

An Experimental Study and Computer Analysis on Oblique Impingement of Diesel Type Spray upon a Plane Wall

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ABSTRACT

The phenomena of oblique impingement of diesel type spray upon a plane wall is investigated by stroboscopic photography technique in a model chamber and modeled by computer analysis method with particular emphasis on the development of wall spray. The experimental study deals with the wall spray tip penetration, tip velocity, and geometric structure at incidence angles of 70, 60, and 40 degree. It is found that there exists a geometric similarity of wall spray at different incidence angles. Based upon the experimental study, a mathematical model of wall spray is developed to describe tip penetration and geometric structure.

INTRODUCTION

Phenomenological or quasi-dimensional combustion models (1)-(4) for diesel engines are aggregation of individual process sub-models. The major sub-models are spray mixing, thermodynamics, heat transfer, and emission formation. With the combustion in diesel engines governed strongly by mixing rate between air and fuel in spray, the spray mixing sub-model which describes the geometric structure of spray and mixing of air and fuel is the essential one of them. Models provide a geometric structure for the fuel spray in attempts to improve the ability of modeling combustion process in swirl interaction, impingement, and divided chamber.

The behaviour of liquid spray impingement vertical to the wall was investigated using holographic interferometry (5) and hydraulic analogue technique (6). Few studies of liquid spray impinging upon the wall with oblique angle were reported and most of those (7), (8) were lack of information on wall spray geometric structure, tip penetration and velocity, which are the basis of setting up a phenomenological combustion model.

The present study is considered in two parts. The first deals with the experimental observation on the phenomena of oblique impingement of diesel spray upon a plane wall by stroboscopic photography technique, with particular emphasis on the development of wall spray. The second part of the study deals with setting up a mathematical

sub-model of wall spray to describe it's tip penetration and geometric structure. This is the first step for a suitable phenomenological combustion model.

EXPERIMENT ARRANGEMENT AND RESULTS

The experiment rig, as shown in Figure 1, consisted of a model chamber with two optical windows which the area is 40mm*80mm and one of them is used as the flat impingement surface at a distance of H=35mm from the nozzle to get the transient wall spray picture following spray impingement, a stroboscopic photography system, and a fuel inject system controlled by the stroboscopic photography system to enable single injection of fuel to be achieved at different time scale.

Table 1 shows the main experiment conditions.

Figure 2 gives the layout of spray, impingement wall which is made of optical glass, light, and camera. Where R_s is defined as the wall spray tip penetration and V_s is it's velocity which is obtained by:

$$V_s(t, \sigma_j, \varphi) = (R_s(t, \sigma_j, \varphi) - R_s(t - \Delta t, \sigma_j, \varphi)) / \Delta t \quad (1)$$

$R_s(t, \sigma_j, \varphi)$ and $V_s(t, \sigma_j, \varphi)$ are variation with time (t), incidence angle σ_j , and angle φ .

The transient wall spray behaviours from the beginning of injection to the end were taken at three different incidence angles of $\sigma_j=70, 60, \text{ and } 40$ degree, as shown in Figure 3(a), (b), (c) respectively. From these pictures, following behaviours were found:

- 1) The geometric structure of wall spray developed in the shape of "leaf".
- 2) At the same incidence angle σ_j , wall spray tip penetration R_s and it's velocity V_s present the maximum at the location of $\varphi=0$ degree, then decay as the increasing of angle φ and are up to the minimum at the location of $\varphi=180$ degree.
- 3) The $R_{s\max}$ and $V_{s\max}$ were reducing but the $R_{s\min}$ and $V_{s\min}$ were increasing as the increasing of incidence angle.

From the pictures taken by the experiment, the variations of R_s and V_s with angle φ and incidence angle σ_j are shown in Figure 4 and Figure 5 respectively. The vertical axis of Figure 4 is a ratio of R_s at angle φ to the maximum $R_{s\max}$ at angle $\varphi=0$. The vertical axis of Figure 5 is a ratio of V_s at angle φ to the maximum $V_{s\max}$ at angle $\varphi=0$. The data at different time points were fitted to be considered as the time mean value. $R_s/R_{s\max}$ and $V_s/V_{s\max}$ are dimensionless functions.

By the comparison between the data shown in Figure 5 and C. D. Donaldson's experiment data of free gas jet impingement (9), it is found that there exists a similarity of both behaviours of liquid spray and gas jet in the variation of $V_s/V_{s\max}$ with incidence angle σ_j and angle φ .

A MATHEMATIC MODEL OF WALL SPRAY GEOMETRIC STRUCTURE WITH OBLIQUE IMPINGEMENT

The flow of spray impinging is characterized by two distinct regions. The free spray region, where the spray decays as if the wall was not be reached, and the impingement region of the spray, where the flow decelerates to the wall stagnation point and a radial wall spray has developed. This paper pays most of attention to the impinging region and sets up a mathematical model to describe its geometric structure and the variation of wall spray tip penetration with and .

The model is developed based on the experiment data shown in Figure 4 and Figure 5 and assumptions as following:

1) The momentum flux per unit radian of the wall spray was relatively invariant for different radii.

2) The nonradial components of velocity on the wall region is to be negligible.

3) The medium in the spray is the perfect fluid.

4) The wall spray thickness Z_0 is varied with R_s linearly:

$$Z_0 = C_z \cdot R_s \quad (2)$$

The simplifying equation of wall spray tip penetration velocity V_s is taken to be hyperbolic with the characteristic functional form:

$$V_s = f(\sigma_j, \varphi) \cdot V_0(t) \cdot dj / R_s \quad (3)$$

and R_s is considered as:

$$R_s = C_w \cdot [f(\sigma_j, \varphi) \cdot dj \cdot \int_{tw}^t V_0(t) \cdot dt]^{1/2} \quad (4)$$

where: $C_w=0.75$ is the modifying constant, $dj=d_0 \cdot (\rho_f/\rho_a)^{1/2}$ is the modifying diameter, and $f(\sigma_j, \varphi)$ is an impingement characteristic function. $f(\sigma_j, \varphi)$ is variation with σ_j and φ and governs the effecation of σ_j and φ on R_s .

The characteristic function $f(\sigma_j, \varphi)$ can be determined by imposing the requirement that

the R momentum of the radial wall spray is related to the total magnitude of the radial wall spray outflow momentum by the spray inclination and angle σ_j :

$$\int_0^{2\pi} \frac{\partial M(\sigma_j, \varphi)}{\partial \varphi} \cdot \cos \varphi \, d\varphi = \cos \sigma_j \cdot \int_0^{2\pi} \frac{\partial M(\sigma_j, \varphi)}{\partial \varphi} \, d\varphi \quad (5)$$

and the magnitude of radial momentum flux per unit radian of the wall spray can be expressed simply as:

$$\frac{\partial M(\sigma_j, \varphi)}{\partial \varphi} = C_{w2} \cdot \rho_m \cdot V_s^2 \quad (6)$$

where: ρ_m is the average density for given streamline defined by φ and only variation with φ and σ_j . C_{w2} is a constant.

Substitution of Eq. (3) into Eq. (6) and Eq. (5) leads to the following integral equation:

$$\int_0^{2\pi} f^2(\sigma_j, \varphi) \cdot \rho_m \cdot \cos \varphi \, d\varphi = \cos \sigma_j \int_0^{2\pi} f^2(\sigma_j, \varphi) \cdot \rho_m \, d\varphi \quad (7)$$

The assumptions of that at the same inject conditions ($V_0(t)$, dj , and H), the total mass in the wall region of oblique impingement spray ($\sigma_j < 90^\circ$) is equal to the total mass in the wall region of vertical impingement spray ($\sigma_j = 90^\circ$) and that $\rho_m(\sigma_j, \varphi=0)$ is equal to $\rho_m(\sigma_j=90^\circ, \varphi)$ lead to the mass equation:

$$\int_0^{2\pi} f^{3/2}(\sigma_j, \varphi) \cdot \rho_m(\sigma_j, \varphi) \cdot d\varphi = 2\pi \cdot f^{3/2}(\sigma_j, \varphi=0) \quad (8)$$

A average density characteristic function $g(\sigma_j, \varphi)$ is defined as:

$$g(\sigma_j, \varphi) = \rho_m(\sigma_j, \varphi) / \rho_m(\sigma_j, \varphi=0) \quad (9)$$

Substitution Eq. (9) to Eq. (7) and Eq. (8) gives the governing equations for $f(\sigma_j, \varphi)$ and $g(\sigma_j, \varphi)$:

$$\int_0^{2\pi} f^2(\sigma_j, \varphi) \cdot g(\sigma_j, \varphi) \cdot \cos \varphi \, d\varphi = \cos \sigma_j \cdot \int_0^{2\pi} f^2(\sigma_j, \varphi) \cdot g(\sigma_j, \varphi) \, d\varphi \quad (10)$$

and

$$\int_0^{2\pi} f^{3/2}(\sigma_j, \varphi) \cdot g(\sigma_j, \varphi) \cdot d\varphi = 2\pi \cdot f^{3/2}(\sigma_j, \varphi=0) \quad (11)$$

Both expressions of $f(\sigma_j, \varphi)$ and $g(\sigma_j, \varphi)$ are found as following:

$$f(\sigma_j, \varphi) = \text{EXP}(-K(\sigma_j) \cdot (\varphi^{1.5} + 0.266) / 2) \quad (12)$$

$$g(\sigma_j, \varphi) = 1 - L(\sigma_j) \cdot \cos(\varphi/2 + 1.575) \quad (13)$$

the incidence parameters of $K(\sigma_j)$ and $L(\sigma_j)$ can be solved through Eq. (10) to Eq. (13) by numerical method and be fitted as the forms:

$$K(\sigma_j) = 1. / (0.29209E-2 \cdot \sigma_j^{0.77} + 0.1443299) - 4.111943 \quad (14)$$

$$L(\sigma_j) = 1. / (0.34487E-2 \cdot \sigma_j^{0.77} + 0.15568104E - 1) - 7.941267 \quad (15)$$

Figure 6 and Figure 7 show the comparison between results calculated by Eq. (3) and Eq. (4) and the experiment data. It can be seen that equations of wall spray tip penetration and

it's velocity are able to describe basically the effect of σ_j and φ on R_s and V_s . Even though there are some errors in magnitude with the possibility of errors due to the simplification and the expression forms of $f(\sigma_j, \varphi)$ and $g(\sigma_j, \varphi)$ the model are satisfied for the requirement of spray mixing sub-model in a phenomenological combustion model of oblique impingement spray combustion process in D.I. diesel engines.

CONCLUSIONS

The stroboscopic photography technique enables complex oblique impingement spray saturation to be studied in considerable detail for wall spray tip penetration and its geometric structure. The photographic records clearly indicate the wall spray process.

A mathematical model which expresses the wall spray geometric structure is set up to meet the requirement of a phenomenological combustion model for diesel engines.

NOMENCLATURE

$C_z = 0.4$, the constant of Z_o
 d_o = nozzle diameter, m
 H = the distance from nozzle to the impingement flat, m
 O = impingement stagnation point
 R_s = wall spray tip penetration, m
 t = time, sec
 t_w = the time at the impingement, sec
 V_o = spray velocity at nozzle, m/sec
 Z = co-ordinate perpendicular to impingement flat

Z_o = wall spray thickness, m
 ρ_f = density of fuel, Kg/m^3
 ρ_a = density of air, Kg/m^3
 φ = the angle included between $R_{s\text{max}}$ and R_s , deg

REFERENCE

1. Shahed, S.M., Chiu, W.S., and Lyn, W.T., "A Mathematical Model of Diesel Combustion," I.M.E. Conference on Combustion in Engines, Cranfield, July, 1975
2. Hiroyasu, H., and Katota, T., "Models for Combustion and Formation of Nitric Oxide and Soot in Direct Injection Diesel Engines," SAE Paper 760129, 1976
3. Dent, J.C., and Mehta, P.S., "Phenomenological Combustion Model for Quiescent Chamber Diesel Engine," SAE Paper 822135, 1982
4. Wang, R.S., and Chen, B.X., "A Multi-Zone Mathematical Model of D.I. Diesel Combustion --- the Calculations of Equilibrium Products, No, and Heat Transfer," Trans. of CSICE Vol, 3 PP333-346, 1985
5. Lakshminarayan, P.A., and Dent, J.C., "Interferometric Studies of Vapourising and Combusting sprays," SAE Paper 830244, 1983.
6. Idoum, A., et al, "An Experimental and Analytical Study of Jet Impingement and Wall Jets in High Swirl D.I. Diesel Engines Using the Hydraulic Analogy," SAE Paper 850263, 1985

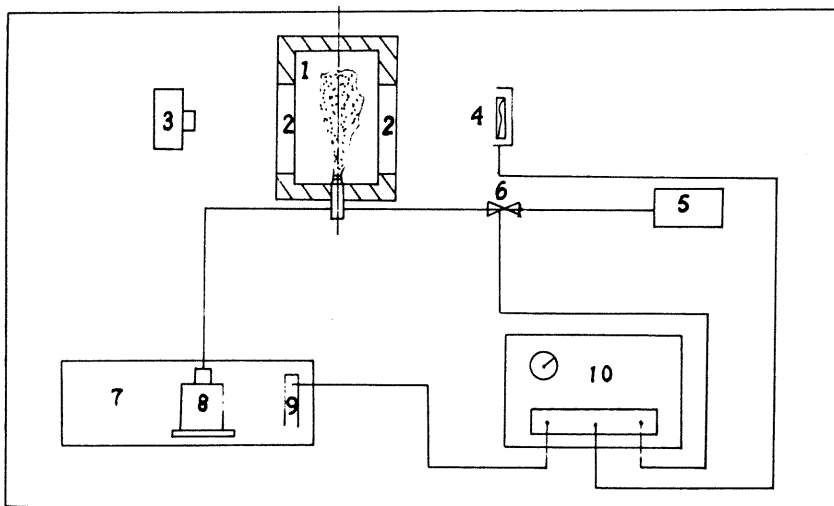


Fig. 1 Experiment Rig

1. Model chamber
2. Optical window
3. Camera
4. Light source
5. Low pressure box
6. Electric magnet valve
7. Fuel injection test-bed
8. Injection pump
9. Angle meter
10. Stroboscopic photography system

Table 1 Experiment Conditions

Nozzle opening Injection Pressure	Fuel	Injection Quantity	Injection Duration	Nozzle Diameter	Air Density
19.7 (MPa)	diesel fuel	0.126 (g)	2.2 (msec)	0.25 (mm)	16.2 (kg/m^3)

7. Kiichiro, T., Jiro, S., and Yoshiaki, S., "Atomization of Spray Droplet Impinging Upon a Hot Surface," Journal of Internal Combustion Engines., Vol.21 No268 PP9-18, 1982.
8. Fujimoto, H., Saito, M., Choh, J.Y., and Senda, J., "Characteristics of A Diesel Spray Impinging on A Flat Plate," XIXth International Symposium, Heat and Mass Transfer in Gasoline and Diesel Engines, ICHMT, Dubrovnik, Yugoslavia, 1987
9. Donaldson C.D., and Snedeker, R.S., " Hypervelocity Kill Mechanisms Program," NRL Memorandum Report 1687, Aeronautical Research Associates of Princeton, Princeton, N.J., ARAP Report No. 64, April 1965.

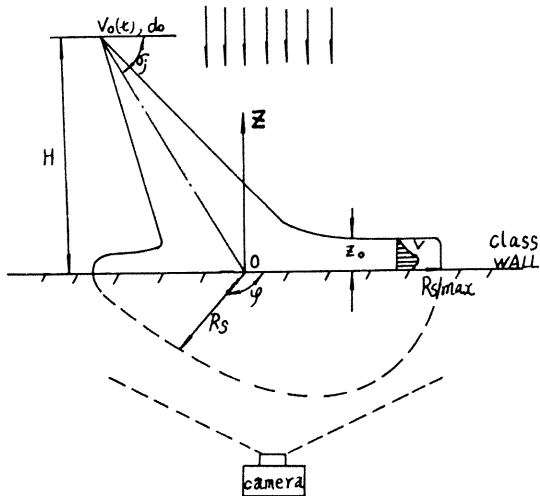


Fig. 2 The layout of spray, impingement wall, light, and camera

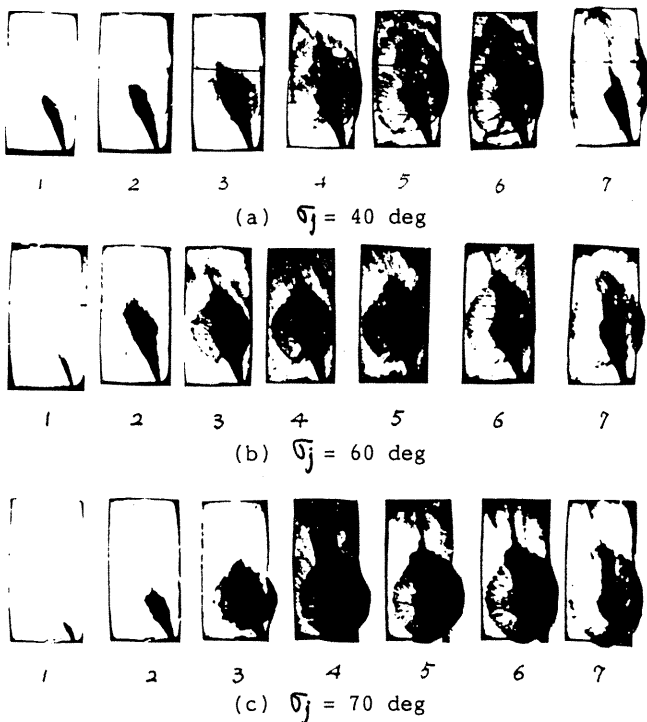


Fig. 3 The transient processes of wall spray, H = 35(mm), $\Delta t = 0.222(\text{msec})$

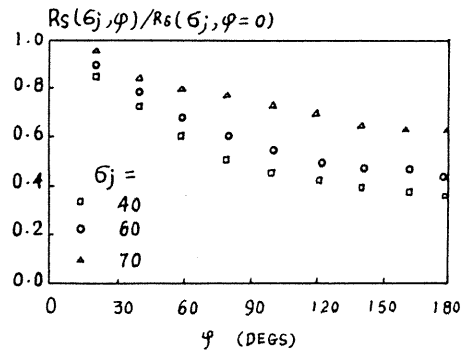


Fig. 4 The variation of wall spray tip penetration with angle ϕ and incidence angle ϵ_j .

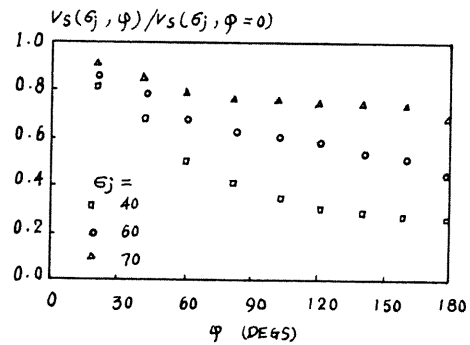


Fig. 5 The variation of wall spray tip penetration velocity with angle ϕ and incidence angle ϵ_j

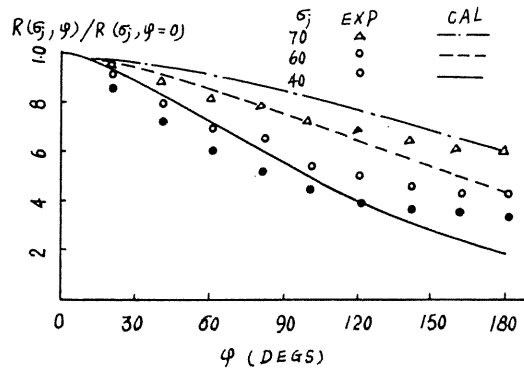


Fig. 6 The comparison between wall spray tip Penetration calculated by Eq.(4) and the experimental data

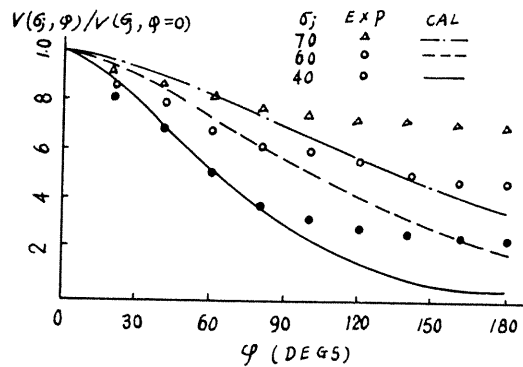


Fig. 7 The comparison between wall spray tip penetration velocity calculated by Eq.(3) and the experiment data