

Characteristics of a Diesel Spray Impinging on a Flat Wall

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ABSTRACT

It is unavoidable that the fuel spray impinges on the wall of piston cavity in a small high-speed DI diesel engine. Then, it is significant to make clear the characteristics of the impinging spray. In the experiments, a single shot diesel spray was impinged on an inclined flat wall into the quiescent atmosphere with a high pressure at a room temperature to simplify the state of the real combustion chamber. The spatial and temporal distribution of the droplets density was calculated by use of data obtained from the laser light extinction method, applying the computed tomography. And photographs were taken by a microflash. Consequently, the spray flows mainly along the wall in the direction of the downstream, when the inclination angle increases. And the remarkable wall jet vortex appears at the peripheral region of the impinging spray in the downstream.

1. INTRODUCTION

Fuel sprays injected into a combustion chamber in a small high-speed DI diesel engine impinge surely on the wall of piston cavity. So the characteristics of the impinging spray are the very significant information on the consideration and the simulation of its combustion processes including the formation mechanism of exhaust emission and the design of the combustion chamber.

One of authors presented previously a paper on the shape of a single impinging diesel spray of JIS first class heavy fuel oil injected through a hole nozzle used in a medium-speed diesel engine⁽¹⁾. The shape, i.e., the spray radius and height were measured only on photographs taken by a microflash and a 35 mm camera. Lately, Naber and Reitz simulated the shape using by KIVA computer code, quoting the data from this paper⁽²⁾. Thereafter, authors experimented on the characteristics of a diesel spray of JIS second class light fuel oil impinging on a flat wall at a right angle, which was injected through a hole nozzle used in a small high-speed DI diesel engine⁽³⁾. They established the calculating method of the temporal and spatial distribution of the droplets density in the impinging spray applying the concentric circle model, using the mean turbidity of the optical path length obtained by the laser light extinction method^{(4),(5)}. The structure of the impinging spray was made clear by this distribution. And they presented the

experimental equations on the spray radius and height on the wall.

However, it is incapable of applying the concentric circle model for the spray impinging on the inclined wall, because the phenomenon can not be axi-symmetric. Then, in the experiments presented here, the computed tomography was applied for this spray, to calculate the spatial and temporal distribution of the droplets density⁽⁶⁾⁻⁽⁸⁾. The spray spread at the major and the minor axes of the shape on the wall and the maximum height were measured by phototographs. As a consequence, the precise information on the internal structure were presented by these data.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The same experimental apparatus and procedure as those shown in the previous paper⁽³⁾ were used in the experiments. JIS second class light fuel oil (specific gravity 0.831 at 15/4 °C, kinematic viscosity 3.81×10^{-6} m³/s at 30 °C) was injected only once into a chamber which had a quiescent atmosphere with a high pressure at a room temperature. And a single spray was impinging on the flat wall made of aluminium whose size was 110 mm in square. The material of wall was as same as that of a piston in practical small high-speed diesel engines. The conditions of the injection and the distance between the wall and the nozzle exit, that is, the impingement distance, were constant. The experimental parameters were the inclination angle of the wall and the ambient pressure, i.e., the ambient density. The experimental conditions are summarized in Table 1.

The instantaneous photographs of the lateral view of the impinging spray were taken by a transmitted light passing through windows installed in both sides of the chamber. The spray spread on the wall was taken instantaneously by photograpy with the scattered light through the wall and a window which was installed in the bottom of the chamber. In this case, the wall was made of acrylate resin. The difference between the over-all weights of the adhering fuel oil on both walls was only within 2 %. Then, there was very little influence of the difference in material on the adhesion of fuel oil. The light source was a micro-flash (flashing time 0.7 μ sec), and the used film was Kodak Tri-X.

Fig.1 displays the schematic block diagram of the optical system to detect the turbidity of the optical path length in the impinging spray. The

Table 1 Experimental conditions

Injection nozzle			
Type	Hole nozzle DLL-S		
Number of holes	1		
Diameter of hole	d_n	mm	0.2
Length of hole	l_n	mm	1.1
Injection pump			
Type	BOSCH	VE	
Revolutional speed	N_p	Hz	15.0
Mean injection pressure	P_{inj}	MPa	13.8
Injection duration	t_{inj}	ms	1.3
Amount of injected fuel	Q_{inj}	mm ³	8.2
Mean injection rate	dQ_{inj}/dt	mm ³ /ms	5.6
Ambient (air)			
temperature	T_b	K	room temp.
pressure	P_b	MPa	1.0, 1.5
density	ρ_a	kg/m ³	12.3, 18.5
Wall			
Impingement distance	Z_w	mm	24
Inclination angle	α_w	deg.	0, 15, 30, 45

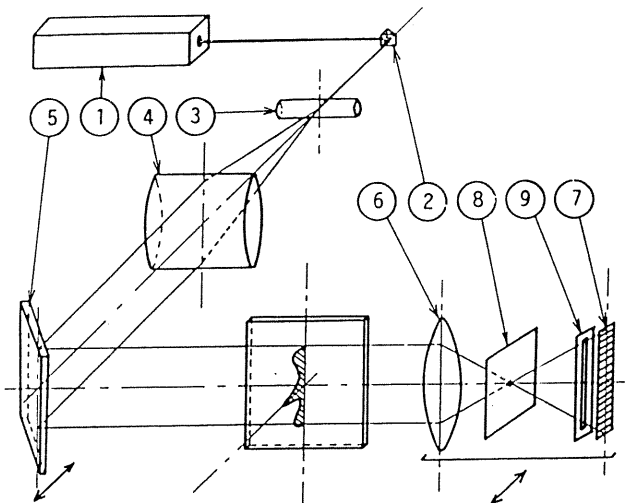


Fig.1 Schematic block diagram of optical systems

light from the He-Ne laser 1 (15 mW, 632 nm) was changed its direction by the mirror 2. The cylindrical lenses 3 and 4 formed a thin sheet of light. This sheet of light was reflected by mirror 5, past through the impinging spray, and was collected through the concave lense 6. The outgoing light was received by the photo diode array 7 (46 elements) at an interval of 1.0 mm, which past through the pin hole 8 and the knife edge 9.

The laser light was projected into the impinging spray at planes parallel to the wall in a range of 1 mm to 10 mm in every 1 mm. The relation among the focal length of lense 6, the position of the array 7 and the interval of each element of the array determined the resolution of measurement. The relation was selected in order to maintain the measuring points at the interval

of 1.4 mm between each point. The measuring range was set 42 mm unsymmetrically with respect to the spray axis, because droplets in the impinging spray flowed mainly to the direction of the downstream as increase of the inclination angle of the wall.

Each signal detected by each element of the photo diode array was taken in order by the data processing system consisting of 16 channels of the operational amplifier and the sample/hold amplifier, the multiplexer and the 10 bits transient memory. The digital logic circuit controlled this system. The sampling time of one channel was 2.5μsec and it took 40 μsec to sample all the data of 16 channels. Two systems were prepared for the experiments. The data are transferred from the system through PIO interface to the CPU then processed.

The measurement of the projection data of the laser light extinction was carried out in 8 directions by means of the rotation of the set position of the injection nozzle. These data were converted into those in 16 directions by the interpolation⁽⁷⁾. The projection data of 30 rows in each direction obtained in the experiments were transformed into 84 data at interval of 0.5 mm by means of the spline interpolation. The reconstruction of the image of the impinging spray was carried out by these data. In the operation, the convolution method was adopted and the used filter function which was modified by Nakayama⁽⁶⁾ was presented by Shepp and Logan⁽⁹⁾. The discussion was made by using the ensemble mean value of 50 data sampled in every measurements.

3.SPATIAL AND TEMPORAL DISTRIBUTION OF DROPLETS DENSITY

Fig.2 is typical examples of photographs of the side view of the impinging spray, the distributions of droplets density at the perpendicular sectional area to the wall, photographs of the back view and the distributions of droplets density at the parallel sectional area to the wall in cases of the distance H from the wall equal to 1 mm, 3 mm and 5 mm. The inclination angle α_w of the wall is 0 deg. and 45deg., and the time t from the start of injection is 0.6 msec, 0.8 msec and 1.2 msec, respectively. S shown in figures means an area where droplets was not existing.

In the previous experiments, for example, by Kuniyoshi et al.⁽¹⁾, the data on the characteristics of the impinging spray were measured on photographs, so only the information on the external form was detected. And photographs taken by the transmitted light displayed shown in Fig.2 include only the qualitative information. However, the structure inside the impinging spray can be discussed by the information with high resolution of the droplets density, such as that shown in Fig.2, obtained by the experimental procedure mentioned above. There are many notches at the peripheral region of the spray on the wall, which appears on photographs taken through the transparent wall. However, there are little notches at the same region on the data of distribution of the droplets density, which is obtained by the reconstruction of the image. This is the reason why the data processing at the reconstruction is carried out using the ensemble mean value of 50 data and the phenomenon is taken by photography only at one injection. And also there is the effect of the

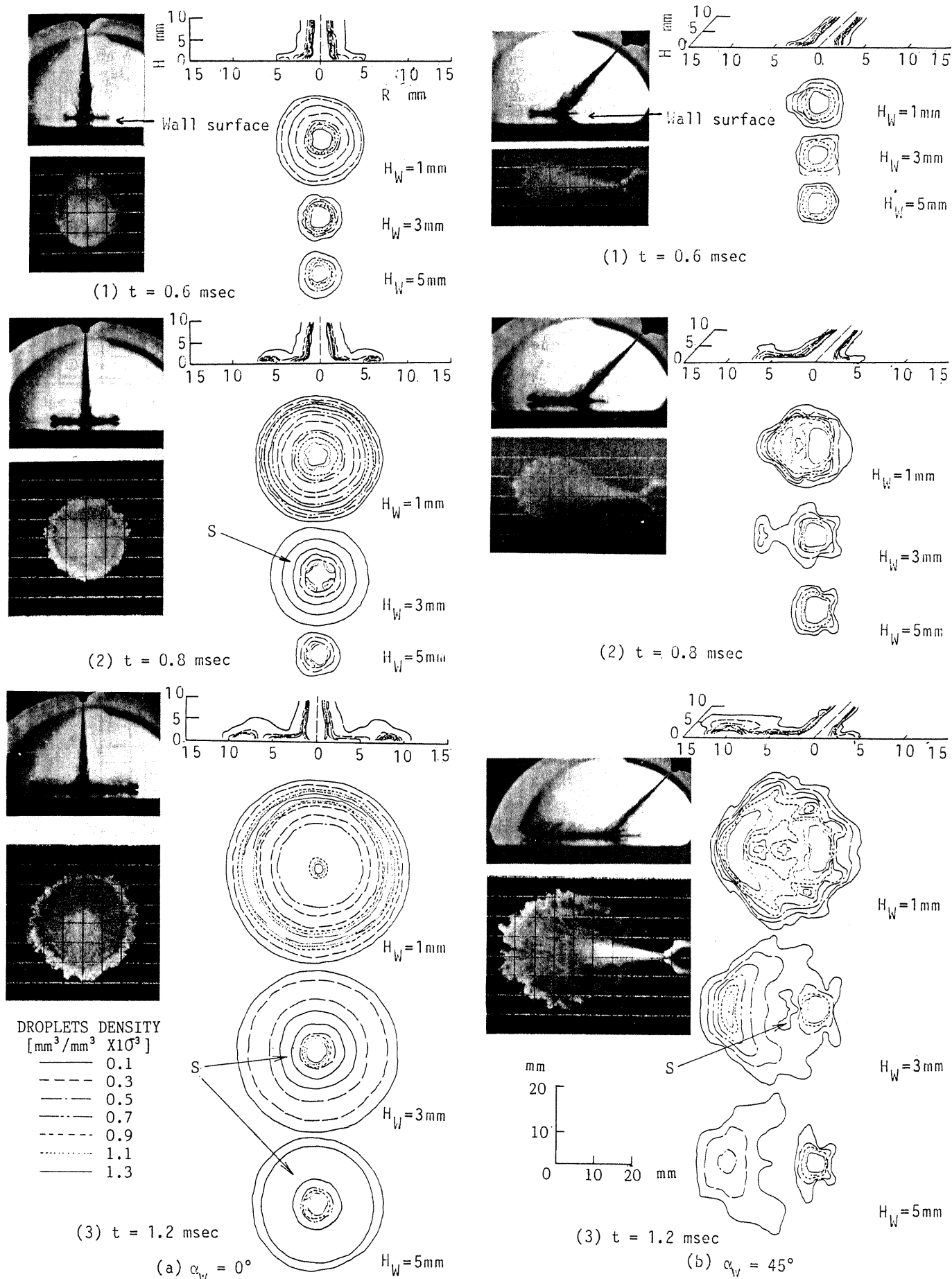


Fig.2 Shape of impinging spray and spatial and temporal distribution of droplets density

thr should value at the data processing.

The spray impinges on the wall at 0.3 msec after the start of injection regardless of the experimental conditions, because the spray flows with the almost uniform velocity within about 0.5 msec, as well known, and the difference between the injection pressure and the ambient pressure is little. At the time t of 0.6 msec after the start of injection, the external sectional shape of the spray on the wall is considered to be a rectangle, such as that in the previous paper (1). However, the shape becomes hollow near the spray axis and rises at the peripheral region, as the time passes. The tendency of hollow and rise is marked as the ambient density ρ_a is increasing. The spray develops mainly to the direction of the downstream and scarcely flows to that of the upstream, when the inclination angle α_w of the wall increases from 0 deg.. As a consequence, the shape on the wall is the circle at the vertical impingement, and changes from the circle to the ellipse. The shape of the ellipse becomes slender, as ρ_a becomes smaller and α_w gets larger. The growth of spray on the wall in the radial direction is decreasing, as ρ_a is increasing, owing to the increase in the resistance of the ambient. The tendency is a same as that of the tip penetration of the free diesel spray.

The droplets density C_f decreases, as t elapses, according to the increase in the spray volume. The distribution shows the small difference in C_f , when the distance H from the wall becomes farrer. At the same time and the same position, C_f increases, as ρ_a increases, because the quantity of the injected fuel is constant, C_f shows the high value near the impinging point and near the wall, regardless of ρ_a and α_w . There is a region of high C_f at all peripheral regions of the spray where the spray height is maximum, in the case of $\alpha_w = 0$ deg.. On the other hand, this phenomenon appears especially at the peripheral region of the downstream when the wall is inclined. In this region, the foregoing droplets lose their momentum and stagnate, then the succeeding droplets outturn and push up them to the upper side of the wall. This state appears typically in the contour line of $C_f = 0.3 \times 10^{-3} \text{ mm}^3/\text{mm}^3$. Namely, there is the wall jet vortex which rolls up droplets at the peripheral regions. The phenomenon becomes remarkable, when ρ_a and α_w increase, and the maximum spray height at this region increases. Accompanying the roll up, the mixing between the droplets and the surroundings is very progressing, the region where C_f is low is increasing and the spray volume becomes larger. As a consequence, the wall jet vortex plays the great roll in the progress of the mixing. On the other hand, in the upstream, the peak of C_f is much smaller and the effect of ρ_a on the peak is much less than that in the downstream. And the phenomenon of the roll up hardly occurs at the upstream. This is the reason why the momentum of the spray is distributed mainly to the downstream after the impingement.

Fig.3 shows the examples of the history of the spray volume by droplets density during the duration of injection. (a) is the case of α_w of 0 deg., and (b) is that of $\alpha_w = 30$ deg.. The ambient density ρ_a in both cases is 12.3 kg/m^3 . The space in this measurement is 60 mm in length, 60 mm in width and 10 mm in height.

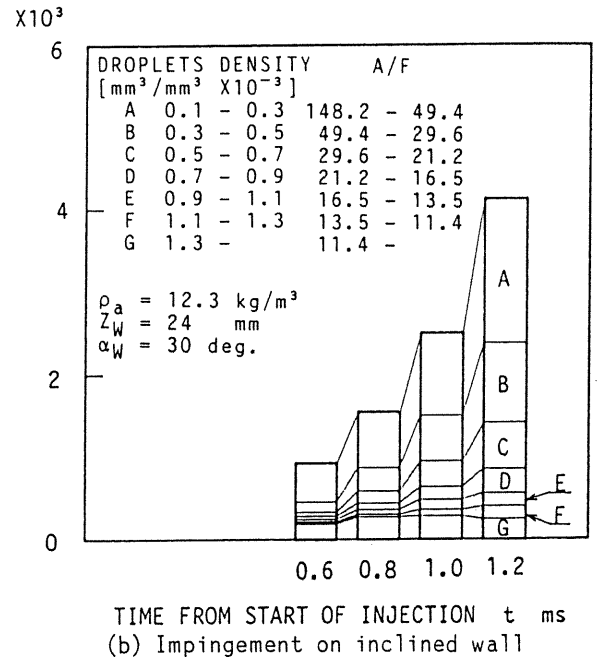
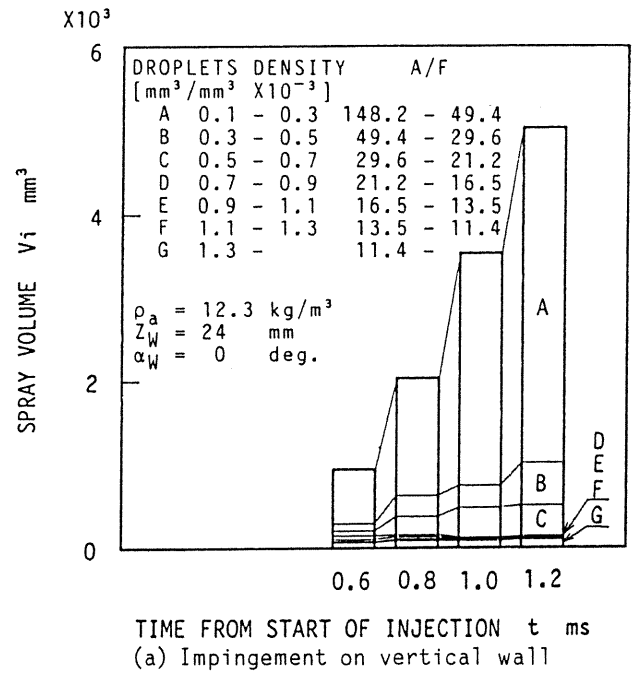


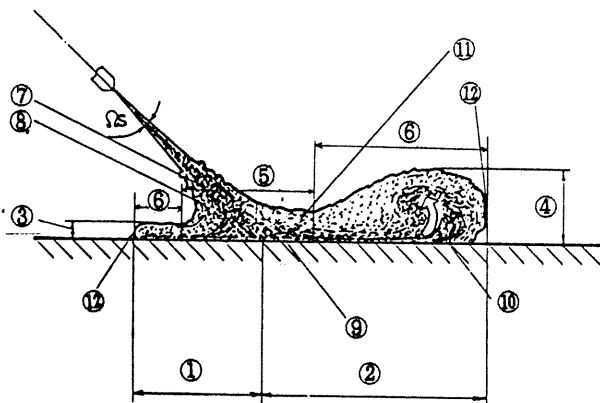
Fig.3 Spray volume by droplets density

It is marked phenomenon that the time history of V_i with low droplets density C_f , that is, high air/fuel ratio A/F, differs from that with high C_f , that is, low A/F. The volumes of the regions A, B and C where C_f is lower are increasing, as the time t from the start of injection passes. The rate of increase in the volume by droplets density is maximum in the region A, unrelated to the experimental conditions. However, the volumes of the regions of B and C have a tendency to increase in ρ_a and α_w , then the rate of volume of the region A to the measured whole volume is decreasing. This is the reason why the effect of the wall jet vortex is decreasing with increase in ρ_a and α_w .

The volumes of the regions E, F and G where C_f is higher are extinguished small and are considered to be constant during the injection period, regardless of α_w and ρ_a , because of region of higher C_f existed mainly near the spray

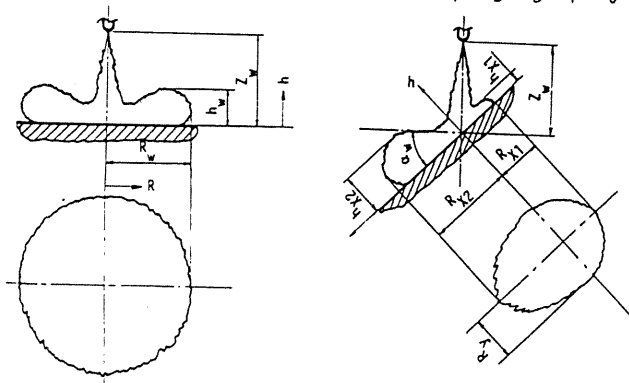
axis and it is almost constant. In the upstream, there is the almost constant volume of the lowest C_f of region A during the duration of injection, when the wall is inclined. However, the volume of the highest C_f of region G is much larger than this volume, and the whole volume belonging to the upstream is much smaller than that belonging to the downstream. Then, the increase in the volume of A, B and C are caused by the flow and its development in the direction of the downstream. As a consequence, it seems to suggest that the entrainment and the mixing are occurred mainly in the downstream. These results, especially the increase in the volume of lower C_f , are very significant for the processes of combustion of the impinging spray. The tendency above mentioned occurs if ρ_a is changed.

Fig.4 is the qualitative model in the case of the impingement on the inclined wall. The state in the downstream is considered to be essentially same as that in the case of the vertical impingement⁽³⁾. However, the phenomenon appears mainly in the downstream in the case of the oblique impingement, according to reasons mentioned above.



- ① Spray radius at major axis in upstream R_{X1}
- ② Spray radius at major axis in downstream R_{X2}
- ③ Spray height in upstream h_{X1}
- ④ Spray height in downstream h_{X2}
- ⑤ Unimpinged part
- ⑥ Impinged part
- ⑦ Main jet region
- ⑧ Mixing flow region
- ⑨ Wall main jet region
- ⑩ Wall jet vertex
- ⑪ Stagnate region
- ⑫ Leading edge

Fig.4 Model of structure of impinging spray



(a) Impingement on vertical wall (b) Impingement on inclined wall

Fig.5 Model of external shape of impinging spray

4. SHAPE OF IMPINGING SPRAY

Fig.5 is the model of the external shape of the impinging spray generalized by using photographs and the distribution of the droplets density shown in Fig.2,(a) is the case of the vertical impingement, that is, $\alpha_w = 0$ deg., and (b) is that of the oblique impingement. The meaning of symbols are as follows:

vertical impingement

h_w : maximum spray height

R_w : spray radius

oblique impingement

h_x : maximum spray height

R_x : spray spread along the major axis of the ellipse

R_y : spray spread along the minor axis of the ellipse

suffix 1,2 : upstream and downstream.

The spray spreads to R_{X1} , R_{X2} and R_y are shown in Fig.6 as functions of the time t from the start of injection and the inclination angle α_w of the wall. Besides the spray radius R_w in the case of the vertical impingement is shown in the both figures, Fig.7 is the effect of α_w on the maximum spray height h_{X1} and h_{X2} in the upstream and the downstream in the case of the oblique impingement and that h_w in that of the vertical impingement. In all the cases, the ambient density ρ_a is 18.5 kg/m^3 .

Every quantities displayed in Fig.6 and Fig.7 increases, as t elapses and their increasing ratio is decreasing after the end of the injection. This tendency appears regardless of α_w . As shown in Fig.2, the development of the spray in the downstream is more remarkable than that in the upstream, when the wall is inclined. R_{X2} and h_{X2} are always larger than R_{X1} and h_{X1} at the same time, and the increasing ratio in the former quantities are bigger than those in latter ones. As α_w is increasing, R_{X2} and h_{X2} are larger than R_w and h_w and the increasing ratio in R_{X2} and h_{X2} are bigger than those in R_w and h_w . On the other hand, the tendencies of R_{X1} and h_{X1} are completely contrary to those R_{X2} and h_{X2} . R_y lies between R_{X1} and R_{X2} , and it is smaller than R_w at the same time. As α_w is increasing, the increasing ratio in R_y is decreasing. Namely, the shape of ellipses becomes slender. Thus, it is notable that the effect of the inclination of the wall on the external shape of the impinging spray is very much evident. The tendency mentioned above exists regardless of the ambient density ρ_a . However, every quantities become smaller and the increasing ratio also become lower, as ρ_a gets larger. This tendency is the same as that of the tip penetration of the free spray.

In the case of the injection through the injection nozzle used in a medium-speed diesel engine which has the higher injection pressure and the larger injection quantity than those in a small high-speed diesel engine⁽¹⁾, the tendency of the external shape of the impinging spray shows the same as that of mentioned above.

6. CONCLUSION

The following conclusions are drawn from these experiments:

(1) The shape on the wall of the impinging spray is the circle in the case of the vertical impingement, and it is the ellipse in that of the oblique impingement. When the inclination angle of the wall increases, the ellipse becomes

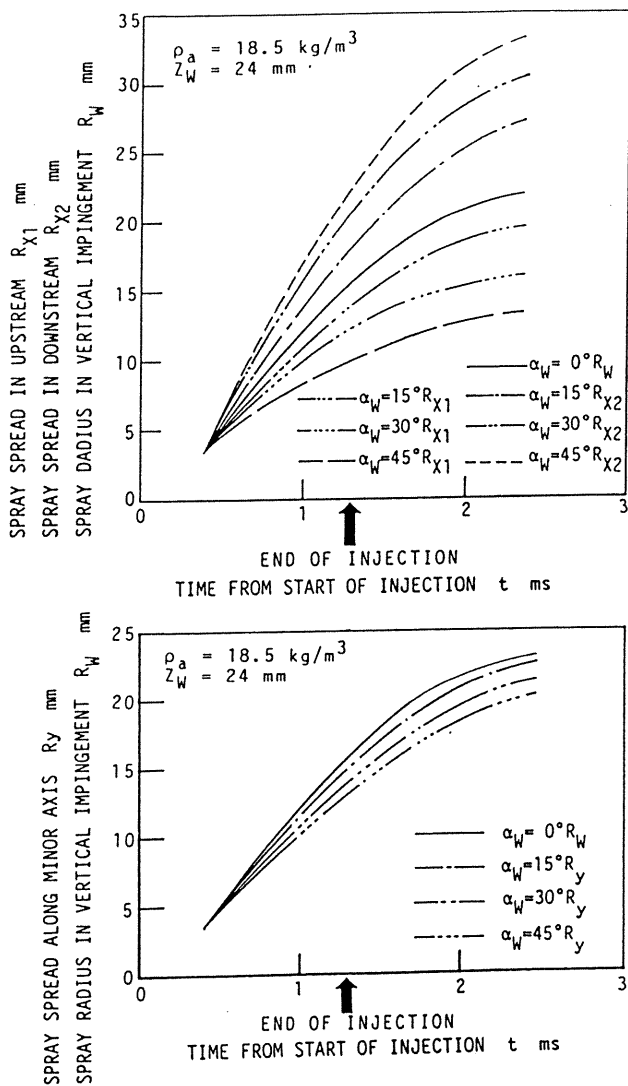


Fig.6 Influence of inclination angle of wall on spray radius in vertical impingement and spray spread in oblique impingement

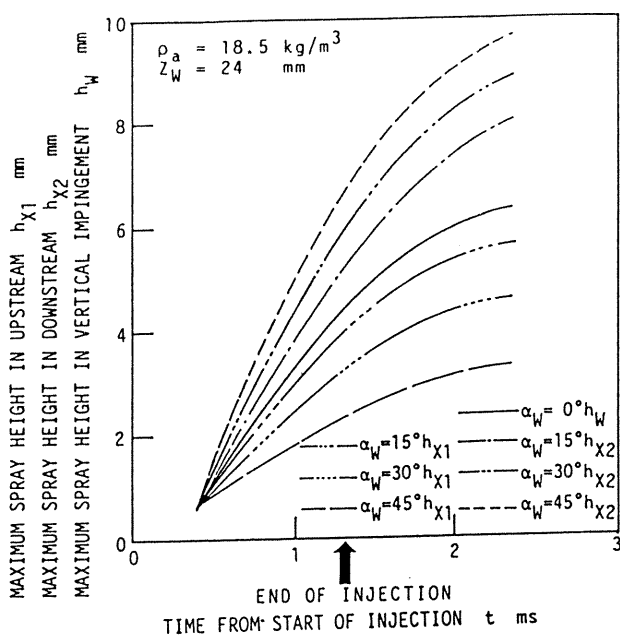


Fig.7 Influence of inclination angle of wall on maximum spray height

slender.

(2) As the inclination angle of the wall becomes larger, the greater the droplets flow in the downstream.

(3) The region of the high droplets density appears at the peripheral region. In this region, the wall jet vortex is occurred, droplets is rolled up by this vortex, then the volume of spray increases and the mixing is facilitated. This phenomenon is more remarkable in the downstream than in the upstream in the case of the oblique impingement.

(4) The droplets density shows the high value near the wall and the impinging point, regardless of the inclination angle of the wall and the ambient density.

(5) The increase in the volume of the impinging spray is caused by the increase in that of the lower droplets density, that is, the higher air/fuel ratio. On the other hand, the volume of the higher droplets density, that is, the lower air/fuel ratio, is nearly constant during the duration of injection, unrelated to the inclination angle of the wall and the ambient density.

(6) The spray spread and the maximum spray height in the downstream and their increasing ratios become larger, when the inclination angle of the wall increases and the ambient density decreases. These quantities in the upstream show the reverse tendency. The spray spread along the minor axis of the ellipse lies between those along the major axis in the downstream and in the upstream.

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