Measurements of Breakup Length in High Speed Jet*

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The breakup length of a high speed jet was studied by measuring the electrical resistance between a nozzle and a fine wire detector located in a spray jet. The maximum injection velocity was 190 m/s and the maximum Reynolds number was 6.4 x 10^4.

In the spray flow region, the breakup length of a liquid jet which was injected at high injection pressure into a chamber has a finite value. As the injection velocity increased, the breakup length progressively decreased and reached a constant value. As the ambient pressure increased, the breakup length decreased.

The effect of L/D (the ratio of nozzle length to the diameter) upon the breakup length was great at atmospheric ambient pressure, but not so great at a high ambient pressure.

Key Words: Internal Combustion Engine, Diesel Spray, Nozzle, Breakup Length, High Speed Jet, Spray Angle.

1. Introduction

The breakup length of a jet is frequently a technical matter of great importance, because diesel combustion is strongly controlled by characteristics of fuel spray which is injected into a combustion chamber. It is well known that concentrations of smoke, total hydrocarbon and nitric oxide in exhaust depend to a great extent on the form, droplet distribution and aerodynamic motion of spray. Therefore, as a basis study of diesel combustion, many engine researchers have studied the diesel spray. For example, there are several theoretical and experimental equations for spray angle, spray tip penetration and droplet distribution (1-9).

The effect of physical properties of liquid, diameter of nozzle and the relative motion between ambient gas and liquid upon the breakup length of a jet have been studied (5-8). But the size of injection nozzles used in many previous studies was larger than that of a nozzle practically used in an engine, and the injection pressure was low. Particularly on the disintegrating phenomenon near the nozzle exit, there is not enough information. For a high speed jet which is always used in a practical diesel engine, existence of a liquid column in the developing spray has been merely conjectured (9-10).

Recently, the direct injection system of the diesel engine used in a small passenger car has aroused general interest in relation to energy saving and fuel economy. In a direct injection diesel engine of a small passenger car, the breakup length of a jet in the spray and the distance between a nozzle exit and a combustion chamber wall are supposed to be equivalent. And the spray formation process is considered to be affected by this phenomenon. So the effect of impingement of a fuel spray at a combustion wall on spray formation is a very important matter.

From these standpoints, the authors believe that it is very important to know the exact breakup length of a high speed jet under the comparable ambient pressure conditions of a diesel engine.

For this reason, the main purposes of this study are to measure the breakup length of a liquid column in a developing spray at a high ambient pressure and to obtain information about a high speed disintegration process of a liquid jet in the spray flow region.

* Received 5th April, 1982.
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2. Experimental apparatus and method

2.1 Experimental apparatus

An apparatus used for the injection experiment of high pressure is shown in Fig. 1. This apparatus was designed to study jet breaking up phenomena over a wide range of operating conditions. It consists of a spray chamber, a liquid injection system, an injection nozzle and a screen wire detector.

The high pressure chamber (12) was designed 160 mm wide, 90 mm depth and 250 mm height in the inner dimensions. The allowable maximum pressure in this chamber was 10 MPa. The pressure in it was also controlled by the regulating valves 7 and 17 to perform experiments at different ambient pressure. In addition, the transparent windows facilitate the photographic observation of the liquid injection process (14).

The liquid injection system consists of an air-driven high pressure pump (1), a pressure accumulator for damping the pressure pulsation (2) and an Hg gas bomb (3). This system was designed for injection pressure from 0.1 MPa to as high as 40 MPa.

A liquid used for testing (water was used in this study) was pumped by the air driven high pressure pump and supplied from the pressure accumulator to the spray chamber, then it was injected into the chamber in such a way that the liquid injection pressure was kept constant during a given injection period.

Fourteen nozzles which played an important part in this study were employed. Figure 2 shows the injection nozzle used in this study. It consists of a nozzle holder which has a pressure tap for measuring an injection pressure, a retaining nut and a nozzle. The exit diameter D and the ratio of the nozzle length to the diameter L/D of a nozzle were similar to the dimensions of a diesel fuel nozzle. The nozzle exit diameter D was 0.3 mm and
the length of nozzle L was from 1.2 mm to 15 mm (L/D = 1/50). The edges of the inlet and outlet of the nozzle and the inner surface of it were polished very fine.

The injection velocity of the liquid jet was calculated as the sectional average velocity in the nozzle.

The electric circuit that was used to detect the position of breakup points in high speed jet illustrated in Fig. 3. The loading voltage at DC 30 volts was always imposed on this circuit. Electric circuit through the liquid column was observed with an oscilloscope.

Figure 4 shows the electrode of the screen detector made of a fine wire screen of stainless steel. This detector could be adjusted vertically along the axis of the jet, and the voltage signals from nozzle to screen wire detector were observed. And the fundamental definition of a breakup length in this study was an average constant length as a continuous part of the liquid jet.

2.2 Definition of breakup length

Typical oscilloscope signals indicating the breakup length are shown in Fig. 5. Injection velocities 5 m/s, 43 m/s and 136 m/s correspond to a laminar flow, a turbulent flow and a spray flow region respectively. When the detector was moving away from the nozzle, the signals showed a low resistance level which meant a solid column. The length of this state was defined as L\textsubscript{b1}, and the length showed the state before a liquid jet was disintegrated into droplets. When the detector was moving farther away from the nozzle, the probability that both signals of a low resistance and signals of a high resistance will happen was fifty percent. The length of this state was defined as L\textsubscript{b2} and this state means the average breaking up point. Furthermore, if the detector was kept away from the nozzle, the signals showed a high resistance level. It meant that there was not a continuous column there or the liquid column was disintegrated into droplets. The length of this state was defined as L\textsubscript{b3}. The breakup length should be measured as the average breakup length, because the breaking up of the jet was a statistical phenomenon. Then, the breakup length L\textsubscript{b} was defined by L\textsubscript{b2} in this study.

3. Experimental results

3.1 Effect of injection velocity on breakup length

Figure 6 shows the measured results of the breakup length in the case of L/D = 4 and an atmospheric ambient pressure. The effects of the injection velocity on L\textsubscript{b1}, L\textsubscript{b2} and L\textsubscript{b3} were almost the same. In the turbulent flow region (from V\textsubscript{i} = 10 m/s to V\textsubscript{i} = 65 m/s), as the injection velocity increased, the breakup length increased. In the spray flow region, as the injection velocity increased, the breakup length progressively decreased. With further increase in the injection velocity, the breakup length reached an almost constant value.

3.2 Effect of nozzle length on breakup length
Fig. 8 Effect of nozzle length on breakup length at $L/D = 50$ and $P_a = 0.1$ MPa

Fig. 9 Effect of nozzle length on typical breakup length ($L_b = L_b2$)

Fig. 10 Effect of $L/D$ on breakup length at $V_i = 150$ m/s

Fig. 11 Effect of nozzle length on breakup length at $L/D = 4$ and $P_a = 3.0$ MPa

Fig. 12 Effect of nozzle length on breakup length at $L/D = 10$ and $P_a = 3.0$ MPa

Fig. 13 Effect of nozzle length on breakup length at $L/D = 50$ and $P_a = 3.0$ MPa

The effects of the nozzle length on the breakup length are shown in Figs. 6, 7 and 8 in the case of an atmospheric ambient pressure. When the injection velocity increased, the breakup behavior remained almost the same in any case. In order to make comparison easily, the effects of the nozzle length on each breakup length ($L_b = L_b2$) are shown in Fig. 9. The absolute length of breakup was shorter at $L/D = 10$ than any conditions.

Figure 10 shows a comparison of the breakup length at the spray flow region ($V_i = 150$ m/s). The breakup length becomes minimum at the finite value of $L/D$. For this phenomenon, the following reason will be considered. In the spray flow region, the internal flow of the nozzle is turbulent. Even in that flow, the velocity profile is rectangular at the nozzle inlet and it becomes parabolic as the entrance length increases. The transition of the velocity profile from rectangular to parabolic causes an unstable disturbance in the flow. This disturbance might cause the breakup length to decrease.

Figures 11, 12 and 13 show the effect of injection velocity on the breakup length in the case of $L/D = 4$, $L/D = 10$ and $L/D = 50$, with a high ambient pressure.
Fig. 14 Effect of L/D on breakup length at $L_0 = L_{12}$ and $P_a = 3.0$ MPa

![Breakup Length vs Injection Velocity](image)

![Spray Angle vs Dimensionless Length of Nozzle](image)

Fig. 15 Spray photographs

$P_a = 3$ MPa ($30$ kgf/cm$^2$) $V_w = 120$ m/s

Fig. 16 Effect of L/D on the spray angle

Fig. 17 Effect of ambient pressure on breakup length at $P_a = 1.0$ MPa

Fig. 18 Effect of ambient pressure on breakup length at $P_a = 4.0$ MPa

(Pa = 3.0 MPa). In these cases, the breakup length was shorter as a whole, as compared with the case of a gaseous environment of an atmospheric pressure, and the difference between $L_{01}$ and $L_{02}$ or $L_{03}$ was reduced, as shown in Fig. 14. The effect of the dimensionless length of nozzle L/D on the typical length ($L_{12}$) did not appear at high ambient pressure. The points of transition from turbulent flow to spray flow are not clear, and the curves of the breakup length smoothly change. It is considered that, at high ambient pressure, the interactive force between the injection liquid and the ambient gas of high density becomes the main cause of the decrease in the breakup length. Therefore, as the pressure of ambient gas increases, the relative difference of the breakup length with L/D becomes smaller.

Figure 15 shows the effect of L/D on the width of spray at a high ambient pressure of $P_a = 3.0$ MPa. It is clear from this figure that the nozzle of L/D = 10 shows a larger width of spray compared with other nozzles. The spray angle which was measured from the photographs of the spray is shown in Fig. 16. In this figure, the spray angle takes the maximum value near L/D = 20. It is supposed from these phenomena that the outlet flow at the nozzle was very unstable in the case of L/D = 20. The reason is that the velocity distribution in the jet was uniform at L/D = 4, and the velocity distribution was of a fully developed turbulent flow at L/D = 50. Then in the vicinity of L/D = 20, the velocity profile at the outlet flow of the nozzle was just transitional flow from laminar flow to turbulent flow and it was the most unstable.
3.3 Effect of ambient pressure on breakup length

The effect of an ambient pressure on the breakup length was shown in Figs. 6, 11, 17 and 18. The breakup length ($L_{b1}$, $L_{b2}$ and $L_{b3}$) decreased with a decrease of the ambient pressure, and the difference between them was small. In order to make comparison easily, the effects of the ambient pressure on the typical breakup length ($L_{b2}$) are shown in Fig. 19. The breakup length decreases as the ambient pressure increases, but there is little difference between the cases of $Pa = 3.0$ MPa and $4.0$ MPa.

The breakup length at the spray flow region ($V_i = 120 \text{ m/s}$ and $V_i = 170 \text{ m/s}$) is shown in Fig. 20. As the ambient pressure increased, the breakup length decreased, and finally the breakup length approached a constant value of 20 mm. This result is a very important fact, because the radius of a combustion chamber of a direct injection diesel engine which is used in a small passenger car, is considered almost equal to the breakup length measured here. Figure 22 shows the effect of the ambient pressure on the configuration of the jet. At an atmospheric ambient pressure, the liquid jet only slightly spread in the radial direction of jet, and the width of the spray was very small. As the pressure of ambient gas increased, the width of spray and the fine droplets in the spray also increased. It is considered that, as the pressure of ambient gas increased, the interactive force between the injected liquid and the ambient gas increased. Therefore, the liquid jet spread in the radial direction and the disintegration of the jet was promoted.

Figure 22 shows the spray angle in the same conditions as Fig. 21. The spray angle increased both in the case of $L/D = 50$ with an increasing ambient pressure, the spray angle also approached a constant angle.

4. Conclusions

The breakup behavior of a high speed jet was studied by measuring the electrical resistance between a nozzle and a fine wire screen detector located in a spray jet. The following experimental results were obtained:
1) As the injection velocity increases, the breakup length increases in the turbulent flow region, but it decreases and finally approaches a constant value in the spray flow region.

2) The effect of the dimensionless length of the nozzle on the breakup length is great at atmospheric ambient pressure, but it does not appear at a high ambient pressure.

3) The breakup length decreases as the ambient pressure increases at any injection velocity.

4) In the spray flow region, the spray angle increases as the ambient pressure increases.

Acknowledgements

The authors wish to thank Mr. H. Osawa and Mr. K. Inaba for their cooperation on this work.

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