

# Analysis of Droplets Evaporation Process of Diesel Spray at Ignition Delay Period using Dual Nano-spark Shadowgraph Photography Method

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## ABSTRACT

Evolution of evaporating diesel spray is complex phenomena; however, it is important process for ignition, combustion and emission formation in diesel combustion. In this research, droplets evaporation process at spray boundary was experimentally investigated focusing on the behavior of evaporating droplets during ignition delay period. In the experiment, nano-spark shadowgraph photography technique was applied to a rapid compression machine.

This study developed a new optical system to observe spray evaporation process. The existing systems can hardly analyze transitional behavior of vapor phase of spray and droplets behavior in high number-density region. The new technology that is named dual nano-spark shadowgraph photography method can record both macro-scale and micro-scale continuous spray images clearly at very short time interval of 15 $\mu$ sec on normal photographic black and white film.

This paper explains the characteristics and advantages of the new dual nano-spark shadowgraph photography method comparing with previously developed shadowgraph photography methods such as single-spark and double spark methods. It is suggested that fairly clear images of spray taken by dual nano-spark shadowgraph photography method offer good information for explanation of the behavior of evaporating spray boundary at early injection period.

## INTRODUCTION

One of the most important strategies for the low emission diesel engines is to control the combustion process. The quality of diesel combustion process is strongly linked with fuel injection process. Diesel fuel injection process will dynamically control spray behavior, which is known to be a strong parameter that affects combustion process. Among many diesel exhaust emission control method, it has been reported that application of high injection pressure could contribute to the better spray atomization and fuel-air mixing hence

reduction of particulate emissions[1, 2]. Macroscopic and microscopic parameters of spray such as spray penetration and cone angle, spray atomization and evaporation, and air-fuel mixing rate process have captured special attention for many years[3-6]. Some of the research applied various method of fuel injection[7-10] and others concentrated on quantitative analysis of evaporating spray[11, 12].

Atomization process during ignition delay period greatly affects diesel combustion quality and emission formation. Authors previously reported that, when fuel is injected, combustible mixture is first formed at midstream of the spray[13, 14]. Figure 1 shows development of self-luminosity flame at diesel atmosphere in a constant volume vessel taken by high-speed digital video camera. The fuel was injected at injection pressure of  $P_{inj}=70\text{MPa}$  into hot ambient temperature of  $T_i=950\text{K}$  and density of  $\rho=15\text{kg/m}^3$ . Referring to the figure, initial luminous flame is observed at  $t=0.44\text{ms}$  after start of injection in the area of  $Z=15\sim 25\text{mm}$  at the midstream of the spray. At  $t=0.59\text{ms}$ , bright flame can be seen developing and covering larger area around the spray boundary including the region that the initial luminous flame is first observed. This result reveals that fuel ignition starts at the midstream of the spray. Hence, midstream of the spray boundary is an interesting area for investigating the process of mixture formation during ignition delay period.

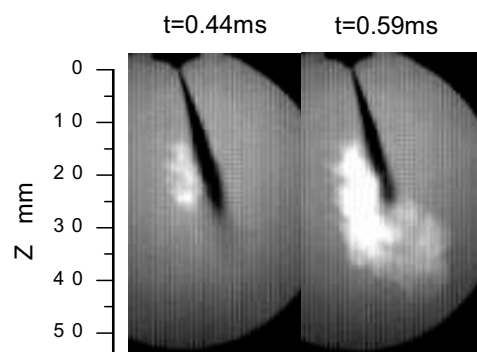


Fig.1 Spray combustion at  $T_i=950\text{K}$ ,  $P_{inj}=70\text{MPa}$

Many researches on the diesel spray atomization were published. Diesel spray atomization mechanism and fuel-air mixing process of diesel sprays are well known with complicated and complex phenomena due to their transient, multi-dimensional, and multi-phase nature. Major emphasis was given on the ambient gas entrainment, wall impingement, and measurement of droplet size and velocity[15, 16].

Authors have previously developed visualization systems of evaporating diesel spray[13, 17]. Some results make clear spray evaporation process and droplets behavior. However, a transitional behavior of spray vapor phase and behavior of droplets in high number-density region have been hardly analyzed before. This study developed a new optical method named dual nano-spark shadowgraph photography method. The new optical system can record continuously evaporating spray clearly with macroscopic and microscopic images on normal photographic black and white film.

This paper will first introduce the newly developed dual nano-spark shadowgraph photography method. In the paper, we explain characteristics and advantages of the new dual nano-spark shadowgraph photography method in detail comparing with previously developed shadowgraph photography methods such as single-spark and double spark methods. Next, we will show some images captured by the new system; then discuss evaporating process of diesel spray.

## EXPERIMENTAL SETUP

The diesel atmosphere was created by a rapid compression machine. The diesel spray was once injected in a constant volume chamber. The one-shot spray behavior was optically visualized. The experimental apparatus shown in Fig. 2 consists of a spray chamber, a rapid compression machine, a single-shot common rail injection system and a nano-spark photography unit.

Figure 3 shows a schematic cross-section diagram of the spray chamber. The spray chamber has a diameter of 60mm and a width 20mm. Inert gas of  $N_2$ -Argon mixture was supplied to the spray chamber by driving piston of the rapid compression machine. The inert gas mixture could prevent the fuel from ignition thus enable the photography of the evaporating spray. The induced gas density inside the spray chamber was kept constant at  $15\text{kg/m}^3$ , which simulated gas density inside the engine cylinder at start of injection. The ambient pressure at start of injection was recorded at  $p_i=1\text{MPa}$  and  $2.4\text{MPa}$  at ambient temperature of  $T_i=298\text{K}$  and  $T_i=700\text{K}$  respectively.

A single-shot common rail fuel injection system was used to inject the fuel into the spray chamber. Injection nozzle was a single-hole nozzle with hole-diameter of  $d_n=0.18\text{mm}$  at an orientation angle of  $15^\circ$  from the nozzle holder centerline. This injection system could vary the injection pressure from  $P_{inj}=40\text{MPa}$  to  $150\text{MPa}$ . The injection period was fixed constant at  $2.0\text{ms}$  in this

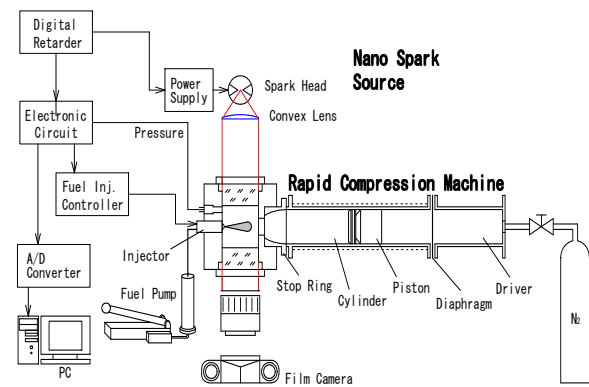


Fig.2 Schematic diagram of single spark method

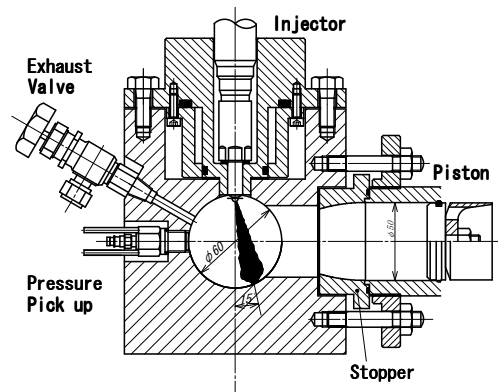


Fig.3 Cross section of spray chamber

study. Diesel fuel JIS#2 (density  $836\text{kg/m}^3$ ) was used in the experiment.

## OPTICAL ARRANGEMENTS AND THEIR CHARACTERISTICS

In this section, authors will elaborate the details of the three optical methods that were employed in this experiment. The methods are single spark shadowgraph method[13], double exposure shadowgraph method[17] and newly developed dual nano-spark shadowgraph method. The spray images of all three methods were recorded on normal photographic film (Fuji Neopan ASA400) by a magnification factor of 3.5 using a still camera (Pentax, 6x7). The images were scanned by CCD scanner (EPSON GT-X970) at high resolution of 3200dpi and 16bit. The planar displacement of each droplet was manually measured using an image analysis system (Media Cybernetics Image-pro Plus).

### Single Spark Shadowgraph Photography Method

#### - Macroscopic and Microscopic Analysis of Spray -

Figure 2 shows the optical arrangement of single spark shadowgraph method used in the study. A spark head providing spark duration of  $30\text{ns}$ [18] was employed to eliminate the blurring of subject. Such short spark duration was needed to capture high quality of spray images including detail images of flying droplets.

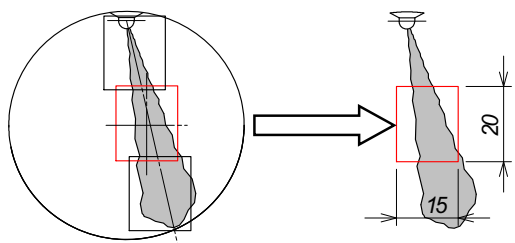


Fig.4 Photography setting for spray images

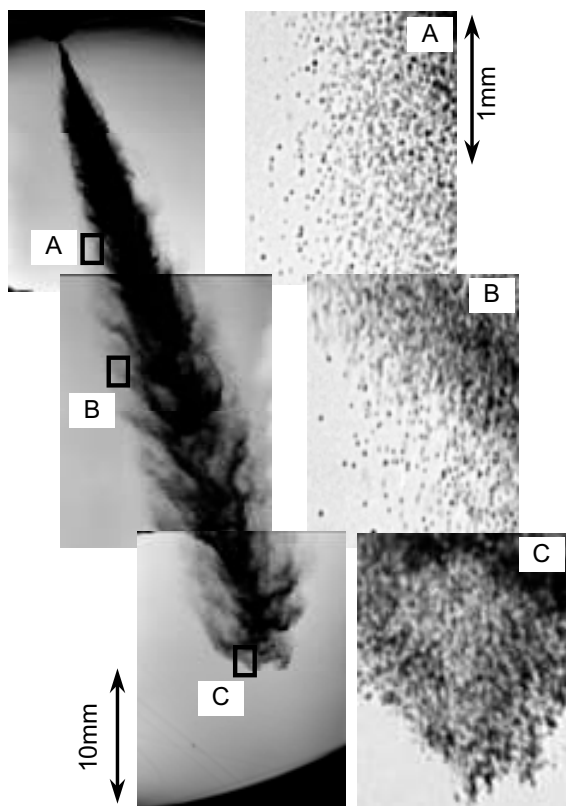


Fig.5 Single spark images  
at  $T_i=298K$ ,  $P_{inj}=40MPa$ ,  $t=0.5ms$

and vapor development[19]. In the series of experiment, the spray images were recorded on black and white 6x7 film (Fuji Neopan ASA400).

To obtain more detail information of fuel spray, magnification factor of 3.5 was applied throughout this experiment. Macro lens (PENTAX 135mm) was separately installed from camera body (Asahi Pentax 6x7) as shown in Fig. 2 to achieved magnification factor of 3.5. As a result, photography of spray was divided into three 15×20mm sections that were upstream, midstream and downstream of the spray as shown in Fig. 4. A complete set of the three spray photos were combined to get a full figure of spray. Spray photos combination task was done precisely according to the scale of each part that was taken prior to the experiment.

Figure 5 shows the non-evaporating spray image obtained by single nano-spark photography method. Experimental conditions were ambient temperature of

$T_i=298K$  and injection pressure of  $P_{inj}=40MPa$ . The significant feature of this photograph is high resolution. Macroscopically, the high-density region can be observed along the spray axis from nozzle tip to the spray tip area. Simultaneously, many branch-like structures can be observed along the spray boundary from the midstream area to spray tip.

Right side figures show magnified images at spray boundary region (areas A, B and C). The images show droplets behavior at upstream and midstream of the spray. Inside every image, highly clear droplets images can be seen. Owing to this images, single spark method offers simultaneous measurement of macroscopic and microscopic parameters such as spray cone angle, spray penetration length, droplets diameter and droplets number at spray boundary region[13].

However, several important parameters to imagine droplets behavior such as droplets velocity, droplets flying angle, droplets size reduction rate or droplets evaporation rate cannot be obtained by single nano-spark photography method.

To obtain these parameters, time depending variations of parameters should be measured. Thus, double exposure photograph method is implemented to obtain the above mentioned parameters.

### Double Spark Shadowgraph Photography Method

#### - Analysis of Droplets Behavior -

Double exposure shadowgraph method aims to expose two images at different timing on the same photographic film. As shown in Fig. 6, independent two nano-spark light sources were employed in this optical arrangement. Light emitted from spark head 2 was concentrated by a lens positioned at spark head 1 focus point and passes along the same path line with the first nano-spark to photo-surface a film. These two nano-sparks were charged with different voltage (first nano-spark: 12kV, second: 10kV) in order to obtain different image intensities of the spray and droplets.

During the process, the camera shutter was first opened

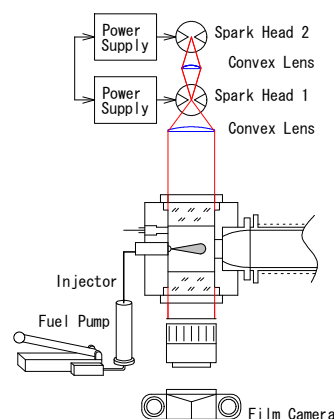


Fig.6 Schematic diagram of double spark method