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# Visualization of cavitation phenomena in a Diesel engine fuel injection nozzle by neutron radiography

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## Abstract

Visualization of cavitation phenomena in a Diesel engine fuel injection nozzle was carried out by using neutron radiography system at KUR in Research Reactor Institute in Kyoto University and at HANARO in Korea Atomic Energy Research Institute. A neutron chopper was synchronized to the engine rotation for high shutter speed exposures. A multi-exposure method was applied to obtain a clear image as an ensemble average of the synchronized images. Some images were successfully obtained and suggested new understanding of the cavitation phenomena in a Diesel engine fuel injection nozzle.

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Keywords; Neutron radiography, Diesel engine, Fuel nozzle, Cavitation

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## 1. Introduction

It is supposed that cavitation occurs inside a fuel injection nozzle of a Diesel engine. The cavitation affects much on the fuel injection and the performance of the engine. Cavitation is often called cold boiling. Boiling occurs due to temperature increase up to the saturation temperature. While, cavitation occurs due to pressure decrease below the saturation pressure. In a fuel injection nozzle of a

Diesel engine, the high pressure fuel ( around several hundreds atmospheres ) is injected into the engine ( around several tens atmospheres ). The rapid pressure decrease in the nozzle causes the cavitation and it affects much on the fuel supply to the engine. Visualization of the fuel cavitation has been required by the researchers of a Diesel engine. Visualization of cavitation phenomena in a simulated nozzle made of optically transparent material have been reported. [1,2]. However, nucleation process of the cavitation depends much on the fuel and the wall conditions in the nozzle. Therefore, visualization of the cavitation

phenomena of a real fuel inside a real metallic nozzle of a Diesel engine has been required. Neutron radiography is suitable for visualizing the fuel behaviors inside the metallic nozzle.

Fig.1 shows illustrations of a fuel injection nozzle when it is open and close. The fuel is filled in the hatched area. The needle moves up and down with half of revolution numbers of the four cycle engine. Each area is called the nozzle chamber, the sac chamber and the nozzle hole as shown in the left figure. It is estimated from fluid dynamics point of view that the cavitation likely occurs in the nozzle hole. The conditions of the fuel outside of the real nozzle have been studied well by optical methods, but no one observed the behaviors of the fuel in the real nozzle and the shapes of the nozzles have been designed by trial and error.

Typical fuel injection rates are shown against the crank angle in Fig.2. Fuel is injected for about 35 degrees in the crank angle, i.e. a nozzle is open for about 10 percents in time. Typical revolution numbers of a Diesel engine are from 600 to 6000 rpm and those of a fuel injection pump are from 300 to 3000 rpm since the fuel is injected once for two engine rotations in a four-cycle engine. The periods of the engine revolution are from 10 ms to 100 ms. The fuel injection time is 1 to 10 ms. Five frames during the fuel injection are necessary to discuss the cavitation phenomena. Therefore, time resolution from 0.2 ms to 2 ms is required.

In this study it was examined whether the cavitation can be visualized in the nozzle hole (about 0.2mm in diameter), the sac chamber (about 1mm in diameter), and the nozzle chamber (about 0.5 mm in width). It was examined how to obtain the images with exposure time from 0.2 to 2 ms synchronized with the fuel injection by the practical neutron radiography system.

## 2. Visualization of Fuel Injection Nozzles

Examples of visualization of gas bubbles simulating the cavitation in the nozzles are shown in Fig. 3. The exposure time is 2 minutes in KUR. A gas bubble in the nozzle chamber, in the sac chamber and in the nozzle hole can be clearly seen by neutron radiography.

Nozzles are axially symmetric except for the holes. Abel transformation can be applied to obtain axially symmetric images from neutron radiography images. Fig.4 shows images taken by a CCD camera with exposure time 4 s in JAERI. The images before and after Abel transformation are shown. The attenuation rates are plotted against the distance from the center axis in Fig.5 before and after Abel transformation. The gap of 0.5 mm at the nozzle chamber filled with fuel could be measured with some blur. It is shown that Abel transformation improve the image at the nozzle chamber well.

It is expected by the results shown above that the cavitations can be visualized if the similar quality image can be reconstructed from many images of short exposure time from 0.2 ms to 2 ms.

## 3. Experimental Apparatus for Visualization of Cavitation in the Fuel Nozzle

Some methods were examined to obtain the images with the short exposure time from 0.2 ms to 2 ms by the practical neutron radiography system. The fuel injections are repeated periodically. Therefore, many images in the same injection condition can be obtained if the exposure is synchronized to the engine rotation. A method is integration of the many images for short time exposure synchronized by a CCD camera to the engine rotation. However, the read out noises are also integrated if many images are integrated. Therefore, multiplex exposures with opening the electrical shutter of a CCD camera by using a neutron chopper was examined. In future, a method will be possible by synchronizing the engine rotation to a high intensity pulsed neutron source generated by an accelerator.

Fig.6 shows the experimental apparatus. A pulsed neutron beam was obtained by the chopper and was irradiated to the nozzle. The neutron image was converted to the optical image and was accumulated by the CCD camera. The slit angle was 3.6 degrees for taking 5 image frames for the fuel injection. Since the cam and the chopper were rotated by the same gear, they were well synchronized. The exposure time was determined by the slit angle. The timing of the fuel injection visualization was determined by the delay angle between the chopper and the cam. The short exposure time images in one rotation were

accumulated in the CCD camera for many rotation numbers to obtain the clear images.

#### 4. Visualized Results

The fuel spray outside the nozzle was visualized and consecutive images were obtained by the present experimental apparatus. Fig.7 shows the consecutive images by an optical method. A nozzle with one injection hole was used. The hole diameter was 0.38 mm. Exposure time was 100 ms by the cooled CCD camera. The shutter speed of one image of rotation number 360 rpm for optical rays was 0.6 ms.

Neutron radiography images were tried to take by high neutron flux system at IR port of HANARO in Korea Atomic Energy Research Institute. A neutron radiography image was taken at the same position as the optical image at 5 ms in Fig. 7. The optical imaging pixel size of the CCD camera was 30  $\mu\text{m}$ .

Five images for exposure time of 20 s were obtained for the rotation number of 360 rpm, i.e., 6 Hz. The images were added after removing star-like noises by a mathematical morphology filter. The total exposure time was 100 s. Therefore, 600 images with shutter speed of 1.67 ms were synchronously integrated.

Fig.8 shows the visualization of fuel cavitation in nozzle hole by the above method. The right image was expanded. It can be seen that the fuel cavitation

occurs in the nozzle hole since the nozzle hole was not filled with the fuel.

#### 5. Conclusions

The visualization of the cavitation phenomena in a nozzle of a Diesel engine was performed by neutron radiography. Obtained results are summarized as below:

1. Various real metallic nozzles of the Diesel engines filled with fuel were visualized by neutron radiography. The fuel and the gas bubbles simulating the cavitation were well visualized in the sac chamber, the nozzle chamber and the nozzle hole.

2. The multiplex exposure method by using a chopper with opening the electrical shutter of a CCD camera was proposed for the visualization of cavitation in a fuel nozzle of a Diesel Engine. The cavitation phenomena in the real metallic fuel nozzle were successfully visualized by neutron radiography with the chopper method.

#### References

- [1] J.Senda, Proc. of ICLASS-97', August 18-22, Seoul, 1997
- [2] S. Kohama, "Internal Combustion Engine Engineering", Industry Pub.

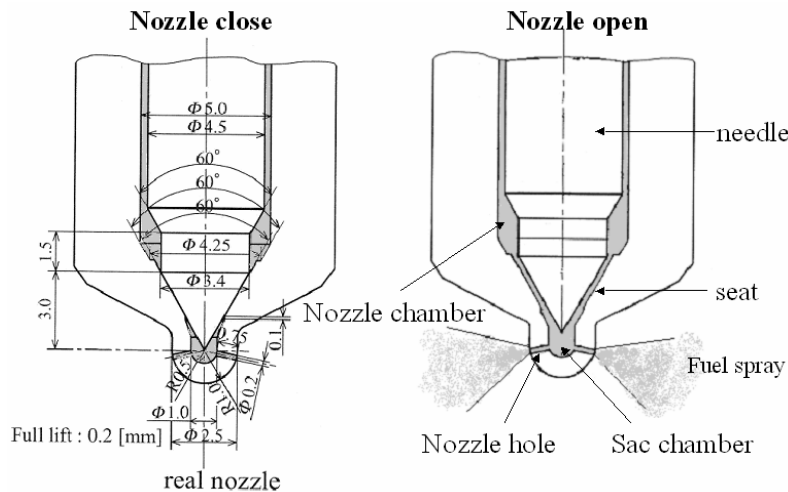


Fig.1 Illustration of a fuel injection nozzle of a Diesel engine

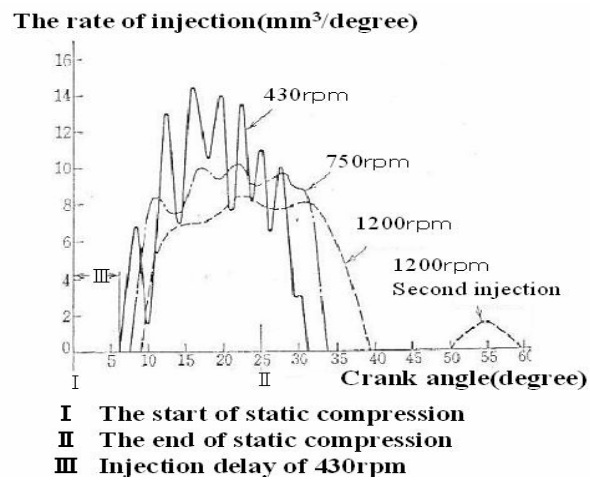


Fig.2 Typical injection rate of fuel from a nozzle

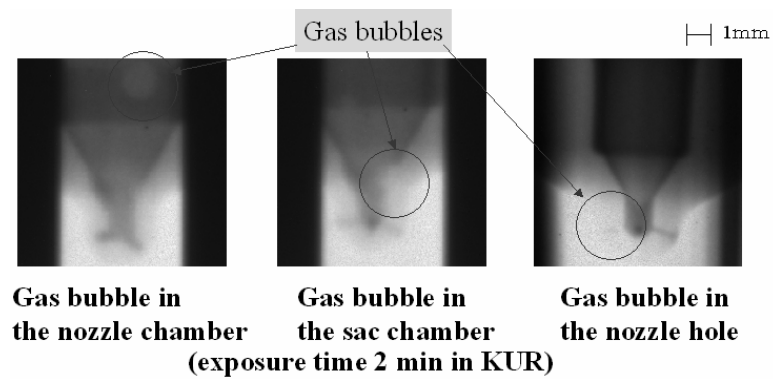


Fig.3 Visualization of gas bubbles in the nozzles

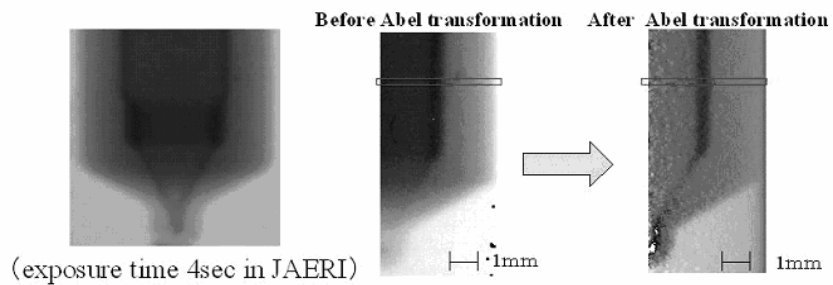


Fig.4 Abel transformation

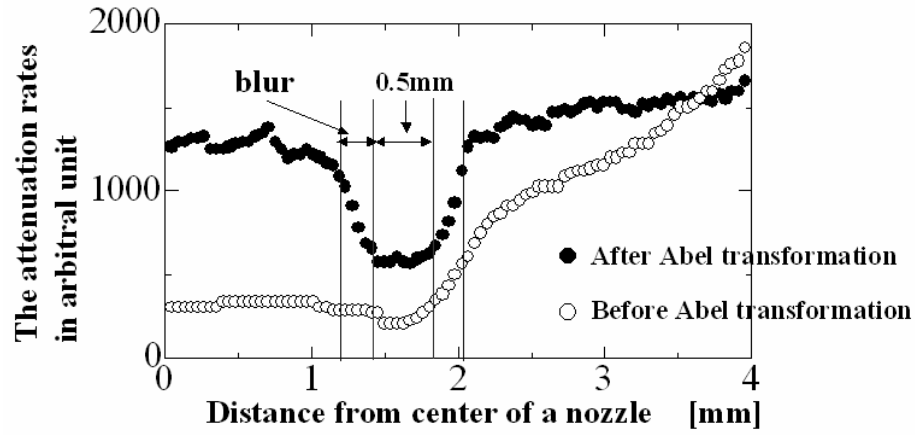


Fig.5 The attenuation rates distributions in cross section at the nozzle chamber

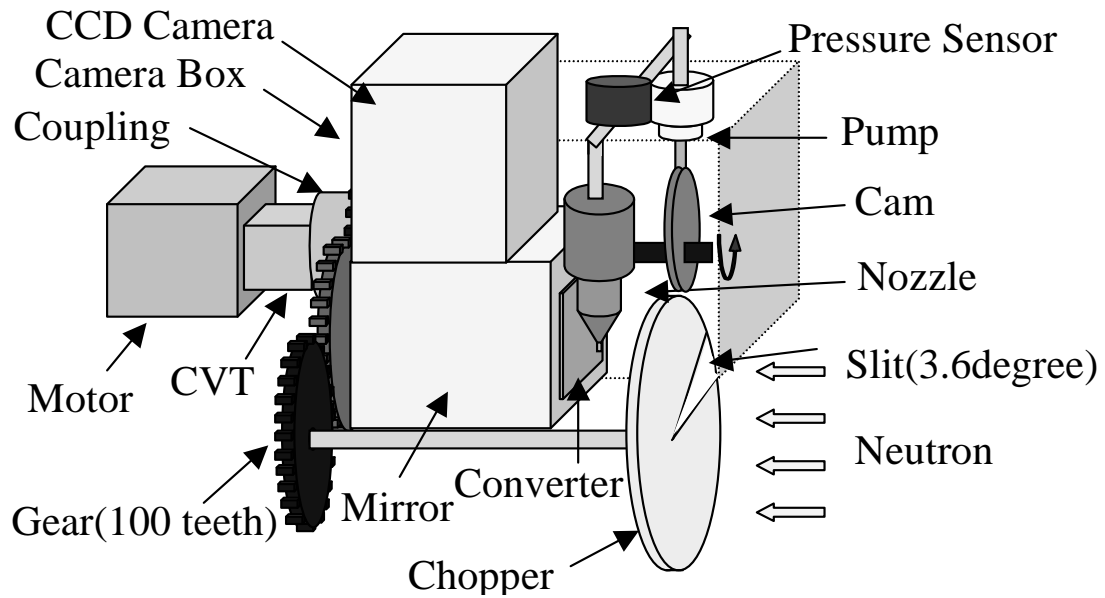


Fig.6 Experimental Apparatus

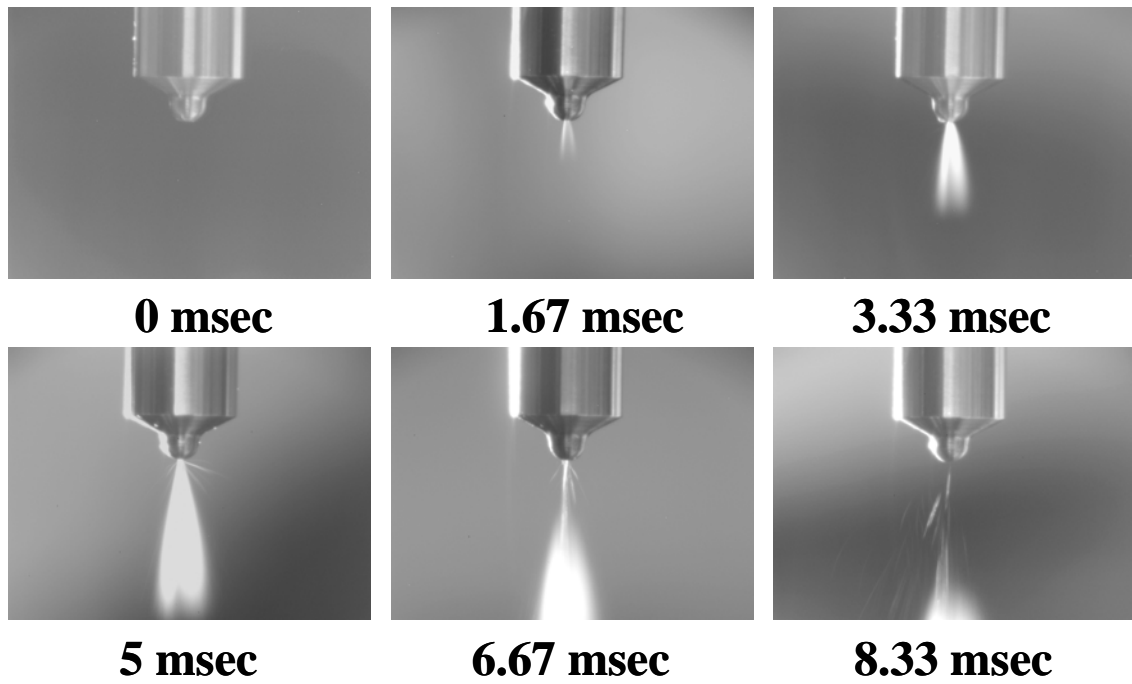


Fig.7 Consecutive optical images of the spray

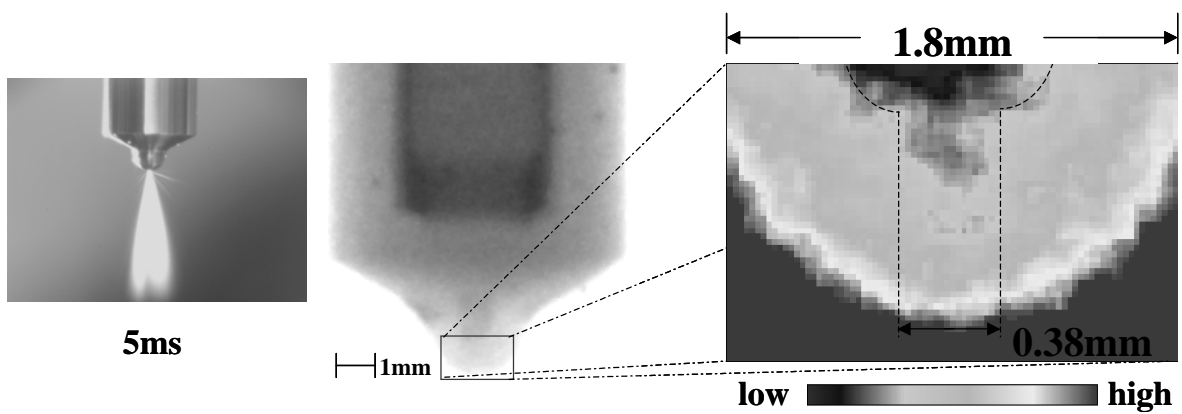


Fig. 8 Visualization of fuel cavitation in the nozzle hole 360 rpm