The Laser Holographic Study on Fuel Atomization of Diesel Spray

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ABSTRACT

This paper presents preliminary experimental study on fuel atomization process of Diesel spray injected into quiescent gas from hole type nozzle. A laser holographic and data processing system for Diesel spray have been developed. Three different holographic methods, that is, in-line holography, off-axis holography and laser shadowgraphy were applied to record and visualize the fuel atomization process of Diesel spray. New atomization phenomenon and inner structure in Diesel spray were discovered and presented here. Information on disintegration process, droplet formation, droplet size and distribution was obtained. Based on microscopic observation and analysis, discription and discussion of the shape and structure of Diesel spray and the mechanism of atomization were made.

Key Words : Fuel Atomization, Diesel Spray Laser Holography

INTRODUCTION

The atomization of Diesel spray is a very important process in Diesel combustion, since it strongly influences spray penetration, evaporation and fuel-air mixture formation in Diesel spray. Therefore, investigation on Diesel spray atomization has been performed by many researchers as the basic study of Diesel combustion. [1-6] However, the physics of fuel injection and atomization of Diesel spray is a very complicated transient process, the contents and symptoms of which are often very difficult to measure and diagnose. The inner structure of Diesel spray is still largely unknown and the detailed atomization mechanism is not well understood.[7,8]

Pulsed laser holography with its ability to freeze three dimensions dynamic test volume with high resolution, which has hitherto never been possible by any other techniques, is a powerful tool for Diesel spray visualization and analysis. [9,10] In this paper, the laser holography including in-line holography, off-axis holography and laser shadowgraphy were applied to record and visualize the fuel atomization process of Diesel spray in three dimensions. New atomization phenomenon and inner structure in Diesel spray were discovered and presented here. Information on disintegrating process, droplet formation, spray shape and structure of Diesel spray from holographic visualization is useful to clarify the mechanism of Diesel spray atomization and will greatly help to promote combustion research.

EXPERIMENTAL TECHNIQUE AND APPARATUS

Holography is a two-step image-forming technique for recording and reconstructing the light waves.[11] Application of the pulsed laser holography enables a record of a high velocity transient fuel spray to be frozen in time. This recording can subsequently be reconstructed into the original three-dimensional form and analyzed at leisure without the deterioration of the sample.

According to the need of Diesel spray research, a special heated and pressurized vessel with two quartz windows for optical access has been developed and a laser holographic and data processing system for Diesel spray have been set up.

The layout of the recording system is shown schematically in Fig.1, The ruby laser is Q-switched with a Pockels cell and emits a 30 to 50 nanosecond light pulse. the optical wedge is used to produce two beams, which are expanded and collimated to the size of the quartz glass window. One is led into the vessel to be transmitted through the spray as object beam. The imaging lens provide a enlarged image of the spray close to the holographic film and relax the resolution requirement of the hologram. The other one is led to the holographic film as reference beam combined with the object beam. All the optical components and the vessel are arranged on a massive isolated table. This off-axis layout could be easily changed into in-line layout by removing the reference beam.

The reconstruction and data processing system is shown in Fig.2. A coherent plane wave provided by a helium-neon gas laser illuminates the hologram which is transported on a three-dimensional motor-driven carriage controlled by computer to reconstruct the fuel spray. The reconstructed real images are magnified and relayed into the TV camera by image lens. The system transforms the video signal into digital signal and provides a image of matrix of 512*512 elements which is quantized linearly with 256 brightness levels from 0 to 255. The digital image is processed by computer with the threasholding and infocus discrimination techniques to open data source for studying the spray atomization.[12,13]

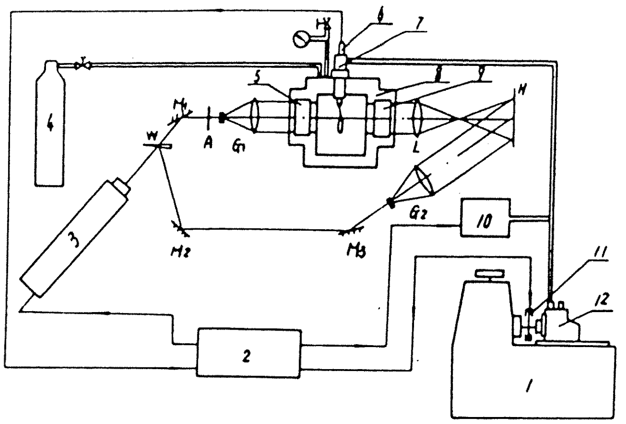


Fig.1 Schematic of holographic system

1. Fuel pump rig 2. System controller 3. Pulse ruby laser
4. Air bottle 5. Quartz window 6. Transducer
7. Fuel injector 8. Pressure vessel 9. Quartz window
10. Auxiliary injector 11. Angle markers 12. Injection pump
W- Optical wedge G- Beam B/C A- Attenuator
M- Mirror L- Imaging lens H- Holographic film

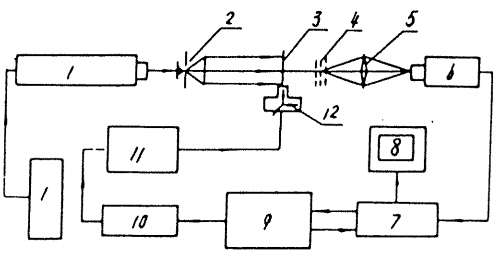


Fig.2. Schematic of reconstruction and data processing system.

1. He-Ne laser 2. Spatial filter/BC 3. Hologram
4. Reconstructed image 5. Imaging lens 6. TV camera
7. Pcvision plate 8. Monitor 9. Computer
10. D/A circuit 11. Step-motor power 12. 3-D carriage

Table 1 Experimental conditions

Fuel	Diesel fuel oil GB-252-64 Density: $\rho = 810\ kg/m^3$ Viscosity: $\nu = 5.5\cdot10^{-6} m^2/s$ Surface tension: $\sigma = 27\cdot10^{-4} kg/m$
Injection Nozzle	Hole type nozzle (Single-hole with orifice dia. 0.35, 0.45 mm)
Nozzle Opening Pressure	18 MPa
Injection Quantity	60 mm^3/stroke
Ambient Gaseous Pressure	0.1, 0.89, 1.5, 2.1 Mpa
Pump	BH2B90YS (Bosch type)
Pump Speed	750 r.p.m

In this work, Off-axis holography and Laser shadowgraphy were used to record the fuel atomization process of Diesel spray. By means of reconstruction, microscopically observation and computer image processing technique, the disintegrating process, droplet formation, inner structure and shape of the spray were studied. The initial atomization length, core angle and mantle angle were measured. In-line holography was used to analyse particle field of Diesel spray. With the help of data processing technique, the fuel droplet size and distribution in Diesel spray was obtained.

The experiments were conducted under conditions as shown in Table 1.

OBSERVATIONS AND ANALYSIS

The Physics of fuel injection and atomization of Diesel spray is a very complicated transient process. In this work, with the help of pulsed laser holographic technique, the inner structure of Diesel spray was visualized in microscopic and three dimensional details and some new atomization phenomenon were discovered.

This work starts with the fuel atomization under atmospheric pressure. It is found that the atomization of the fuel spray goes through the following stages.

(1) When just injected, the spray is close to cone-shaped fuel column with extremely high density, as shown in Fig.3(a). The tip of the spray usually appear flatten due to air resistance. Sometimes the tip may also appear wedged because it is overtaken by succeeding fuel due to sharp increase in injection pressure. small number of fine sluggish fuel droplets in the edge of fuel column could be observed.

(2) At the initial developing stage of the spray, the liquid fuel injected becomes unstable and disintegrates into fragments and ligaments that, in turn, break up into droplets. There are clouds of sluggish atomized droplets in the immediate vicinity of the spray-core. It is worth noticing that the tip of the spray composed of fragmental and ligamental fuel structure remains to be unatomized. The typical photograph is shown in Fig.3(b).

(3) At the fully developed stage of the spray, the atomization process tends towards steady. The spray tip further breaks up into droplets and disperses. Numerous small atomized droplets form spray mantle, as shown in Fig.3(c).

The fuel atomization process under higher ambient gaseous pressure varied from 0.89 to 2.1 Mpa is further examined. The ambient gaseous pressure has great influence on the atomization process. The higher the ambient gaseous pressure, the more unstable the spray and the shorter the atomization length. It is found that the inner structure of the spray under high ambient gaseous pressure is similar in shape to the axially compressed inner structure under atmospheric pressure. The fact that higher ambient gaseous pressure results in dense spray also causes difficulty in the spray visualization. Fig.4 shows break-up of the fuel spray under higher ambient gaseous pressure, which is drawn according to microscopic observation and analysis of the reconstructed images.

The investigation further shows that the

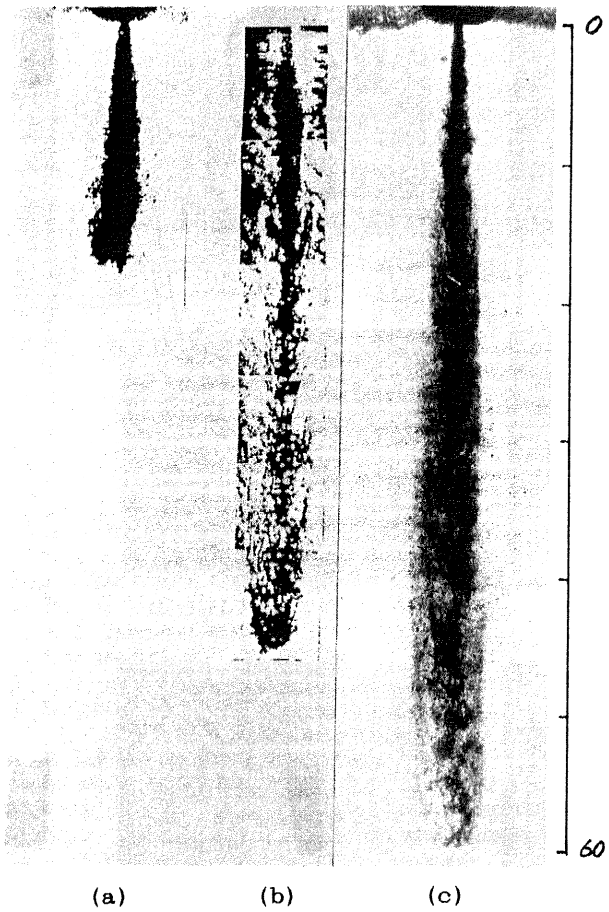


Fig.3 Development of Fuel spray (Pa = 0.1 MPa)

Fig.4 Break up of fuel spray (Pa = 0.89 MPa)

atomization of diesel spray usually exhibits three modes of disintegration described as wave, dendritic, and chaotic disintegration.

In the wave mode, the initial disturbances, liquid-air aerodynamic interaction and surface tension cause the previously smooth fuel column to be wavelike with very many irregularities, which further becomes unstable and disintegrates into fragments, and subsequently break up into droplets, as shown in Fig.5(a-f). When this occurs, the resulting droplets tend to be large and have large momentum, which continue to move in the original injection direction. Due to high injection pressure in Diesel engine, wave disintegration is highly irregular and consequently droplets size are much more varied.

At the same time, in the dendritic disintegration shown in Fig.5(c,g-j), the high relative velocity between the outer fuel column layer and air, combined with air friction, causes the irregularities on the fuel column surface to be torn into swept-back ligaments, which rapidly further break up into fine droplets due to the above mentioned force. Fig.6 shows the development of the disintegration. As the relative velocity and ambient gaseous density increase, the size of the ligaments decreases and their life becomes shorter. The resulting droplets tend to be small and quickly become sluggish to form spray mantle.

The chaotic disintegration is most prominent when the relative velocity and ambient gaseous density are both high. Large gas shearing force crushes wavy liquid column and swept-back ligaments into droplets, as shown in Fig.5(k,l). This mode could occur even before wave or ligament forms if the gas shearing force is large enough. In consequence, it tends to produce better atomization and fine droplets.

The atomization of Diesel spray is usually capable of exhibiting all three modes of disintegration. The wave mode usually occurs in the inner part of the spray, the dendritic mode in the outer of the spray, and the chaotic mode in the both. Three different modes usually occur simultaneously, and their relative importance can greatly influence both the mean droplet size and the droplet size distribution.

From the photographs and analysis, the following inner structures of Diesel spray can be seen.

(1) Wavelike fuel structure.

(2) So-called dendroid fuel structure which consists of wavelike liquid column, swept-back ligaments and atomized droplets, exactly like the trunk, branchs and fruits of a tree.

(3) Fragmental and ligamental fuel structure.

(4) Atomized fuel droplets.

It is worth noticing that in above modes of disintegration perforated fuel structure could be observed. As Fig.5(i,j) illustrated. This phenomena may be caused by liquid cavitation. But its detailed mechanism is still not clear.

On the bases of the large number of experimental observations carried out on the hole type nozzle which are dealt with in this work, it turned out that (1) The injected Diesel fuel does not break up immediately after injection. There are break-up process and atomization delay in Diesel spray. (2) There exist multiple mechanisms in atomization process which all contribute to the fuel atomization. Among them liquid-gas aerodynamic interaction mechanism holds an important position.

THE SHAPE AND STRUCTURE OF DIESEL SPRAY

Based on experimental observation and analysis on the hole type nozzle, the structure and shape of Diesel spray can be seen as divided into three regions, that is, the spray core, post-atomization region and spray mantle, as shown in

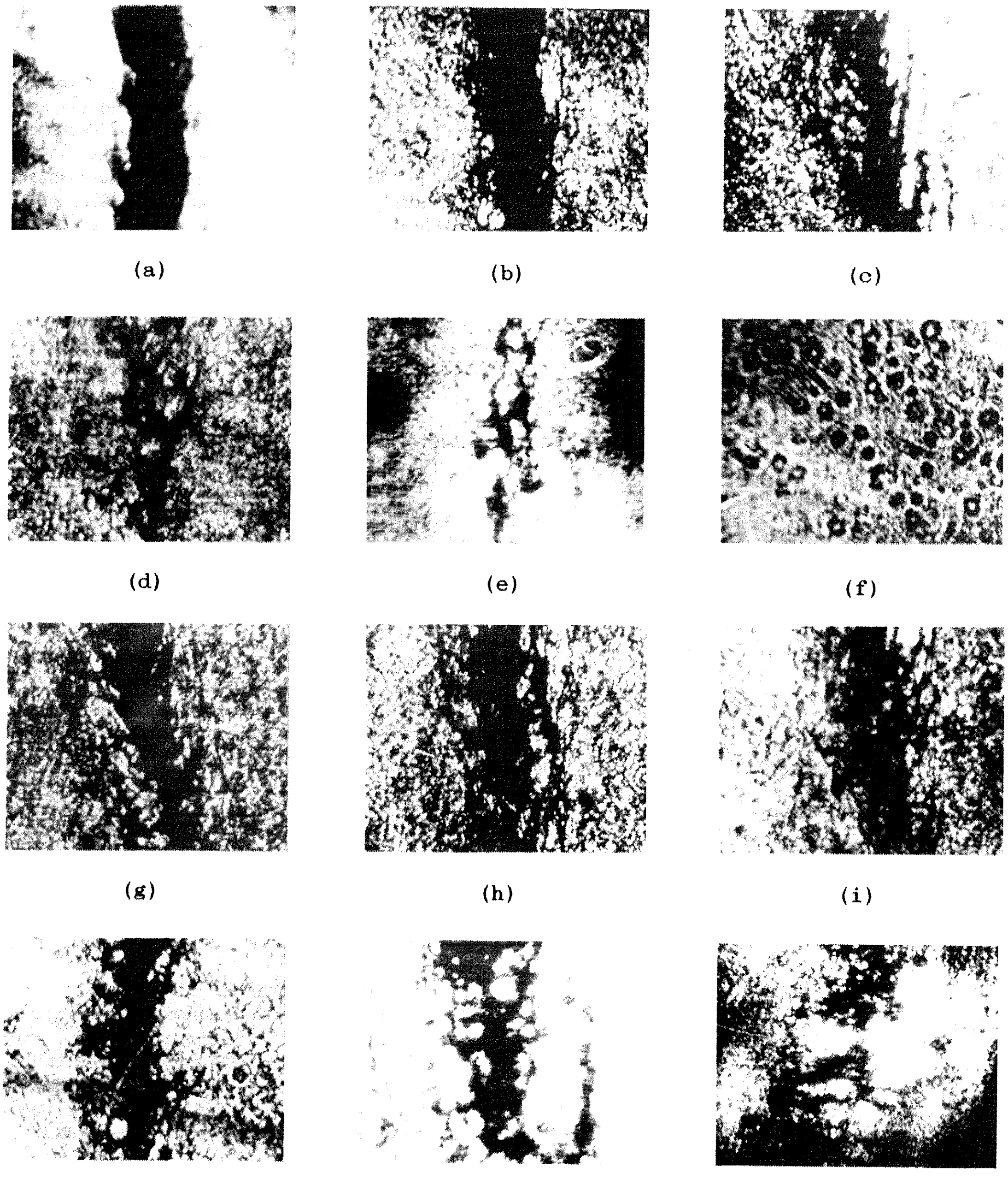


Fig.5 Reconstructed images of inner fuel structure
(Off-axis holography)

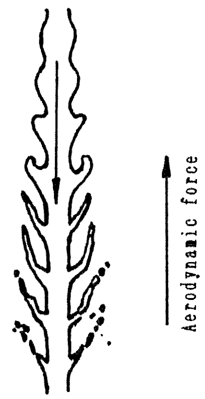
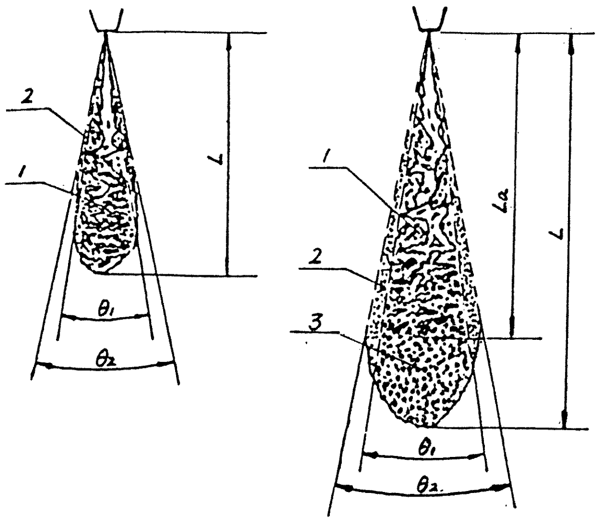


Fig.6 Development of dendritic fuel structure

Fig.7. Where L is the spray penetration, La the atomization length, θ_1 and θ_2 is the core angle and mantle angle respectively.

The core region mainly consists of wavelike, dendroid, fragmental and ligamental fuel structure and fuel drops. The postatomization region that only appears at fully developed stage is composed of large number of atomized drops. While numerous small satellite droplets form spray mantle. The droplet momentum and droplet number density is far larger in the core and postatomization regions than in the mantle.

In order to analyse the shape and structure of the spray quantitatively, the atomization length, spray angle and droplet size distribution were further measured.



(a) (b)

Fig.7 The shape and structure of Diesel spray
(a) Initial developing Stage
(b) Fully developed stage
1. Core region
2. Spray mantle
3. Postatomization region

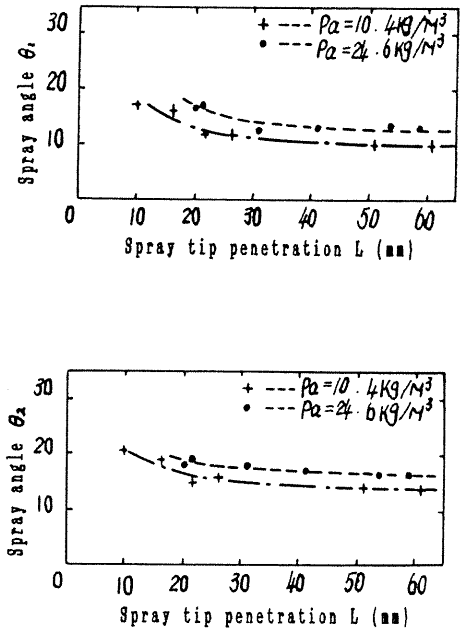


Fig.8 Development of Diesel spray angle

The Initial Atomization Length

So-called atomization length is the length from nozzle to point where the fuel atomization finished. Diesel fuel injection and atomization is a very complicated transient process. So the atomization length is not a constant and very difficult to measure. In this work, preliminary measurement of initial atomization length is conducted by means of off-axis holography and laser shadowgraphy. It is found that ambient gaseous density and diameter of nozzle have large effect on the atomization length. Increase the ambient gaseous density from 10.4 kg/m^3 to 24.6 kg/m^3, the initial atomization length shortens from 58 mm to 41 mm. The following expression of initial atomization length was made from the data obtained from this investigation and by applying the jet atomization theory of Levich.[14]

$$La = 19.3 \cdot d \cdot (\rho_f / \rho_a)^{0.5} \quad (1)$$

where ρ_f and ρ_a is the density of fuel and ambient gas respectively, d the diameter of nozzle.

The Spray Angle

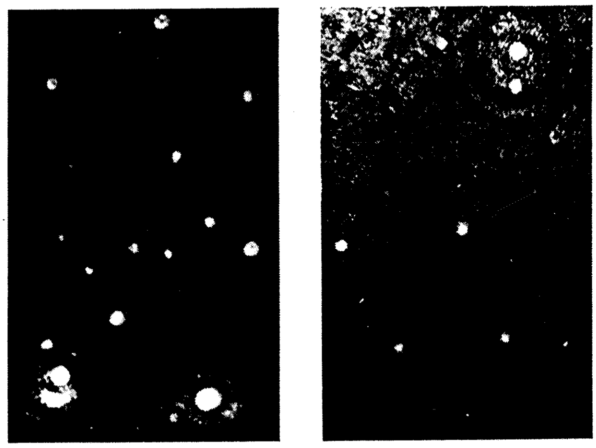
The Diesel spray angle including the core angle θ_1 and mantle angle θ_2 were defined and measured by means of laser shadowgraphy. It is found that as injection just begins, θ_1 and θ_2 are both large and are close in value due to large static air resistance and outstripping of succeeding fuel, which means poor atomization. With the development and penetration of Diesel spray, θ_1 and θ_2 decrease and subsequently tend to approach an almost constant value at the fully developed stage. Fig.8 shows the development of the spray angle at two different ambient gaseous density. It is seen that the effect of the ambient gaseous density on the spray angle is large. The θ_1 and θ_2 increase with an increase in ambient gaseous density. Based on experimental results, once the parameter of fuel injection system is fixed, correlation between the spray and ambient gaseous density at fully developed stage is found to be:

$$\text{tg}\,\theta_1 = 0.822 \cdot (\rho_a / \rho_f)^{0.35} \quad (2)$$
$$\text{tg}\,\theta_2 = 1.14 \cdot (\rho_a / \rho_f)^{0.35} \quad (3)$$

The Droplet Size And Distribution

Due to high droplet number density of Diesel spray, the fuel droplet size and distribution was analysed by sampling a slice of the spray using in-line holography. Fig.9 shows the reconstructed images of fuel droplets in Diesel spray under atmospheric pressure. The data of holograms were analysed by the computer data processing system and some example of droplet size distribution at different sampling positions is presented in Fig. 10. It is seen that fuel droplets below 30 μm in diameter make up 94 per cent of the total. The fuel droplets size decreases with an increase in distance between nozzle and sampling position.

The effect of the ambient gaseous pressure on droplet size in Diesel spray was also examined. The results indicate that change in ambient gaseous pressure varied from 0.89 to 2.1 Mpa appears to have no remarkable influence on droplet size. However, the droplet size under higher ambient gaseous pressure mentioned above tends to be smaller than that under atmospheric pressure. The reason why could be explained as follow. Increasing ambient gaseous pressure results in increase in gaseous density and therefore promoting fuel disintegration which contributes to better atomization and tends to produce small droplets. On the other hand, increasing ambient gaseous pressure results in decrease in the spray velocity and penetration which leads to poor atomization and tends to produce coalescence of droplets. The relative importance of two opposing effects controls the effect on droplet size of Diesel spray.



(a) Z = 4.5 cm (b) Z = 7.5 cm

Fig.9 Reconstructed images of fuel droplets in Diesel spray (In-line holography) Z is the distance between nozzle and sampling field

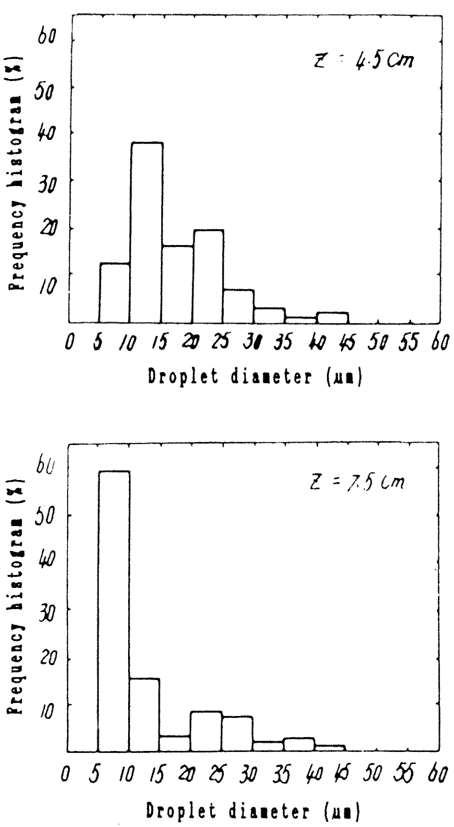


Fig.10 Droplet size distribution at different sampling position.

CONCLUSION

(1) Laser holography provides a powerful tool for recording and visualizing the basic atomization process in Diesel spray and opens a new data source for studying atomization mechanism of the spray.

(2) The atomization of Diesel spray usually exhibits three modes, that is, wave, dendritic, and chaotic disintegration. Their relative importance can greatly influence both the mean droplet size and droplet size distribution.

(3) There exist multiple mechanisms in the atomization process which all contribution to fuel atomization, among them liquid-gas aerodynamic interaction mechanism plays an important role.

(4) The injected Diesel fuel does not break up immediately after injection. There are a break-up process and atomization delay in Diesel spray. The shape and structure of Diesel spray could be classified into core region, postatomization region and spray mantle.

(5) The measurement and analysis of the initial atomization length, core angle and mantle angle, droplet size distribution in Diesel spray will produce quantitative data in the refinement of the spray model.

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