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Experimental and Numerical Study of the Diesel Fuel Spray from Pintle Nozzles

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ABSTRACT

This paper describes an experimental study of the diesel fuel spray from pintle nozzles by using a high pressure chamber at room temperature with high-speed photography and Q-switched ruby laser holography. It is found that at the early stage of injection there is a hollow conical region in the fuel spray injected from the pintle nozzle with a large divergence angle. The main stream lines of the spray are deflected inward and approach the nozzle axis at some distance downstream from the nozzle exit. Thereafter the spray becomes a circular one and its characteristics are similar to those of the spray from a hole-type nozzle. Based on the modification of the Hiroyasu's expression, a semi-empirical relationship is proposed for calculating the breakup length of the pintle nozzle spray.

In this paper a mathematical model for predicting the penetration and trajectory of diesel fuel spray injected from the pintle nozzles is also developed. It has been applied to the analyses of air jets issuing from ordinary annular nozzles and diesel spray injected from Model ZS45S2 pintle nozzle, a fairly good agreement between the calculated results and the experimental data is obtained.

INTRODUCTION

The mixing of the liquid fuel spray controls combustion heat release and the efficiency, emissions, maximum output and noise of the engine and is a complex process in which a number of physical effects either remain unknown up to now or have largely been ignored in previous theoretical studies of sprays. These include the structures of different types of fuel sprays, particularly those injected from pintle nozzles, the main physical process involved in fuel atomization, and the lack of accurate and useful experimental results for spray model development and evaluation. Owing to these, Prof.Hiroyasu [1] had to use hole-type nozzle spray model instead of pintle nozzle one in his IDI diesel combustion modeling. Therefore, a major goal of this study is to fill this gap. The objective of this work is to characterize the pintle nozzle spray and to develop its mathematical model on the basis of the fundamental understanding of the physical processes provided by the experimental study.

EXPERIMENTAL STUDY OF DIESEL FUEL SPRAY

Experimental Study with the High Speed Photography

Experimental Apparatus and Methods. An outline of the experimental apparatus for visualization and assessment of the global structure of the spray is shown in Fig. 1. A cylindrical high pressure chamber (120mm inside diameter x 250mm width) with glass windows on two opposite sides is used for diagnosing the spray. A calibration scale to facilitate the measurement of the spray penetration is provided in the chamber. This chamber is designed to withstand pressure up to 8 MPa.

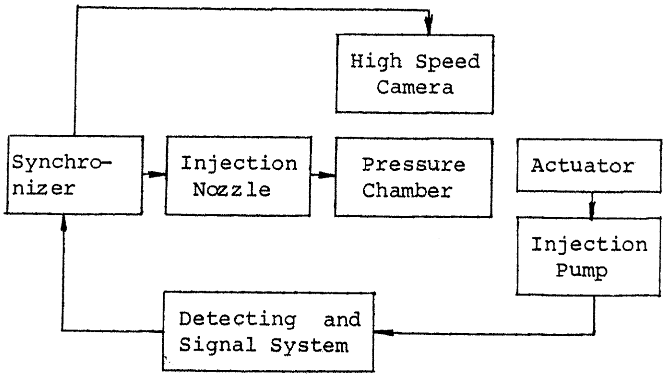


Fig. 1 Schematic diagram of experimental apparatus

In this study we use a newly designed apparatus which is capable of automatically controlling the number of injections of diesel fuel in coordination with the high speed camera (10000 frames/sec.). This apparatus works in the following manner. Before observation, the fuel sent from the injection pump driven by a continuously adjustable eletromotor with a speed rang of 0-3000 rpm is returned to the fuel tank. For observation a trigger signal is released by a magnetic pick-up attached at the bottom dead centre on the pump cam shaft, which togeter with the synchronization pulses supplied by the camera provides for control of the injection system. Following release of the hgih-speed camera, the signal triggers a delay circuit and it is possible to vary the timing and number of fuel injection. While fuel is injected, the injection pressure and nozzle needle lift are monitored with the transient recorder and synchroscope.

Results and Discussion. Table 1 shows the conditions of the experiment. In order to study statistically representative curves concerned with the changes of spray in time, many photographs have been taken at the same condition of the injection.

Table 1. Experimental Conditions

Run	Injection Nozzle	Back Pressure (MPa)	Nozzle Opening Pressure (MPa)	Pump Speed (rpm)
1	Single hole nozzle (ϕ0.4)	0.98	16.7	750
2		1.96	19.6	1000
3		2.94	22.6	1000
4	ZS4S1 pintle nozzle (with 4°cone angle)	0.98	13.7	750
5		1.96	16.7	1000
6		1.96	19.6	1000
7	ZS45S2 pintle nozzle (with 45°cone angle)	2.75	16.7	1000
8		1.96	16.7	1000
9		0.10	16.7	1000

Photographs of the whole spray gives an overall view of the spray shape as shown in Fig. 2(A), (B), (C) which are taken correspondently in the case of runs (7), (8), (9) in Table 1. From the above photographs it is clear that in the region near the nozzle exit, the shape of the spray from the Model ZS45S2 pintle nozzle is appreciably dissimilar to that from the hole-type nozzle and Model ZS4S1 pintle nozzle. The sprays injected from the latter two nozzles show similar spreading. As shown in photographs (A), the fuel spray emerges from the Model ZS45S2 pintle nozzle with a large divergence angle as a annular jet and exhibits a bell-like shape. Hereafter the main streamlines of the spray are deflected inward and then approach the nozzle axis. Thus the spray becomes a circular one and its characteristics are similar to those of the spray from a hole-type nozzle.

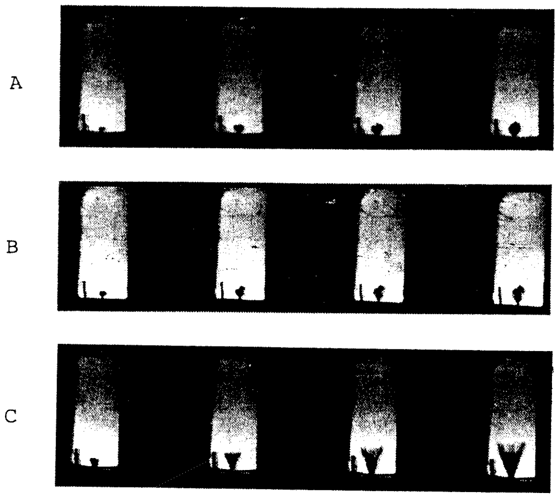


Fig. 2 Effect of back pressure on spray configuration at early stage of injection.

It is interesting to note in Fig. 2 (C) that the back pressure is an important factor affecting the initial curvilinear motion of the spray. At the atmospheric pressure, the pattern of the spray is shown as a hollow cone and spreads out in a straight line.

Experimental Study with a Pulsed-laser Holography.

Experimental Apparatus and Methods. Experiments are carried out in a test facility using a conventional in-line holographic arrangement. A layout of the holographic system and the high pressure chamber is shown in Fig. 3. The Q-switched pulsed ruby laser (1) has a wave length of 694.3nm, an output of 1J and a pulse duration of 40ns. The object beam is collimated to the size of the glass window with a spatial filter and a convex lens (2). It is then led into the high pressure chamber (5) and is transmitted through the spray. The imaging lenses (3) are placed between the spray and the holographic plate (4). The high pressure chamber has a cylindrical shape of 130mm inside diameter and 300mm height with good optical access (80mm × 120mm organic glass windows). Fuel injection into the high pressure chamber is from a centrally mounted injector(7) with pintle nozzle. Single injection of the fuel is achieved by an injection control circuit. Because the application of the in-line holography technique to high density spray with typically more than one drop per mm³ is uncertain, the experimental arrangement is equipped with a means (8) by which spray samples of appropriate thickness can be isolated for holographic study when the behavior of the spray in the region near the nozzle exit is observed. There is a calibration wire(ϕ44μm) in the chamber with a regulating apparatus by the use of which the wire can be located at the focal plane in the spray. Image reconstruction and photography is obtained by the re-illumination of the developed hologram with a continuous helium-neon (He-Ne) laser beam and a microscope camera.

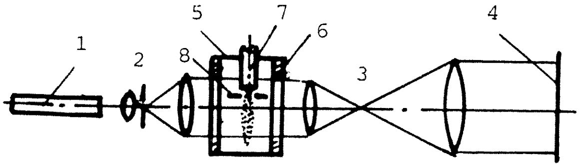


Fig. 3. Layout of holographic recording system and high pressure chamber

Experimental Results and Discussion. The experiment is carried out under the conditions shown in Table 2.

Table 2. Experimental Conditions

Run	Injection Nozzle	Back Pressure (MPa)	Nozzle Opening Pressure (MPa)	Note
A	ZS45S2	2.0	17.2	No slit
B	ZS45S2	1.5	17.2	No slit
C	ZS45S2	0.8	17.2	No slit
D	ZS45S2	2.0	13.2	With slit
E	ZS45S2	1.5	13.2	No slit
F	ZS15S15	1.5	16.7	No slit
G	ZS15S15	1.5	16.7	With slit

It must be pointed out that a dense spray region where the laser beam can not be transmitted is seen as a shadow. These shadow photographs of the spray taken at the experimental condition (B) are shown in Fig. 4. It demonstrates clearly the flow characteristics of the pintle nozzle spray at the early stage of the injection.

a) The Interior Structure of the Pintle Nozzle Spray

Fig. 5 shows the photographs of the interior structure of the spray under the condition (D) in Table 2. As shown in this figure, the nipple-like shadow on the photographs is the image of a fuel drop which is attached far away from the slice of the spray to the bottom plate of the sampling device and has no effect on the experimental result.

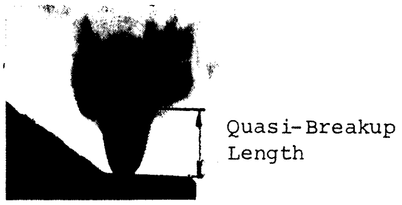
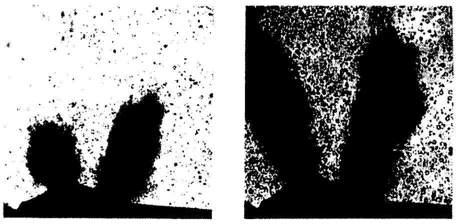


Fig. 4 Shadowgraphs of the pintle nozzle spray



A B

Fig. 5 Sectional view of the pintle nozzle spray at the early stage of injection

The macroscopic observation from Fig. 5 shows that there is a hollow conical region in the fuel spray at the early stage of injection. From the observation of spray images varying the moment of exposure, the change in spray characteristics, such as the spray penetration, spray angle, and the degree of atomization can be obtained. As shown in Fig. 5 A-B, during injection a jet-core which is close to a liquid column having extremely rich desity in fuel is generated and few breakup droplets are found at a very short distance from the nozzle. After that breakup droplets are observed at the periphery of the spray and around the spray tip (Fig. 5B).

b) The Breakup Length of the Pintle Nozzle Spray

Like the hole nozzle spray, the spray injected from the annular slot of the pintle nozzle starts breaking up after an atomization delay. Hiroyasu et al. [2] investigated the breakup length of the hole nozzle spray and proposed an empirical expression for it. But so far as the pintle nozzle spray is concerned, the similar work has not yet been done.

On account of the complexity of the injection process with the pintle nozzle, a concept of quasi-breakup-legnth of the spray is introduced here for the convenience of application. Based on the macroscope analysis, it is defined as a axial distance between the nozzle tip and the position at which the shear layer of the spray is increased suddenly because significant dispersion in radial direction of the spray starts.

In order to have an insight into this problem, microscope observations in the periphery of the spray near the nozzle are made. It is found that large droplets can only be seen in the region just after the quasi-breakup-length. This demonstrates clearly the onset of spray atomization at the end of this length.

Based on the above concept, the treatment of the experimental data obtained under the conditions of A, B, C, F in Table 2 is carried out and the results are compared with the corresponding values calculated by the Hiroyasu's empirical expression for breakup length of spray from the hole nozzle. This comparison shows the same tendency of both spray tip penetrations and a differential in absolute quantity. Accordingly, based on the modification of the Hiroyasu's expression, a semi-empirical relationship is proposed using the curve fitting method to calculate the breakup length of the pintle nozzle spray and is given by

$$\begin{aligned} S_b &= 0.39\sqrt{2\Delta P/\rho_1}\,t_b, \\ t_b &= (28.65\rho_1 t_0/\sqrt{\rho_a \Delta P})C, \end{aligned} \qquad (1)$$

where S_b = breakup length (mm); t_b = breakup time (s); Δp = pressure differential across the nozzle hole (Pa); ρ_1 = fuel density (kg/m); ρ_a = air density (kg/m^3); t_0 = width of annular slot of the pintle nozzle at the main injection stage (m); C = modified index, which is given by the following expression

$$\begin{aligned} C = (2/d_0)^{1.5}\{A[1+\frac{|\ln(P_b/0.8)|}{B}] \\ +\frac{1}{2}(1-A)[1-\cos(\frac{\pi\cdot P_b}{0.8})]\}, \end{aligned} \qquad (2)$$

where d_0 = diameter of the needle tip (mm); P_b = back pressure (MPa); A,B = constants, for $P_b \geq 0.8$ (MPa), A = 0.9763, B = -3.4654; for $P_b < 0.8$MPa, A = 0.967, B = -16.982.

A MATHEMATICAL MODEL FOR THE PINTLE NOZZLE FUEL SPRAY

In a previous paper [3], one of the authors developed a mathematical model for the prediction of the hole nozzle spray behavior under high swirl conditions. In this study, much attention will be focused on the development of a theoretical model to predict the spray characteristics of pintle nozzles.

In the past, aerodynamic characteristics of the annular swirling jets and the interference of the two-dimensional turbulent jets discharging parallel to and offset from a solid boundry have been investigated both experimentally and theoretically by some investigators. [4-6] The essential features of these flow are very similar phenomenologically to what is observed by the authors in the region near the pintle nozzle with a large divergence angle.

Formulation

According to the results of experimental observation, the fuel spray injected into still surroundings from the pintle nozzle can be considered as an annular jet emerging at an divergence angle. Because of the existence of the lateral pressure difference across the jet which results from the reduced mass entrainment in the interference region surrounded by the jet. The main stream-lines of the annular jet deviate from straight lines and show a curvilinear motion tending to merge into a single jet at some downstream station as shown in Fig. 6. In this work the authors present a simplified analysis based on the previous work and integral methods.

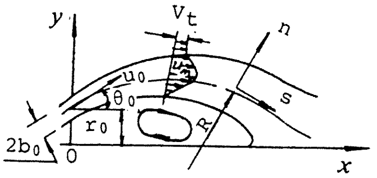


Fig. 6 Notation used in the flow analysis.

Chiu, W. S. [7] and Sinnamon, J. F. [8] made contributions to the difficult problem of mixing of fuel spray. Their interests were limited to single phase condition so as to simplify considerably the theoretical approach. The current model adopts this simplification and the formulation is based on the solution of the integral equations for continuity, momentum conservation. Further simplifications are:

(1) Similarity profiles are used to describe the distributions of velocity and concentration across the jet. The velocity in recirculation region is negligible.

(2) A force due to the static pressure difference acts in the direction perpendicular to s axis on the inner and the outer surfaces of the jet with the width 2b.

Taking into account the annular jet to be axial symmetric to X axis, from the above assumptions, the continuity and momentum equations are as follows:

$$\begin{aligned} &\frac{d}{ds}\iint_A c\rho u\,dA = 0 \\ &\frac{d}{ds}\iint_A \rho u\,dA = \frac{d\dot{m}}{ds} \\ &\frac{d}{ds}\iint_A \rho u^2 dA = V_t\frac{d\dot{m}}{ds} + \frac{d}{ds}\iint_A P\,dA \\ &-\iint_A \rho u^2\frac{d\theta}{ds}\,dA = V_n\frac{d\dot{m}}{ds} - \iint_A\frac{\partial P}{\partial n}\,dA \end{aligned} \tag{3}$$

where A = cross- sectional area of annular jet; θ = angle between the jet centerline and stationary positive x axis; u = the velocity of the jet; r = distance between jet axis and x axis; s = distance along jet centerline; p = pressure; V_t,V_n = tangential and normal component of swirl velocity respectively; u_m = instantaneous jet centerline velocity; C_m = instantaneous jet centerline fuel concentration; b = half width of jet cross-section; ρ = local jet density; $d\dot{m}/ds$ = air mass entrained per unit length of the jet in unit time.

The solution to Equation (3) are obtained by assuming appropriate velocity and concentration profiles. At the current cross-section, they are expressed by

$$\begin{aligned} &u = (u_m - V_t)\cdot G(\eta) + V_t \qquad n > 0 \\ &u = u_m G(\eta) \qquad n < 0 \end{aligned} \tag{4}$$

$$c = c_m F(\eta) \tag{5}$$

where $G(\eta) = 1 - \eta^{1.5}$, $F(\eta) = (1 - \eta^{1.5})^2$

The local jet density can be written in the form

$$\rho = \rho_a/[1 - c_m F(\eta)(1 - \beta)] \tag{6}$$

where β = Rv/Ra; Rv, Ra = universal gas constants of fuel vapour and air respectively.

To evaluate the pressure integral in Equation (3), P is assumed to vary linearly across the jet according to

$$P = \frac{P_d(S)}{2}\left[1 - \frac{n}{b(S)}\right] \tag{7}$$

It can be seen from the Equation (7) that $P = P_d(s)$ when $n = -b(s)$.

In the case of a pair of plane jets or a plane jet near a screen, Krasheninikov, et al. [9] proposed a correlation for the pressure difference P_d across the jet boundaries as

$$P_d = \frac{\rho_a V_e^2}{2}\left(\frac{1}{\cos^2\gamma_2} \quad \frac{1}{\cos^2\gamma_1}\right) = \psi(S)\frac{\rho_a V_e^2}{2} \tag{8}$$

where ψ is the function that characterizes the change in the conditions of air flow toward the jet along its trajectory, which can be determined step by step in solving the simultaneous differential equations; γ is the angle between direction of the inflow velocity and the normal to the jet boundary; Ve is the entrained air velocity component normal to the jet boundary, and

$$V_e = E\,u_m \tag{9}$$

E is a constant related to the rate of growth of the jet width.

The above is about the main region formulation. As for the initial region, here uses Equation (1) to predict the length of the spray potential core. For the purposes of the calculation, the transition region is ignored so that the corresponding parameters on the transition cross-section can be derived by expressing the conditions of conservation between the nozzle and this cross-section, as described by Sinnamon [8].

As mentioned above, the annular jet impinges on the axis of symmetry at some finite downstream location x_m beyond which it behaves like a single hole nozzle spray. Because the merging of the jet is very complex and little information is given on this process, the merge region is assumed to begin at the point of intersection of the curved jet inner surface with the symmetric axis of the nozzle, and the momentum flow of thejet downward the end of the merge region to be equal to the product of that at the beginning of this region times (1 + cosθ)/2. The increase of the entrained air mass due to the enhanced mixing in the merging region is assumed to compensate for the loss of the jet mass returned into the recirculation region. After the conversion of the annular jet into a single round jet, its penetration can be predicted by using the spray mixing model for hole-type nozzle developed by the authors.

Results and Discussion

The computer program is written and the four equations in db/ds. du_m/ds, dc_m/ds and $d\theta/ds$ are solved numerically by the Gear method, using the Subroutine DGEAR from the Honeywell DPS 8/52 computer library.

In order to check the validity of the present mathematical model, it is first used to predict the initial trajectory and the pressure in the recirculation region associated with a air jet issuing from ordinary annular nozzles for which experimental data are available in the reference[10].

In Fig.7 is shown the spatial trajectory of the central streamline for some different nozzle dimensions. It is illustrated that the characteristics of the flow pattern are determined only by nozzle dimensions and not by the value of exit velocity.

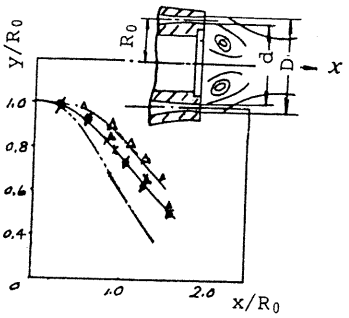


Fig. 7 Spatial trajectory of the central streamline

d/D	Measured Value	Calculated value	Initial velocity (m/s)
0.8	△	—·—	25
0.9	▲	———	25
0.9	×	———	50
0.9	♦	———	70
0.95		—·—	

This model and calculation method, which have been proved to be applicable, are also used to calculate the flow pattern of pintle nozzle sprays. The calculated results are given in Figs. 8, 9. As shown in Fig. 8, when variations in the ambient pressure are made, the main streamlines take the different paths. At the atmospheric pressure, they become straight lines in the direction decided at the nozzle exit as seen from the experimental results mentioned above (Fig. 2C). This can be explained by the Fig. 9 that the ambient pressure has significant influence on the value of the static pressure difference acting across the jet which decreaes with decreasing the ambient pressure.

It has been clarified from the calculated results that the nozzle configuration angle, distance between nozzle and slot axes and the slot width can also affect the flow pattern of the spray significantly. Hence at the early stage of injection, the shape of the spray from the Model ZS45S2 pintle nozzle is appreciably dissimilar to that from the Model ZS4S1 pintle nozzle.

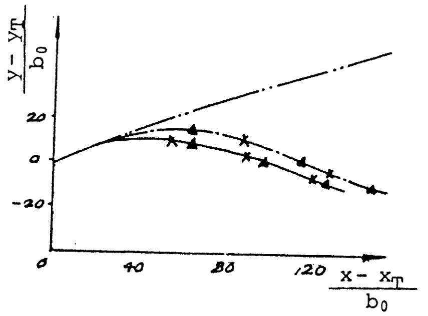


Fig. 8 Effects of injection velocity and back pressure on the trajectory of the spray.

Mark	Back pressure P_b (MPa)	Initial velocity Uo (m/s)
—·—	0.1	63.04
×	2 (—·—)	63.04
▲	2.8 (———)	186.0

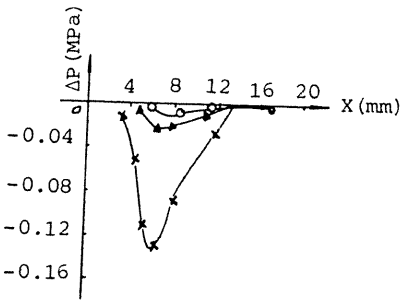


Fig. 9 Variation of the static pressure with the back pressure

Mark	Uo(m/s)	P_b(MPa)
o—o	70	2
▲—▲	63	2.8
×—×	186	2.8

It has been proved by comparing the calculated values with the experimental values that this calculation method is applicable to predict the penetration of the pintle nozzle sprays.

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