A Study on the Structure of Diesel Spray (2-D Visualization of the Non-Evaporating Spray)

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ABSTRACT

In this study, as a first step to make clear the detailed structure of diesel sprays, two-dimensional visualization of intermittent non-evaporating unconfined sprays are performed by using a laser sheet illumination technique. In order to get instantaneous 2-D sectional images of spray, a sheet of laser light from a frequency-doubled Nd-YAG laser (532 nm, 7ns), approximately 0.2 mm thick, is used as a light source. From the photographic results and their image analysis, it is made clear that there is a certain regularly spaced branch-like structure in the spray. The spacing between the branches, an order of a few millimeters, is nearly constant throughout the injection period, and it gets shorter with the increase of the ambient pressure. This branch-like structure still exists after the end of injection, and it is supposed that there is a strong heterogeneity of droplets density in the spray for relatively long period.

INTRODUCTION

A diesel engine is one of the major prime movers owing to its superiority in thermal efficiency. However, due to the recent severe regulations for the pollutant emissions from diesel engines, it is needed for us to understand in more detail the combustion mechanism of diesel engines.

A fuel spray is one of the key technologies in diesel combustion, because combustion processes are strongly influenced by the mixing process, that is, by the distribution of the fuel droplets and vapor in space and time. Owing to this importance, there are extensive works in this field. The mechanism of the jet break-up was studied photographically (1,2), and the importance of liquid surface-air interaction, liquid turbulence and cavitation on the mechanism was reported. The break-up length was measured with intrusive probes (3), and the effects of ambient pressure and nozzle diameter were discussed. The averaged droplet size and distribution of droplets density were studied by using a laser diagnostic technique (4,5). It was reported that the higher injection pressure gave a more homogeneous field of fuel concentration. However, these works were rather limited to the information of spray periphery or the information integrated along the line-of-sight.

In order to get information about the structure of the inner part of the diesel spray, the use of a two-dimensional visualization technique is hopeful. However, the application of this technique to diesel spray seems to be rather limited (6,7,8), and the understanding of the structure of the inner part of the spray, especially the spatial heterogeneity of droplets density, is still incomplete.

In this study, as a first step to understand the structure of diesel spray in more detail, the laser sheet 2-D visualization of intermittent non-evaporating unconfined sprays are performed. The spray is injected into a pressurized spray chamber built for optical study, and the effects of ambient pressure on the spray structure are preliminarily analyzed.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus consists of an injection system, a spray chamber, and an optical system. Fig.1 shows a schematic diagram of the experimental apparatus. The liquid fuel fed from a pressurized fuel tank (0.4 MPa) is injected by a fuel injection pump in a vertically downwards direction through a single hole nozzle mounted on the top of a spray chamber. The fuel injection pump used in this study is an ordinary diesel pump (Bosch Type A, plunger diameter 6 mm) driven by a variable speed electric motor. The diameter of the nozzle hole is 0.3 mm and the length to diameter ratio of it is 2.8. The spray chamber built for the optical study of fuel sprays has three windows, and the initial 110 mm of the spray can be observed in three directions which are at right angles each other. The diameter of the chamber is 160 mm, more than 500 times wider than the nozzle hole, to insure a negligible effect of the wall on the spray.

Fig. 2 shows a schematic diagram of the optical set-up. In order to get instantaneous 2-D sectional images of spray, laser light of a frequency-doubled Nd-YAG laser (532 nm, pulse width of 7 ns) is used as a light source. The beam of a laser is shaped into a thin sheet approximately 0.2 mm thick through three planoconvex cylindrical lenses. The laser sheet passes through the center axis of spray, and the elastically scattered light from the spray droplets is photographed by still camera or CCD camera (768x 493 pixels) at right angles to the plane of laser sheet. The intensity of the scattered light is relatively high, which enables to use the laser in lower power, about 10 mJ per pulse.

The laser pulse is synchronously triggered by a signal made by a crank shaft encoder mounted on the fuel pump and a delay circuit so that a picture of the spray at a different timing during injection, penetration and development process of the intermittent spray can be observed. The images acquired by CCD camera are digitized on 256 grey levels with a resolution of 512x512 pixels and stored by the image analyzer and personal computer. The field of view of the camera was adjusted so that the full images through the window could be observed, and the resulting spatial resolution was approximately 0.25mm per pixel.

In the experiments, the fuel was injected into the spray chamber filled with pressurized nitrogen at room temperature. The pressure was changed from 0.1 MPa to 1.53 MPa, and the effects of ambient pressure on the shapes and structures of non-evaporating unconfined intermittent sprays were studied.

RESULTS AND DISCUSSIONS

All the results reported in this paper are obtained under the injection conditions summarized below.

Fuel	JIS #2 diesel oil
Fuel pump speed	900 rpm
Nozzle opening pressure	20 MPa
Amount of fuel injected	27 mm^3/stroke
Injection period	2.1 msec
Ambient gas	Nitrogen
Ambient pressure	0.1 MPa - 1.53 MPa

Photographic Results

As for the following sequences of photographs, it should be noted that each photograph was taken during a different cycle. However, the photographs shown below are selected from many more photographs so that they represent the typical features of the spray shape or spray structure.

Photographic results are shown in Fig.3, and Fig.4, which illustrate the development of the spray and the effect of the ambient pressure respectively. The white region in the photographs indicates the existence of spray droplets. The brightness of white region is related to the local drop concentration and size distribution, and thus it is a qualitative measure of the droplets density. The condition of camera iris was changed by every photograph so that the image of spray could be easily seen. Thus direct comparison of the light intensity between the photographs has no validity.

Photographs in Fig.3 show the images of spray under the ambient pressure of 1.53 MPa, at timing of 0.25, 0.5, 1.0, 2.0, 3.0, 4.0 ms after the start of injection. As the spray tip reaches a certain point, which depends on the conditions of injection, the shape of the spray tip is transformed suddenly. The time between the injection start and this transformation is quite short ($\sim$0.1 ms). After this transformation, a certain branch-like structure, which stretches backward from the central core of spray, can be seen. The development of this branch-like structure is indicated in photographs. It should be noticed that the photographs are the images of the sectional view of the spray. Thus it cannot be clearly said whether this structure is a group of branches or a series of cones, but here this structure could be called as the branch-like structure or the "branches" for present.

This structure appears almost regularly inside the spray. It should be noted that, in the photographs during the injection period (0.25 ms $\sim$ 2 ms), this branch-like structure cannot be seen clearly. This can be attributed mainly to the influence of multiple-scattering owing to the high density of spray droplets. This branch-like structure can be seen more clearly even after the end of injection period (3.0 ms, 4.0 ms), and the position of this structure roughly corresponds to

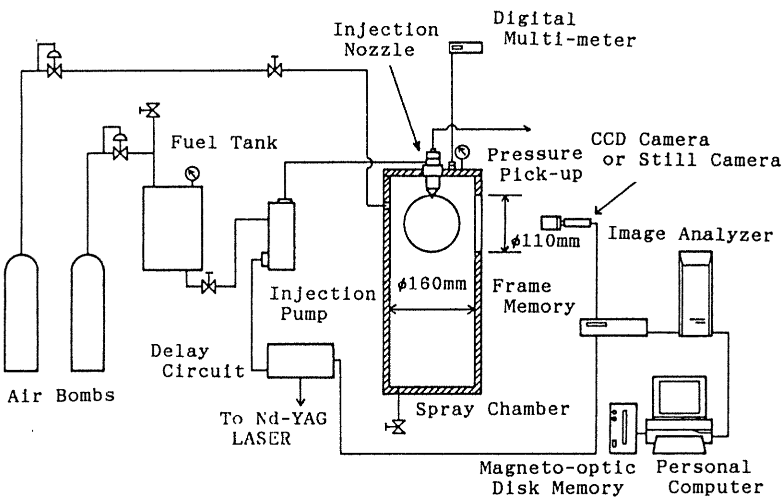

Fig.1 Schematic of experimental set-up

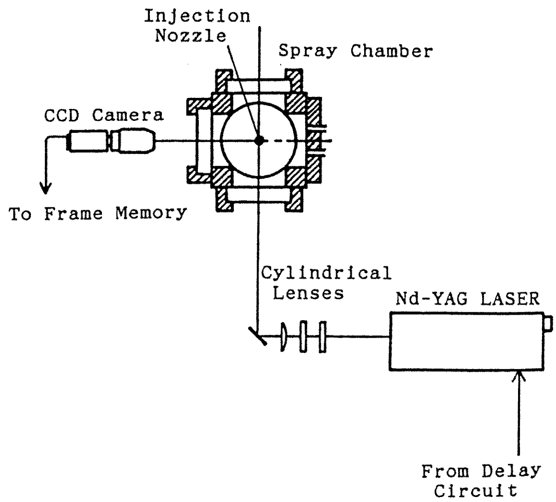

Fig.2 Schematic of optical set-up

that in injection period. The branch-like structure is especially clear in the region near the nozzle. This fact suggests that there is strong heterogeneity in the spatial distribution of fuel droplets in the spray for relatively long period, and that there is stronger heterogeneity during the injection period, even though it is not clearly seen in the photographs owing to multiple-scattering effects.

Besides this branch-like structure, there exists a very dense core at the center of the spray during the injection period. From a closer examination of the photographs, it is observed that this core stretches almost straight-forward to a certain point very near the nozzle tip, and after this point it looks to meander slightly, which results in the wavy shape of spray core. The distance between this point and the nozzle tip is about several millimeters, and this distance depends upon the ambient pressure. The wave length of wavy shape of spray core almost agrees with the spacing of the branch-like structure in the near nozzle region, which suggests the strong relationship between the branch-like structure and the meandering of the spray core. The wave length and amplitude of it grows gradually as it goes farther from nozzle tip. More detailed discussion about this meandering is performed later.

Photographs in Fig.4 illustrate the effect of ambient pressure. The ambient pressure of each series is atmospheric pressure (0.1 MPa), 0.59 MPa, 1.08 MPa and 1.53 MPa, respectively. In each series, the timing of photographs is 1.0 , 2.0 and 4.0 ms. The branch-like structure mentioned above is also observed in each series, and it has fundamentally the same feature even though the ambient pressure changes. However, some differences can be seen between the four series. As is often said, the spray tip penetration gets shorter, compared at the same timing from the start of injection, with the increase of ambient pressure. The spray angle increases gradually with the increase of ambient pressure. By the close observation of the photographs, the spacing between the "branches" decreases with the increase of ambient pressure.

Spray Tip Penetration

Fig.5 shows the growth of spray tip penetration with time from the start of injection. As is often said, the penetrating length stretches itself reducing its growing rate with time, and gets shorter with the increase of the ambient pressure. Under atmospheric pressure, the spray tip goes out of the field of observation at about 1 ms after the injection start. On the other hand, under the pressure of 1.53 MPa, the tip penetration shows the saturating tendency at about 110 mm.

Fig.6 shows the increase of the sectional area of the spray with time. In this paper, the sectional area is determined as follows. The raw image taken by CCD camera is low-pass filtered by averaging the neighboring 8 pixels in order to cut off the high frequency noise of image. Then the pixels with brightness lower than 10% of the maximum are regarded as background level, and the rest are defined as the sectional view of the spray. As shown in Fig.6, the sectional area of the spray increases almost linearly with time throughout the period observed.

Length scale of branch-like structure

As mentioned before, there is a certain branch-like structure inside the spray, and strong heterogeneity of the spatial distribution of the spray droplets exists. As the first step to quantify this branch-like structure and heterogeneity, the quantification of the spacing between such "branches" along the spray axis is performed.

The "branches" picked up here are defined as follows. The raw image taken by CCD camera was first differentially filtered in the direction perpendicular to the spray axis. Then the point with maximal brightness in this direction was extracted and the characteristic structure was enhanced. Fig.7 shows a typical example of the enhanced images. This picture was extracted from the photographic result of 2.0 ms, 1.53 MPa, and the raw image is shown in Figs. 3 and 4. The "branches" in the enhanced image correspond well to the branch-like structure in the original raw image.

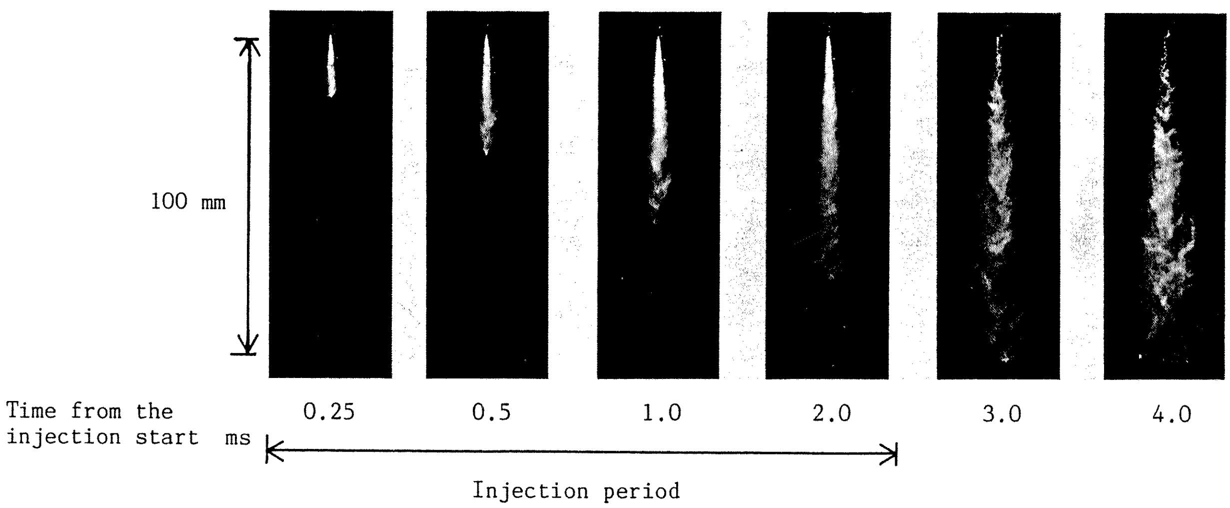

Fig.3 Photographs showing temporal evolution of spray at ambient pressure Pa=1.53 MPa

As mentioned in the section of photographic results, the spray core begins meandering from a certain point near the nozzle. This characteristic point is quantified also from this enhanced image. In the region very near the nozzle tip, the image of the spray stretches almost straightforward until this point (A in Fig.7). This point is almost spatially fixed throughout the injection period, and at this point a certain protrusion in the spray core is observed. This is the first perturbation observed in the spray, and there is no recognizable perturbation in the upper stream of this point. As is mentioned earlier, the resolution of CCD camera is relatively low (0.25 mm/pixel) and there might be perturbations or small "branches" between the nozzle tip and this point, but they cannot be observed.

After some distance forward from the point of first perturbation, the first "branch" is generated. In the region near the point of the first perturbation, the wave length of the wavy shape of central core almost agrees with the

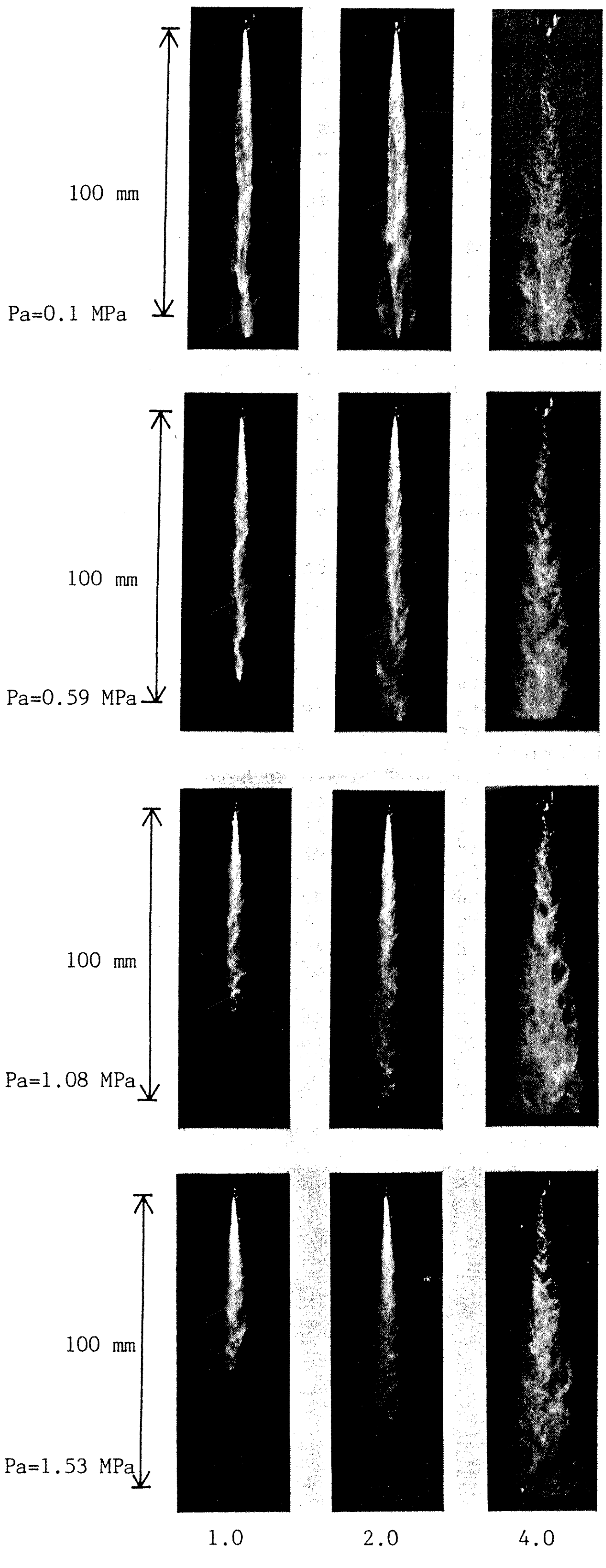

Fig.4 Photographs showing effect of ambient pressure Pa on spray structure at three different time from the injection start

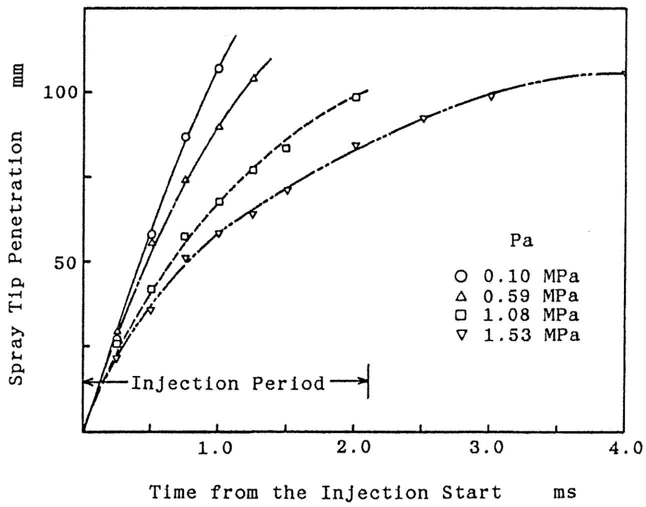

Fig.5 Development of spray tip penetration with time

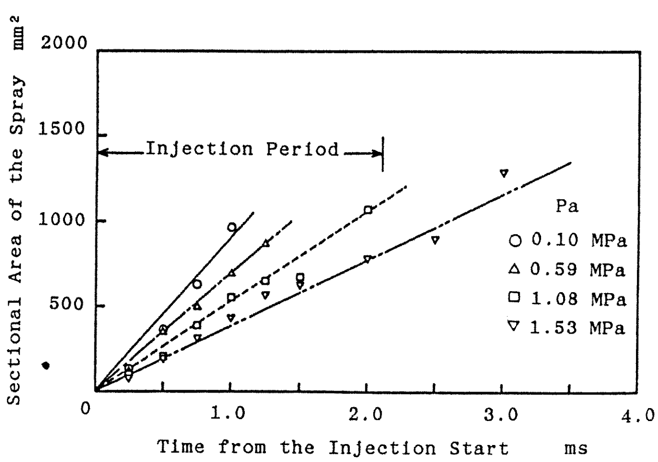

Fig.6 Development of sectional area of the spray with time

spacing of the branch-like structure. Furthermore the "branches" appear to be generated at the summits of the wavy shape. This fact suggests that a certain perturbation in the liquid phase is amplified by the interaction with the ambient air, and grows up to an event such as bursting or so, which results in the branch-like structure. This structure penetrates together with the development of spray as it slightly meanders.

In the spray tip region, the "branches" are sometimes not so clear in the photograph, and only the root and the top of the "branches" can be seen. However, there are also clear "branches". In this region, the brightness of the central core becomes weaker and the wave length of the wavy shape gets longer than in the region near the first perturbation point. By the close observation of the images, it can be recognized that "branches" with lower brightness are generated at the points in the midway of the subsequent summits and "branches" with higher brightness are generated at the summits of the wavy shape of the central core. This fact suggests that there exists a larger scale structure together with the branch-like structure.

Fig.8 shows the mean spacing between the "branches" averaged within each photograph with time, Ls, at the ambient pressure of 0.1 and 1.53 MPa. At each timing, the spacing between the "branches" varies randomly within the width of variation as shown by individual symbols of data. This variation corresponds to 2 or 3 pixels. The horizontal lines shown together with each datum represent the mean values averaged over the period investigated. It is apparent that, under the same conditions, the spacing of the "branches" is almost constant throughout the period investigated, even after the end of injection. The spacing between "branches" decreases with the increase of the ambient pressure.

Fig.9 shows the distance between the point of first perturbation and the nozzle tip, Lp, with time at the ambient pressure of 0.1 and 1.53 MPa. The lines in Fig.9 represent the mean values averaged similarly to those in Fig.8. In the case of 0.1 MPa, the spray in the near nozzle region has already broken up after the end of injection period, and then the point of the first perturbation cannot be determined. The distance between this point and the nozzle is almost constant throughout the period observed under the same conditions. This length also decreases with the increase of the ambient pressure. The general tendency of this length is fundamentally the same as that of the spacing between the "branches", Ls.

Fig.10 shows the effect of the ambient pressure on the spacing between the "branches", Ls, and the distance between the nozzle tip and the point of the first perturbation observed, Lp. Each datum is a mean value averaged over the period investigated, as mentioned in Figs. 8 and 9. The width of variation is shown together with each datum. As mentioned earlier, both spacings, Ls and Lp, decrease with the increase of ambient pressure, and show saturating tendency near 1.53 MPa. This fact shows that the ambient pressure influences this structure, suggesting the

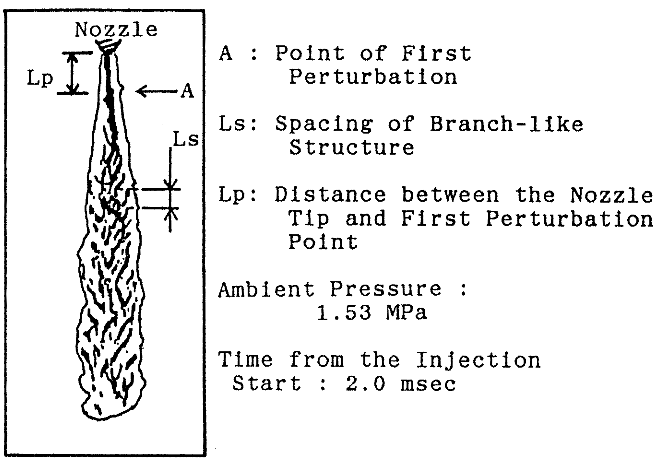

Fig.7 Typical example of the feature of the spray

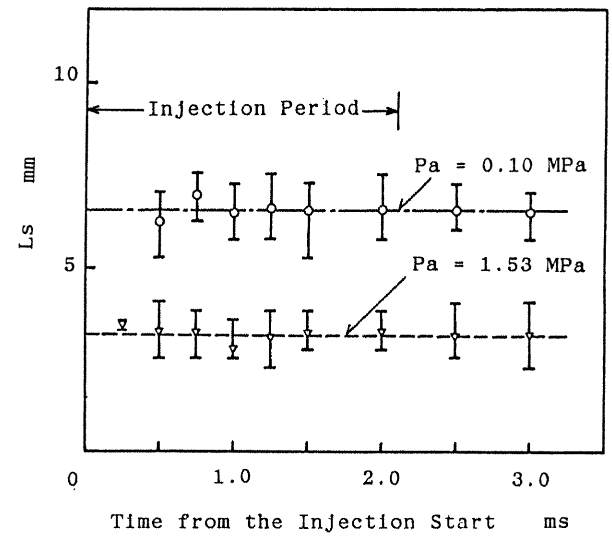

Fig.8 The mean spacing between the "branches" Ls vs. time

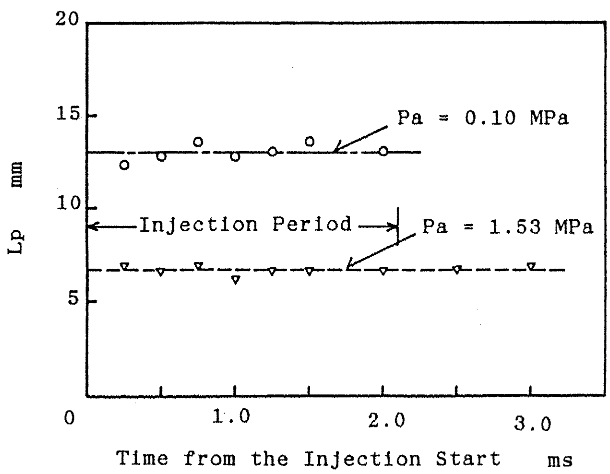

Fig.9 The distance between the point of the first perturbation and the nozzle tip Lp vs. time

interaction between the ambient gas and the spray. The two curves resemble each other, which suggests that there exists a certain mechanism inside the spray, of which scale is small as the order of the spacing between the "branches", and that the branch-like structure and the point of the first perturbation are in close relation with this small scale mechanism.

CONCLUSIONS

(1) By using a laser sheet illumination technique, instantaneous 2-D sectional images of intermittent non-evaporating unconfined spray are observed and preliminarily analyzed.
(2) There is a certain regularly spaced branch-like structure in the spray.
(3) The spacing between the branches is an order of few millimeters and nearly constant throughout the injection period.
(4) This spacing decreases with increase of ambient pressure. However, it shows a saturating tendency near 1.53 MPa.
(5) The branch-like structure still exists after the end of injection, and strong heterogeneity of droplets density in the spray lasts for relatively long period.

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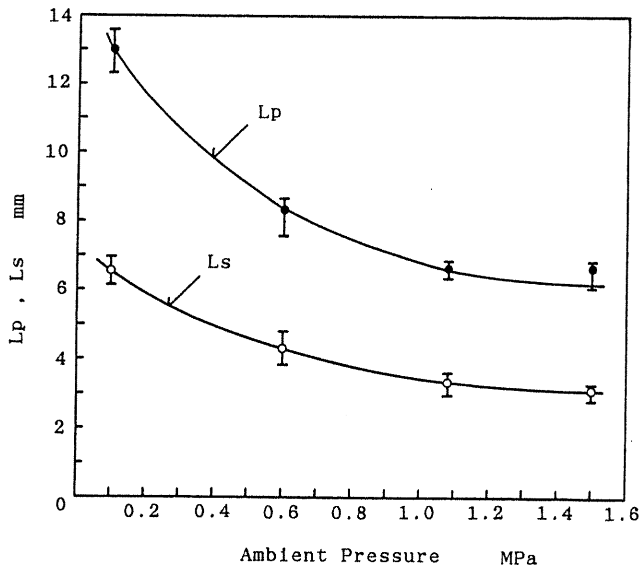

Fig.10 The effect of the ambient pressure on the characteristic lengths Ls and Lp