Measurement of Diameter and Volume Density Distribution in Diesel Fuel Sprays by Means of Holographic Technique

X.Y. Gao and G.D. Hu
I. C. Engine Institute
Dalian University of Technology
Dalian 116023
P.R. China

ABSTRACT

In this paper, the fundamental principle of the holographic measurement system in diesel fuel spray is described. Moreover, the application of measurement for droplet size and its volume density distribution in diesel fuel sprays in actual single-cylinder diesel engine is discussed emphatically. Major technical parameters and key techniques are presented.

INTRODUCTION

Because the pulsed laser holography has many good qualities, such as high time response and spatial resolution, great information capacity and being suitable for non-contact measurement, it gains more advantages over other measurement means in diesel spray field research. However, holography in practical application is still very difficult due to the complicated condition in actual diesel engine and the actual injected fuel jet being composed of many small droplets with very high velocity and wide range of the droplet size. In the past, most scholars studying diesel fuel sprays laid particular stress on the study of parameters such as depth of penetration L and cone angle, but didn't develop the research in droplet-size characteristics in fuel sprays until recently, and they did it isolatedly. Few searched for the essential relation between macroscopic characteristics and microscopic characteristics in spray field and studied the effect on the whole combustion process resulted from the coordination between those characteristics and combustion chamber.

Generally, the number of droplets is enormous in a spray of diesel engine, e.g. for a millilitre diesel oil, the average diameter of droplets is 25.4 after atomization, so there are 1.22 x 10^8 droplets. Therefore, it is meaningless and impossible to measure all or most of the droplets. The macroscopic distribution is very useful research goal.

Applying single pulse laser holography to record the spray region of sprays can analyze the droplet-size characteristics and evaluate the spray quality of spray system. In addition to process the droplet-size data with computer, dw & ds of droplets and droplet frequency diagram can be obtained.

Applying double pulse laser holography can record whole region of sprays. By processing the interference fringe we can obtain the volume density distribution in vaporization and atomization regions of sprays, and we can obtain the volume density distribution in high concentration and core region of sprays by pseud-color processing. Aided by the image processing system, we can draw the various concentration regions of sprays conveniently and catch the real sight of the spray parameters in actual diesel engine such as depth of penetration L and cone angle.

In summary, applying means mentioned above can analyze the diesel spray more completely and perfectly. They can also be applied to other type of spray study.

MEASUREMENT OF THE DIAMETERS OF SPRAY DROPLETS

In-line holography

In-line holography, with the advantages that its optical path is uncomplicated and convenient to adjust and the requirements for the coherence of light source and the resolution of record medium are low, compared with microphotography, can be three orders of magnitude higher in record depth of field and obtain the three-dimensional record and reconstruction of the spray droplet field. Therefore, it is very suitable for the measurement of diesel spray droplets. With the application of reconstructing and data processing system in dense droplet field, the application and development of in-line holography are improved and popularized.

In-line holography is interferential double imagery technique in which object light, reference light and illumination light are located in optical axis. The in-line holographic recording optical path diagram of droplets (the upper) and that of reconstruction (the lower) are shown in Fig.1. The droplet whose diameter is d is located in coordinate original point. When illuminated by the unit amplitude plane wave whose wavelength is and Zo, the distance from record medium plane to the droplet, meets the far-field condition, the droplet is recorded. The condition is as follows:

\[ Z_0 = \frac{N \lambda}{d}, \quad N > 1 \]
Fig. 1. In-line holography

where \( N \) is the far-field number, whose sampling range is limited by reconstructed image quality. Generally this is proved by practice:

\[
1 < N < 50
\]

(2)

There is a limitation for the density of droplets. High density could make the image quality poor even indistinguishable. The conception of density shadow is ordinarily used to describe the limitation. If the area of the transverse section of a recording space is \( S \), there are a number of droplets in it, and the diameter of the \( i \)th droplet is \( d_i \), the conception of density shadow is defined as the ratio of the sum of the cross-section area of all the droplets to \( S \), i.e.

\[
C = \frac{\pi}{4S} \sum_{i=1}^{n} d_i^2
\]

(3)

It is proved by practice that sampling \( C \leq 5\% \) is appropriate.

Recording system

Holographic recording system is shown in Fig. 2. The following should be taken into account while designation.

Choice of light source: we chose a pulsed ruby laser with an output greater than 50mJ, generally, a impulse duration less than 30 ns, and coherent length greater than 0.5 m.

Choice of pick-up camera: in order to take pictures of whole spray field without moving the optical system and keep the enlargement factor constant, we adopted confocal system. The enlargement factor is 2-7. The resolution ratio is \( \lambda / m \). The enlargement factor should be greater than 2 because of considering the resolution of coherent board, and no more than 7 because the output of light source is considered and it's easy to give rise to air breakdown in confocal point. In the same time, in order to improve the resolution, decrease object distance and increase aperture as far as possible.

Fig. 3. Reconstruction and data processing

The system includes an adjustable optical system, a TV camera system, a frame memory device and a JWL computer hondrometer with its peripheral equipment, etc. The hologram \( H \) is held on three-dimension adjustable mount and is illuminated through an extender len by a collimated He-Ne laser. The reconstructed image of the hologram magnified by len appears on the cathode of the camera and after remagification, a clear oil droplet planar image is formed on the screen. When moving the hologram along the direction of laser beam i.e. the Z direction with the help of the mount, the different focused images of different layers can be obtained successively. When the hologram is moved in the X or Y direction, the images of different sampling regions are obtained.

The information about the droplet size over the planar image field is turned into digital signals which are sent to the frame memory. Data stored in the frame memory can be read to the computer for processing, JWL which
classified the droplet with respect to their diameters prints out the results of diameter classification and their statistical values. Fig.4. gives an example of reconstructing and processing image.

![Image](image.png)

**Fig. 4. The reconstructed image of droplets**

**MEASUREMENT OF VOLUME DENSITY DISTRIBUTION IN DIESEL FUEL SPRAY FIELD**

**Double-exposure off-axis holography**

Generally, there is a definite physical correlation between volume density of spray field \( p(x,y,z) \) and refractivity field \( n(x,y,z) \). If we regard the vaporized oil spray as perfect gas, according to Gladstone-Dale equation, we can set up the following related equations:

\[
\begin{align*}
\n \frac{2(n-1)}{\rho} = \Sigma \frac{4}{\rho} = \frac{RT}{p} \\
\end{align*}
\]

\( \rho = pRT \)  
(4)

where \( \Sigma \) is characteristics refractivity, which is the function of medium and the wavelength of light passing through the medium.

Apply laser holography and interferential means i.e. double-exposure off-axis holography, we can obtain \( n(x,y,z) \) and then calculate \( p(x,y,z) \) by inversion. Since it is non-contact, the measurement has little influence on the spray field and can be quantitative.

Double-exposure laser holography usually record instantaneous object waves on the same medium and form hologram independently. While images are reconstructed, the interference fringe are produced because of the interference between two wave fronts.

When taking hologram, we record hologram i.e. expose for the first time while injection with a fixed rotation speed, then expose for the second time in the same condition. What is called double-exposure method.

When reconstructing the double-exposure hologram, we can observe the interference fringes on the double-exposure hologram.

**Actual optical path**

The diagram of the actual optical path is shown in Fig.5. The parameters of the engine and laser device on which experiment is performed are listed in the following tables.

![Diagram](diagram.png)

**Fig. 5. Double-exposure off-axis holographic system**

**Table 1 - engine parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of engine</td>
<td>EL50</td>
</tr>
<tr>
<td>Stroke number</td>
<td>2</td>
</tr>
<tr>
<td>Scavenging pressure</td>
<td>0.12MPa</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>750rpm</td>
</tr>
<tr>
<td>Cylinder diameter/stroke</td>
<td>150mm/225mm</td>
</tr>
</tbody>
</table>

**Table 2 - laser device parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>XJ-1</td>
</tr>
<tr>
<td>Output</td>
<td>250mJ</td>
</tr>
<tr>
<td>Impulse duration</td>
<td>30ns</td>
</tr>
<tr>
<td>Coherent length</td>
<td>1m</td>
</tr>
</tbody>
</table>

**Fringe processing technique**

By reconstructing the double-exposure hologram, processing the interference fringe and calculating inversively, we can obtain volume density and temperature distributions of the spray field. The method has few problems in theory, and performed by J.C. Dent in practice, but because they are obtained from actual diesel engine, the actual hologram carry a lot of noise information due to the limited condition. It brings difficulty to actual calculation.

Applying computer and what is called the skeleton method of slenderized fringe tracking, we can draw the fringes which are complicated and difficult to distinguish with computer conveniently, resulted in improving the precision of inverse calculation for an order of magnitude.

**Fringe tracking criterion**

a. Scan the images and search for the point meeting detection criterion. When the signal is achieved, take it as current point (h,k) in the curve being tracked.

b. Detect the neighborhood of the point (h,k) and apply proper tracking algorithm, which depends on the grey scale of candidate point, the distance from the current point and its direction. Once find a perfect candidate point, take it as the next current point.

c. If can't find the point meeting detection criterion, the fringe tracking is over. Then continue to track the next fringe.

**Fringe tracking** According to fringe tracking criterion, the skeleton curve of interference fringe obtained by fringe tracking really reflect the characteristics of interference fringe. Fig.6 is an example of fringe tracking.
to the prior appointed color. Therefore, the spray volume density distribution can be obtained from the color images. A pseudo-color image of spray is shown in Fig. 7.

Fig. 7. Pseudo-color Image of a Spray

Comprehensive measurement of volume density distribution. Putting the methods mentioned above into use can take the pictures of spray distribution in cylinder.

They provide effective analytical means for studying combustion in diesel engine. A kind of spray distribution is shown in Fig. 8, 9.

Fig. 8. Vapour Concentration.

Fig. 9. The Spray Volume Density Distribution
CONCLUSION

a. Referring to the photoraphic parameters which is designating by author, can take the clear pictures of droplets in oil spray conveniently.
b. We can obtain droplet sizes and their distribution in spray field by applying JWJ droplet size analytical system.
c. The interferential images of volume density in spray vaporization region can be obtained by using double exposure interferential holography.
d. Applying the skeleton method of interferential fringe tracking, we can distinguish interferential fringes precisely, and make it easy to calculate inversely.
e. The volume density distribution of high concentration spray can be obtained by using pseud-color technique.
f. Applying the three methods mentioned above, we can analyze spray distribution law and atomization characteristics comprehensively and provide important means for the research of combustion mechanism in diesel cylinder.

REFERENCES

5. K.J. Wu etc.," Measurements of Drop Size at the Spray Edge near the Nozzle in Atomizing Liquid Jets" Submitted to Phys. Fluids.