of spray droplets by size, velocity, and spatial density is an important applied problem. Spraying processes are used in the medical, fuel and energy industries. Atomization is a complex multi-phase mechanical process that is carried out using nozzles and is characterized by the flow of liquid inside the nozzle, disintegration at the edge of the nozzle, splitting and breaking into small droplets when mixed with the gaseous phase, followed by evaporation or combustion. The desire to determine the true distribution of liquid droplets (particles) motivates many researchers. There is a variety of optical methods that are commonly used for measurements in sprays [1, 2, 3]. In simple cases, when the particle flux density is low and their images do not intersect, it is possible to obtain a distribution of liquid droplets (particles) sufficiently close to the true distribution by various optical methods, in particular, using Interferometric Particle Imaging (IPI) [4,5] and Glare Point Technique (GPT) methods [6]. With an increase in particle density, the results obtained by the IPI and GPT methods begin to diverge. In this regard, we make efforts to determine the causes of this discrepancy. Some questionable results obtained by the GPT method are easier to verify than the results obtained by the IPI method. In the case of individual distorted drops one can deal with them manually, because GPT method operates with focused high resolved images of droplets. On the other hand, the IPI method can be used for a much larger area than the GPT method, and developed IPI software is much less time consuming (e.g. Actual Flow software with IPI Kit).
Serious limitation of GPT concerns measurements of small droplets. In case of one-to-one imaging system droplets should be larger than 40-50 μm. In opposite IPI measurements are limited for large droplet sizing because spacing between fringes with increasing of droplets size becomes smaller. Another intrinsic problem of IPI is overlap of interferometric images in case of highly concentrated sprays [13]. In this paper we suggest an approach to verify the IPI method using wavelet transforms at...
the stage of processing IPI particle images. Comparison with GPT method is done for the case when GPT gives reliable results.

2. Results

2.1. IPI and GPT methods

The process of registering IPI and GPT droplet images is as follows. At some distance from the nozzle, drops of a transparent sprayed liquid acquire a spherical shape. In this area one can estimate the size of the droplets by their diameters. Drops (2) (see in figure 1) are illuminated with a short (10 ns) laser flash (1) formed in the form of a narrow band of light (“knife”) about 1 mm thick. The laser beam, reflected and refracted by a drop of liquid, forms two glares. The distance between them is proportional to the diameter of the drop with a certain coefficient depending on the angle of illumination [1, 2].

CCD cameras, synchronized with a laser, register the images of glares.

The difference between the IPI and GPT methods is that in the GPT method the camera captures focused glare images (3). The light glares (point light sources) on the drops are in focus, and the diameters of the drops are calculated by multiplying the number of pixels between the glares by a scale factor and a coefficient depending on the angle of illumination. In the case of the IPI method, a defocused image of the same glares is recorded, or rather, the pattern of interferometric fringes, and the drop diameters are calculated from the frequency of this interference pattern. To correctly understand why interference patterns are seen in the form of narrow strips, it should be noted that the IPI method uses cylindrical lenses that compress these images along one of the coordinates (in our case, vertically) to reduce their spatial overlap.

In papers [7, 8, 9, 10, 11, 12], these methods were compared for dense and sparse flows and it was shown that it is possible to measure droplets diameter simultaneously using the IPI and the GPT methods. Typical IPI and GPT images are shown in figure 2. The results of droplet sizing are close within the limits of error with a significant and rough filtering of non-valid particles only. Therefore considerable parts of distribution responsible for drops with largest and smallest sized are not detected.
We aimed in this work to recognize cases when droplets sizes, determined by the IPI and the GPT methods are substantially different. For this purpose, the flow was considered with a small density of about 3-7 drops per matrix frame of 24 by 36 mm and a resolution of 4004 by 2671 pixels (see figure 3). Also, we used a continuous two-dimensional wavelet transform to determine the dominant frequency in vicinity of each droplet.

2.2. Wavelet analysis

Wavelet transform was used for GPT image pre-processing in [18] and proved its efficiency. Some specific details should be emphasized in case of using wavelet analysis for IPI images. The continuous wavelet transform of a 2D map $f(x,y)$ is defined by

$$w(s,x,y) = \frac{1}{s^{3/2}} \int_{-\infty}^{\infty} f(x,y) \psi \left( \frac{x-x'}{s}, \frac{y-y'}{\delta} \right) dx' dy', \quad (1)$$

where $s$ is the spatial scale and the function $\psi(x, y)$ is 2D Morlet wavelet function with a satisfactory spatial resolution ($\omega = 2\pi, \sigma = 2$). The partiality of (1) is that we don’t dilate $\psi(x, y)$ in $y$ direction ($\delta$ is fixed). Wavelet coefficients are normalized by a factor $s^{3/2}$ in order to get the maximum intensity at scale corresponding scale of dominate interferometric component.

The result of wavelet analysis is shown in figure 5. One can see that of the seven images, the size of the droplets is determined only in four. The two drops in the bottom are outlined in the same color contours, indicating that the size is unambiguously defined in the image area.
The two upper images of droplets include areas dominated by wavelet coefficients corresponding to different sizes of droplets. It means that there are several spatial frequencies in interferometric pattern. It can be a result of parasitic glares or complex non-spherical shape of the droplet. In that case it should be treated as invalid droplet. There is another source which can lead to the variation of spatial frequency and to the systematic error. The optical distortions due to imperfection of lens and interferometric images compression can also provide the variation of spatial frequency.

Results of droplet sizing obtained by different methods are summarized in table 1. Using of wavelets can help to localize the distorted parts of the interferometric image and seriously improve the quality of measurements. Thus, it is possible to determine the value of the effective size and determine its confidence interval, which would include the value of the size obtained on the basis of GPT method.

Table 1. Sizes (in pixels) of droplets from figure 5 which are determined by different methods. Non-valid determining are highlighted by gray backcolor.

|   | GPT     | IPI by wavelet | IPI by AF IPI Tit |
|---|---------|----------------|-------------------|
| 1 | 9.3±0.1 | 10±1.1         | 22                |
| 2 | 8.0±0.1 | 9.5±1.2        | 23                |
| 3 | 12.3±0.1| 12.5±1.1       | 13                |
| 4 | 12.9±0.1| 13.5±1.8       | 14                |
| 5 | 7.7±0.1 | 8.0±0.8        | 18                |
3. Conclusions
As a result, it was shown that IPI images can have a highly inhomogeneous structure. This leads to a significant variation in the period of the interference image and, as a consequence, to an increase in the error in determining the drop size. The proposed error estimation algorithm allows one to introduce an additional selection criterion and obtain statistically comparable results obtained by the IPI and GPT methods.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research and by the Perm regional government under project No. 19-08-00574.

References
[1] Tropea C 2011 Annual Review of Fluid Mechanics 43 399-426
[2] Fansler T D and Parrish S E 2014 Measurement Science and Technology 26 012002
[3] Gouesbet G and Gréhan G 2015 International Journal of Multiphase Flow 72 288-297
[4] Maeda M, Kawaguchi T and Hishida K 2000 Measurement Science and Technology 11 L13
[5] Kawaguchi T, Akasaka Y and Maeda M 2002 Measurement Science and Technology 13 308
[6] Van de Hulst H and Wang R 1991 Applied optics 30 4755-4763
[7] Zama Y, Kawahashi M and Hirahara H 2004 Optical review 11 358-364
[8] Zama Y, Kawahashi M and Hirahara H 2005 Measurement Science and Technology 16 1977-1986
[9] Hess C F and LEesperance D 2009 Experiments in fluids 47 171-182
[10] Lacagnina G, Grizzi S, Falchi M, Di Felice F and Romano G P 2011 Experiments in fluids 50 1153-1167
[11] Qieni L, Kan H, Baozhen G and XiangW 2016 Optics express 24 16530-16543
[12] Qieni L, Xiaoxue Y, Baozhen G and Tingting C 2018 Optics Express 26 1038-1048
[13] Bocanegra Evans H, Dam N, van der Voort D, Bertens G and van de Water W 2015 Review of Scientific Instruments 86 023709
[14] Sukhanovskii A, Batalov V and Stepanov R 2016 AIP Conference Proceedings 1770 030023
[15] Sukhanovskii A, Batalov V and Stepanov R 2019 Exper. Thermal and Fluid Science 103 29-36