Characteristics of Impingement Diesel Spray Adhesion on a Flat Wall

A THESIS
Submitted by

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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CO_2	Carbon dioxide
DI	Direct injection
EGR	Exhaust gas circulation
HC	Hydrocarbon
H_2O	Water
HSDI	High spreed direct injection
NA	Natural aspirated
NO_X	Oxides of nitrogen
PDA	Phase doppler anemometer
PDPA	Phase doppler particle analyzer
PIV	Particle image velocimetry
PM	Particulate matter
PCCI	Premixed charge compression ignition
HCCI	Homogeneous charge compression ignition
PDS	Planar droplet sizing
SMD	Sauter mean diameter

Nomenclature

A_d	Impingement disk area	[mm^2]
$A_{d.critical}$	Critical area of disk	[mm^2]
A_{adh}	Adhered area	[mm^2]
$D_{d.critical}$	Critical diameter of disk	[mm]
D_d	Impingement disk diameter	[mm]
D_n	Nozzle hole diameter	[mm]
D_{SMD}	Sauter mean diameter	[μm]
h_{adh}	Average adhered thickness	[mm]
H	Height of post-impingement spray	[mm]
f_{press}	Correction factor for ambient pressure	[-]
k	Modification area factor	[-]
L_w	Impingement distance	[mm]
m_{inj}	Mass of a single shot injection fuel	[mg/injection]
m_{adh}	adhered mass	[mg]
$m_{adh.critical}$	Critical adhered mass	[mg]
N	Number of injections	[-]
P_a	Ambient pressure	[MPa]
P_{inj}	Injection pressure	[MPa]
V_{inj}	Injection velocity	[m/s]
V_{imp}	Impingement velocity	[m/s]
$V_{imp.n}$	Normal impingement velocity	[m/s]
$V_{imp.r}$	Radial impingement velocity	[m/s]
T_a	Ambient temperature	[°K]
$t_{critical}$	Critical thickness of liquid film	[mm]
t_{adh}	Thickness of adhered film	[mm]
t_{asoi}	Time after start of injection	[msec]
t_{ais}	Time after impingement start	[msec]
t_{is}	Time of impingement	[msec]
We	Weber number	[-]
We_{inj}	Weber number of droplet	[-]
We_d	Weber number of droplet at impingement	[-]
$We_{d.n}$	Weber number of droplet at normal impingement	[-]
$W_{s.imp}$	Spray width just before impingement	[mm]
Re	Reynold number	[-]

α_{adh}	Adhered mass ratio	[-]
β_{adh}	Adhered mass ratio with ambient pressure effect	[-]
θ_{d}	Inclination angle	[deg.]
ρ_{fuel}	Density of fuel	[kgm^{-3}]
ρ_a	Ambient density	[kgm^{-3}]
σ	Surface tension	[kg/s^2]
μ_{l}	Fuel viscosity	[g/mm-s]
μ_{a}	Ambient viscosity	[g/mm-s]
τ_{inj}	Injection period	[msec]

Abstract

Many researchers since last decade were looking forward on improving diesel engine performance with keeping low harmful emission. Wall impingement of fuel spray is known as the main contributor to direct injection high-speed diesel combustion, so it becomes an important factor in reducing diesel exhaust emissions. Since the combustion chamber in a diesel engine is too small to mix injected fuel and surrounding gas perfectly, wall impingement of the spray is considered to be inevitable in the engine. Non-evaporated spray research for basic understanding of spray behavior is conducted. The aim of this study is to clarify the fundamental characteristics of non-evaporated impinging spray and adhesion behavior of fuel by measuring the adhering fuel mass on a wall. In this study, a fuel injection system, a high pressure vessel and an image processing unit for impingement spray were used. Experimental investigations were carried out with various injection pressures from 40 MPa to 170 MPa and ambient pressures from 0.1 MPa to 4.0 MPa. The impingement distances were set from 30 mm to 90 mm and various sizes of impingement disk were used. The results show, the adhered fuel mass affected by impingement distances. The adhered mass ratio was inversely proportional to injection pressure. Regardless of injection pressure and impingement distances, it was found that the adhered fuel mass became constant with increasing the diameter of the impingement disk. Thickness of liquid film tended to decrease with increasing of injection pressure. Moreover, the adhered fuel mass ratio decreased with an increase of the inclination angle of disk. General modified adhered mass ratio was introduced to summarize the adhered mass with combinations of various impingement distances, disk sizes, inclination angles and injection pressures. Weber number which was calculated by approaching velocity of droplet to the impingement wall was more dominant factor than the Weber number obtained by droplet absolute velocity. However, the impingement of lower Weber number droplet produced thick film and adhered fuel mass was little influenced by the Weber number. From the results of experimental works, the empirical equations concerning the adhered mass ratio were derived. At higher ambient pressure and higher the injection pressure, adhered mass fuel tended to decrease. As for long impingement distances such as 70 mm and 90 mm, adhered fuel mass in high ambient pressure condition such as 4 MPa was half of that under 1 MPa condition. Finally, it was found that the adhered mass ratio could be correlated by using Weber number and Jet number.

Chapter 1

Impinging diesel spray and its research problems

1.1 Introduction

Over the last decade, study and research on diesel spray have progressed significantly. Many research works have been performed by automotive engineers to improve the performance of diesel engines and to reduce the exhaust emissions as well as fuel consumption.

In a high-speed DI diesel engine, behavior, structure and characteristics of diesel spray have been investigated by many researchers **[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]**. From the viewpoint of spray combustion in the piston cavity, spray impingement on a cavity wall and fuel film adhering to its wall surface have a strong influence on combustion processes, engine performance and also characteristics of diesel exhaust harmful emissions. However, there are a few studies on impinging diesel spray with regard of adhering fuel on the cavity wall. Then it is necessary to understand the effect of fuel adhering when the spray impinges on the cavity wall.

In this chapter, various aspects of impinging diesel spray available in current literatures are reviewed in order to have a better understanding of the impinging diesel spray on the wall. Also, the adhering fuel, which is formed when the spray impinges to a wall, is discussed as an important factor in wall impingement spray. Furthermore, an understanding of the impinging diesel spray mechanisms is crucial for finding the best way on improving engine performance as well as reducing emissions which occurred in the combustion process. The information and knowledge obtained from literatures could give a clear view of the impinging diesel spray in this study.

1.2 General views of diesel spray

1.2.1 Diesel sprays in the combustion process

Figure 1-1 shows the block diagram of the diesel combustion process **[15]**. In the figure, it shows that the primary factor which control the combustion process is coming from the mixing process between injection system, air swirl and turbulences in the cylinder, and spray characteristics. The spray characteristics control the vaporizing characteristics and the ignition delay characteristics and finally give a great influence on the combustion process and also the exhaust emissions.

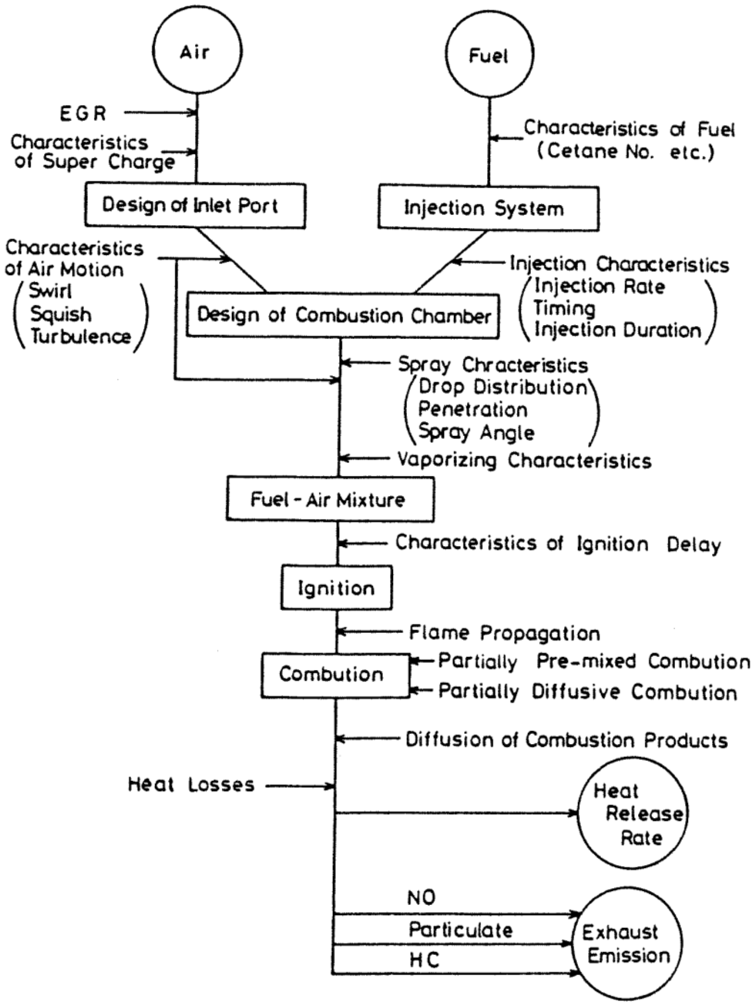

Figure 1-1 Block diagram of diesel combustion **[15]**

Figure 1-2 shows the diesel spray combustion and its behavior in DI diesel engine **[16]**. First process of diesel spray formation was atomization and followed by mixing process between fuel and air. The short break-up length, high swirl, high squish and wide spray which produced from small hole nozzle and high injection pressure, could promote better distribution of spray as well as the rapid atomization of spay. The rapid atomization of spray is needed in order to have good engine performance and also less exhaust emissions from the combustion chamber.

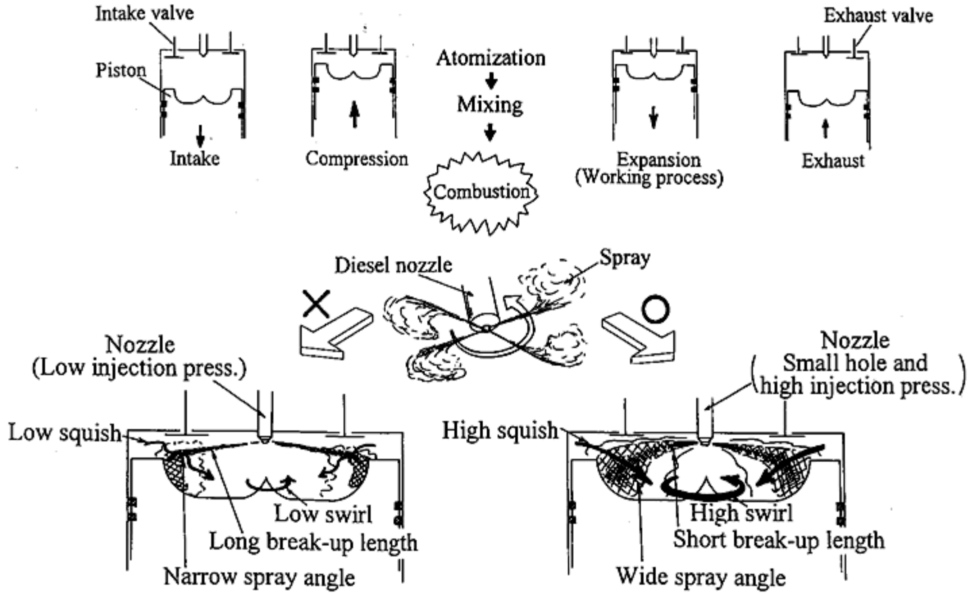

Figure 1-2 Diesel spray combustion in DI diesel engine **[16]**

For better understanding of the spray characteristics, **Fig. 1-3** shows the characteristic parameters of a diesel spray and also well known as macroscopic parameter **[17]**. Those parameters shown in **Fig. 1-3** are the important parameters in free spray and they are related to each others. The movement of the spray tip and break-up length gives clues to understand the disintegrating process of a fuel jet. Spray angle and droplet size are the result of the disintegrating process. A wide of spray angle usually meant the spray having a short breakup length and short core of spray, while narrow spray angle resulted to long breakup length. The adhesion of fuel on the wall normally occurred from the long breakup length condition. As shown in **Fig. 1-2**, a spray with long breakup length resulted in high HC and PM emissions. Diesel spray was a spray which droplet size distribution was in a range around few micrometers to 40 micrometers. The mean droplet size of spray or so called Sauter mean diameter (SMD), represent as the volume-surface mean diameter of spray. The SMD was one of the representative mean diameter and very popular in diesel spray study. It was very important in estimating the size of droplet for better understanding of the evaporation process. Turbulence also counted as one of the important parameters where it was usually activated mixing and evaporation in periphery region of the spray. Further, the intensities of the turbulence was more important in order to promote combustion process inside the spray.

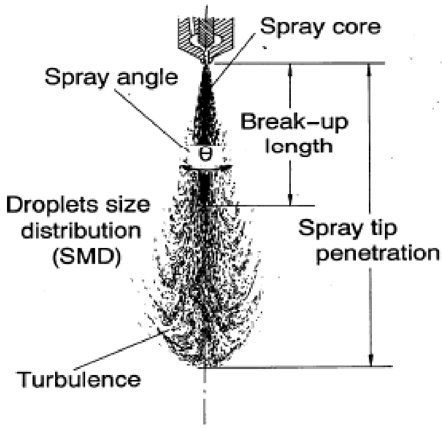

Figure 1-3 Characteristics parameter of diesel spray **[17]**

Structure and shape of impinging spray had been described by Katsura et al. **[18]** as shown in **Fig. 1-4**. They described the impinging spray was separated by two parts namely as unimpinged part and impinged part. An unimpinged part was similar as a free spray structure as shown in **Fig. 1-3** but impinged part was somehow different. The impinged part was divided by several regions. In the wall main jet region, the spray velocity decreased after impingement and also high droplet density appeared along the impingement wall. Stagnate region that occurred at the edge of impinged part due to droplets in the periphery regions, were pushed upward and resulted to loss of momentum. Also, the wall jet vortex phenomena appeared at a peripheral region of the impinging diesel spray. In this region, the density of droplets was large and turbulent mixing occurred between spray and surrounding gas. In this region also, the spray height could be measured for further impingement spray analysis **[18, 19, 20, 21, 22]**.

As described above, both of free spray and impingement spray are heterogeneous in their structures and shapes. In a practical diesel engine, since very short time is allowed for mixing and combustion process between injected fuel and air, the lack of homogeneity in the carburetted mixtures, and the heterogeneity and rapid variations in the temperature do not allow for the ideal combustion process. It would be worse when the adhering fuel deposited on the piston or cavity wall. Adhered fuel caused to the incomplete combustion of hydrocarbons results in the formation of a wide range of harmful gaseous components. Thus, more homogenous spray structure is required for complete combustion in the engine and also for developing advanced combustion system.

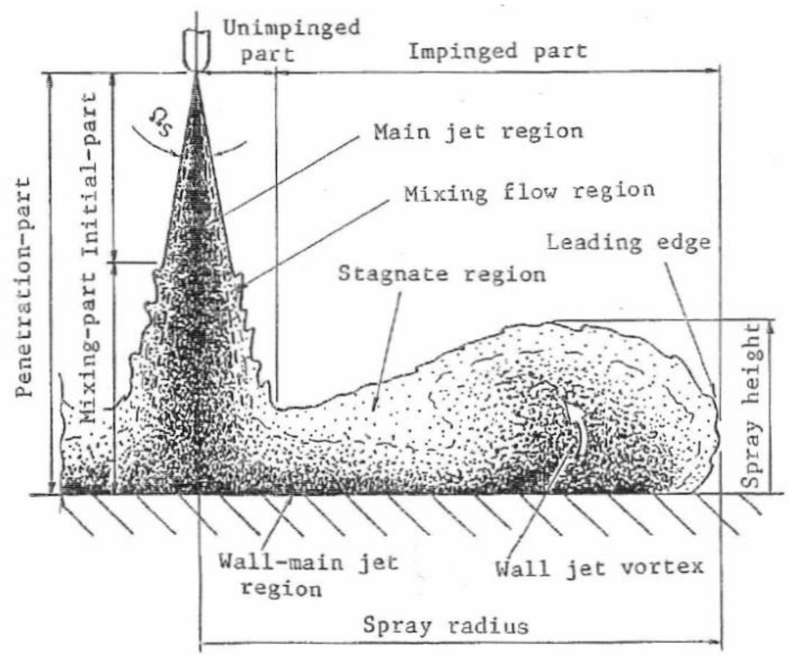

Figure 1-4 Structure and shape of impinging diesel spray **[18]**

1.2.2 Wall impingement and its spray-wall interaction

(a) Wall impingement

Recently the combustion chamber in a diesel engine tends to be small in order to reduce fuel consumption, and injection pressure tends to increase as compared with a conventional diesel engine. Wall impingement of the spray might occur due to downsizing of the engine and high pressure of fuel injection, and unevaporated diesel fuel was adhered on the wall of cavity. The impingement spray causes the emission of hydrocarbon (HC) and soot from the diesel engine. Therefore it is important to understand the spray-wall interaction and adhesion characteristics of impingement diesel spray.

Ko and Arai **[23]** had investigated the characteristics for pre- and post-impingement diesel spray by analyzing the spray penetration and also the spray volume. As shown on **Fig. 1-5**, the horizontal solid lines in the figure indicate the wall distance from the nozzle tip. Obviously we can observe that the penetration rates had the same growth pattern for all wall distance cases except for the free spray cases. At the impingement distances L_w = 10 mm, the slope after impingement was steeper than the others impingement distances. It shows, that the shorter impingement distance, the higher momentum of droplets and resulted to the high energy transfer during rebound. Kim et al. **[24]** investigated the penetration length of sprays under non-evaporating condition and injection pressure from 40 MPa to 100 MPa. They found that almost similar trend of spray path penetration as **Fig. 1-5**.

Volume of wall impingement sprays is shown in **Fig. 1-6 [23]**. The spray volumes of L_w = 30, 50 and 70 mm show almost the same values even though there were small differences between these values. Results also show that the spray volume for all impingement cases are higher than free spray case. They concluded that, the volume of spray could be increased more than free spray case if the spray broke up before impinging on the wall. It was also reported by Tsunemoto et al. **[25]** that the spray volume and area which contacting with air were increased by spray impingement. However, in case of projected area, spray did not changed in volume and area that contacting with air. Tanabe et al. **[26]** studied the behavior of impinging spray onto projection of the flat wall. They reported that penetration length and the spray height was increased by increased of nozzle opening pressure.

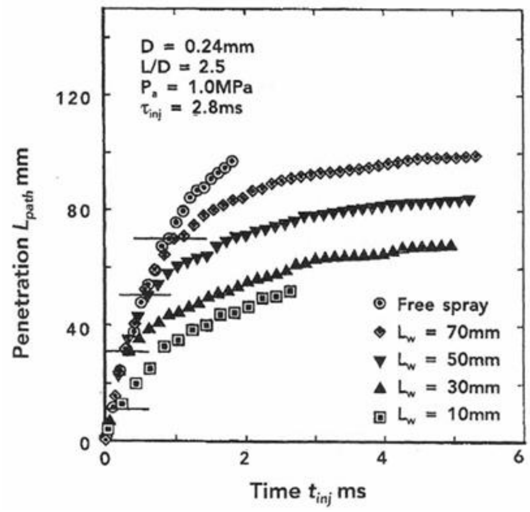

Figure 1-5 Penetration of wall impingement sprays **[23]**

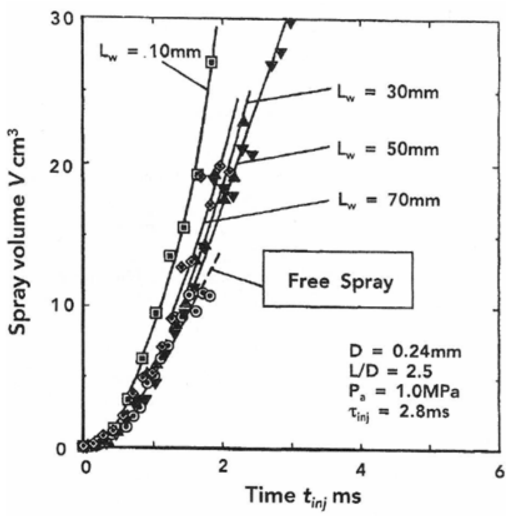

Figure 1-6 Volume of wall impingement sprays **[23]**

(b) Impingement spray behavior

Montajir et al. **[27]** measured the development of spray near the cavity wall in a combustion chamber geometry. Effects of the spray development in the chamber were investigated based on wall distance from the nozzle tip, shape of the cavity entrance, position where spray impinges on the wall, and so on. They found that the combustion chamber with round lip and optimum wall distance gives better fuel distribution.

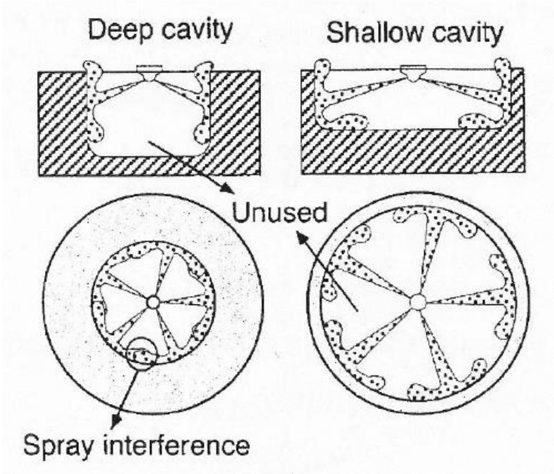

Figure 1-7 Effect of cavity size on spray development **[27]**

As shown in **Fig. 1-7**, they also suggested that, shorter wall distance (deep cavity) could cause to interference between the injected sprays, while too long wall distance (shallow cavity) could create un-used space between two neighboring sprays. Thus, the optimum of wall distance is important in order to get a minimum adherence of spray on cavity wall.

Katsura et al. **[18]** pointed out that by shortening the impingement distance, the droplet density becomes higher and changed accordingly along the wall. Zurlo et al. **[28]** was measured the droplet size distribution of post impingement spray by using polarization ratio measurement technique. They reported that droplet size was smaller when closed to the wall compared to the droplet far from the wall. Another researcher **[29]** investigated the effect of wall distance on the SMD of the post impingement spray. They found that as the impingement distance decreasing, the SMD of the post impingement spray became smaller. By using Exciplex Fluorescence Method, Senda et al. **[30, 31]** proposed 2-D images concerning the concentration distribution of vapor and liquid phases which acquired simultaneously. The observed vapor phase growth upward clearly from the wall to the periphery region while the liquid phase expanded mainly along the wall in the radial direction. Then, it was found that small droplets near the tip of the liquid phase evaporated rapidly due to the hot ambient surroundings, and then the evaporated fuel mixed and diffused with the surroundings.

Arai et al. **[32]** conducted a multi-stage spray with three split sprays at one injection. They suggested the total volume and mean equivalence ratio were affected by the injection interval between split sprays. Almost similar investigation from Arai et al. **[33]** and Nishida et al. **[34]** on the diesel spray with split investigation. They reported that, mass measured from the second stage of injection was large compared to the mass that was measured in interval between the first and second stages of injection.

Since the diesel spray was not necessarily to impinge vertically to the wall of the engine cylinder, effect of the inclination angle of impingement became important for the impingement of a diesel spray. Arai **[35]** reviewed many kinds of diesel spray impingement phenomena including combustion of impingement diesel spray to an inclined wall. As for inclined diesel spray impingement, Fujimoto et al. **[36]** investigated the effect of impingement distance, injection pressure and ambient pressure on characteristics of inclined impinging diesel spray. They found that higher downward flow of spray became appearing when increasing the inclination angle wall.

Ebara et al. **[37, 38]** estimated the spray penetration under the effect of inclined wall impingement. According to them, as the inclination angle increased the spray path penetration became shorter compared to the free spray. They concluded that, mixing process between spray and surrounding was promoted in the cases for larger inclination angles (like normal impingement). However, they were not discussed the effect of inclined wall on the flow of impinged spray along the wall.

Further they enhanced their research on the inclined impingement spray by used of image analysis visualized by YAG laser sheet **[39, 40]**. Skeleton images had been introduced by them in order to discuss the effect of wall distance and inclination angles on high density of the spray zone. **Figure 1-8** are the example of the effect of wall angle on a skeleton spray. Effect of wall distance on the skeleton images was clarified in **Fig. 1-9**. It was observed that liquid column impinged on the wall and high density of spray layer occurred for short impingement distances such as L_w = 10 and 20 mm. They suggested that the high density zone occurred due to roll-up motion of the spray layer on the wall surface. Besides, at L_w = 30 and 50 mm, the high density zone distributed along the some height from the wall. They considered that spray completed the breakup process during impinging on the wall.

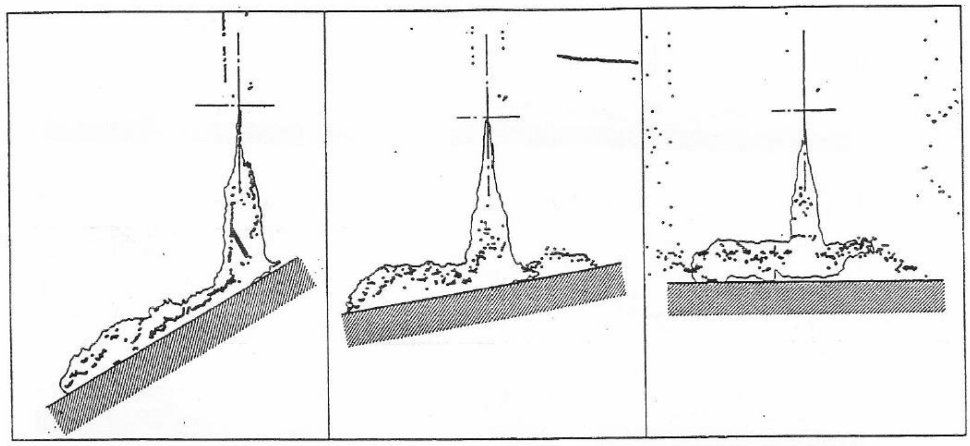

Figure 1-8 Effect of wall angle on a skeleton spray **[40]**

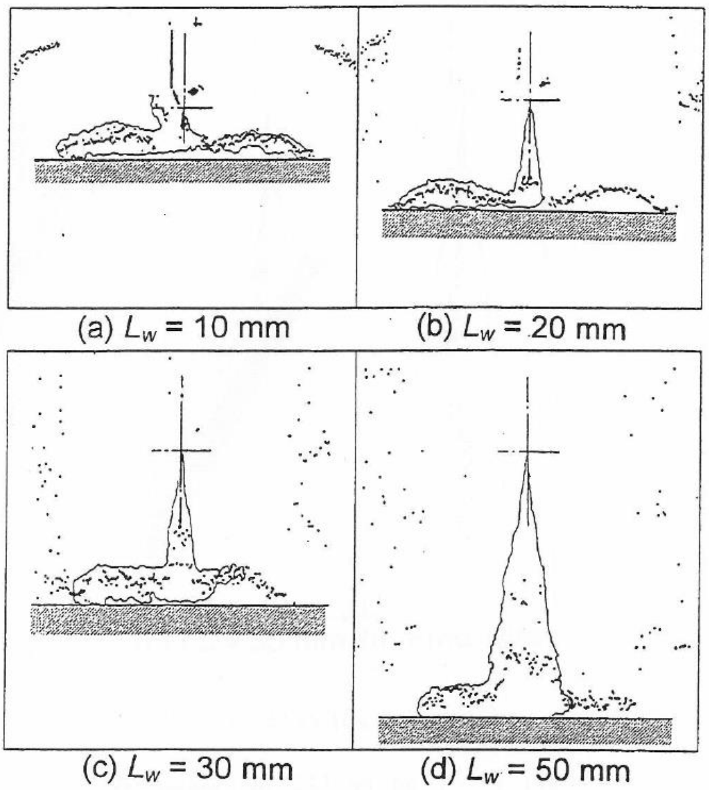

Figure 1-9 Effect of wall distance on a skeleton spray **[40]**

Ishikawa et al. **[41]** pointed out that the impingement location of a diesel spray had a strong influence on engine emissions, because impingement fuel mass and spray behavior after impingement were strongly related to the impingement location. Sakane et al. **[42]** investigated the behavior of non-vaporizing diesel spray impinging on a flat wall by shadowgraphic image analysis. They reported