Structure and Formation of Diesel Fuel Spray

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Abstract

Research and development studies in internal combustion engines are set on a turning point due to requirements mostly purify the polluted environments. Naturally, basic studies concerned about engines are objected to elucidate formation mechanism of harmful matters, such as nitric oxide (NO_x) and particulate matters. And for diesel engines, phenomenon in combustion chambers are analyzed in several approach ways in order to obtain detail understandings in closed and hardly observing space. In this article, it is discussed that the formation mechanism of diesel fuel sprays, mostly non-evaporating free diesel sprays. From that it would be promoted some new innovations in internal combustion engines of next generation.

Introduction

Diesel fuel spray could be recognized as a droplets laden gas jet. It consist of small size droplets (10~100μm) with high ambient density gas (≈15~25kg/m^3) induced by high issue velocity liquid jet (≈ 200m/s~). Following are brief discussions about treatment in spray motions.

It used be treated as accumulating in distances of flying single droplet, such as Riehm, Triebnigg, Kuehn, or Wöljyen(1), which were acted on resistant force due to dynamic pressure ($\propto \rho_a u_{rel}^2/2$, ρ_a : ambient gas density, u_{rel} : relative velocity between drop and gas). Then, its coefficient C_D was argued and experimented due to particle *Reynolds* number $Re_p(=d_p u_{rel}/\nu_a$, d_p : particle diameter, ν_a : ambient gas kinematic viscosity). Then, it turns into accumulating in interference between droplets and ambient gas. That is, drag force acted on droplets from ambient gas in dynamic pressure order should be inducement force act on ambient gas. This is as same as mentioned by Sass(1), Tanasawa(2), also Schweitzer(3) and set into quasi-theory by Wakuri et. al(1960) and Dent(1971). They give this concept as empirical formula of spray tip penetrations(4)(5).

Recently, development in computational technology could make it possible to simulate with calculations. This trial was deduced previously by Kamimoto and Matsuoka (1975). They assumed that dynamic pressure to droplets should be different inside and front edge of spray(6). This is what KIVA(1985) and KIVA II(1987) intended to model for fuel spray as Discrete

Droplets Method (DDM)(7)(8). In those codes, fuel is assumed to be some cells which contain many smaller size particles. And those particle cells, namely *parcel*, are treated as *Lagrangian* matter which move any position in space. And the space filled with gases are treated as *Eulerian* matter which needs computational meshes in calculation. The interaction between parcel and gases, namely fuel droplets and ambient gas, is calculated by drag force in dynamic pressure formula.

In those studies above mentioned are clarified that motion in diesel fuel spray could be treated with *Momentum* conservation law. Thus, notation turns into how and what control the momentum conservation process. The following sections, it was tried to reveal this aspect in conjunction with previous and recent results of studies.

Spray Structure and Formation

Diesel fuel spray could be represented by several peculiar characteristics. Those are spray angle θ, spray tip penetration l, the *Sauter* mean diameter d_{32} and breakup length l_b. **Figure 1** shows these parameters of liquid fuel spray(9). For more detail descriptions, θ would be divided into spray cone angle and equivalent spray angle, l would be divided into proportional to time duration and proportional to square root of time duration. The mean diameter both overall spray and local distribution would be available. And l_b is still under investigations due to complexity in its determination and measuring.

Those parameter should be the result of atomization mechanisms. **Figure 2** shows the possible mechanisms due to phenomenon in spray. That is, three main causing, 1) disintegration of liquid, 2) inducement and entrainment of ambient, 3) distribution of droplets would be main factors which results into spray characteristics. In argument on governing mechanism of those phenomenon sometimes fall into conflicting in case of discussion based on measured results of spray characteristics.

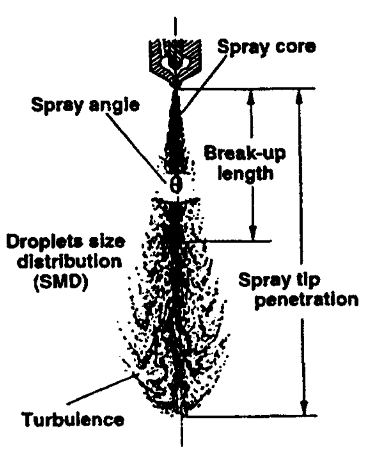


Fig.1 Parameters of a spray by Arai, M(1994)

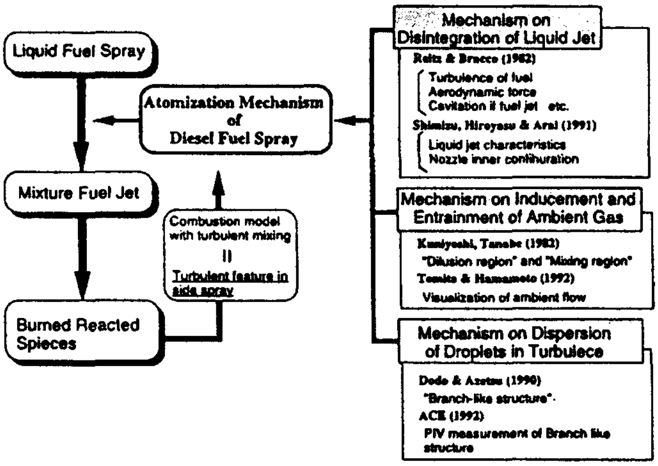


Fig.2 Mechanisms in spray atomization

For instance, atomized droplets should be results of shearing by ambient which is the essential action of momentum exchange process. Cavitation in liquid fuel might be one of mechanisms of atomization, but it should not be only one because of momentum interchanging process surely exist in diesel fuel spray. And this shear force should be argued in both magnitude and tendency in conjunction with viscosity. Viscosity would represent the efficiency of momentum exchange and also the efficiency of dissipation of turbulent energy. Emphasis is that any factors of injection parameters, such as density or viscosity, should not be neglected in order to clarify the atomization mechanism of diesel fuel spray itself.

Structure Model

Figure 3 shows flow chart in diesel fuel spray due to spatial region from up stream to down stream(10). This flow diagram is obtained with experimental analysis with nozzle contribution(11), and ambient gas contribution(12), and numerical analysis(13) on spray structure and characteristics. In this section, it is discussed on "vortices motion" and "viscosity aspects" in spray phenomena.

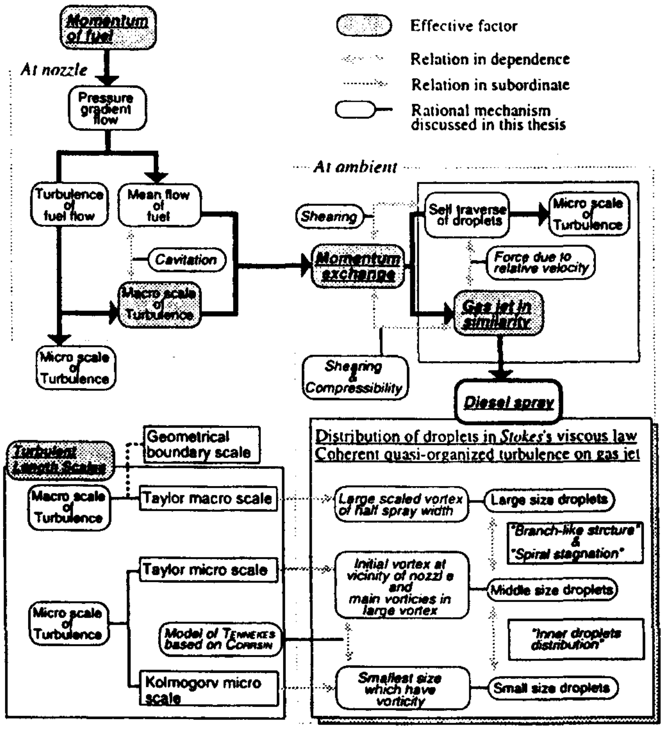
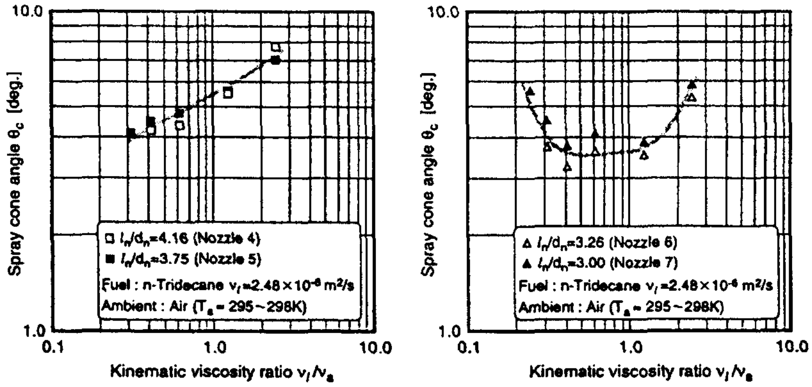


Fig.3 Cascade process on the formation mechanism of Diesel fuel spray

<u>**Spray Divergence**</u> - **Figure 4** shows change in spray cone angle θ_c (distance from nozzle 2<z<10mm) with nozzle parameter l_n/d_n (d_n:nozzle hole diameter, l_n: nozzle hole length). It is supposed that at low density conditions, turbulence of fuel is brought out in larger d_n (small l_n/d_n) nozzle. **Figure 5** shows change in spray cone angle θ_c with variation of needle valve lift l_v under full lift. It is supposed on the results that turbulence in sac chamber is hardly dissipated and spread at ambient. **Figure 6** shows change in flow patterns with planar model



(a)Larger l_n/d_n with smaller nozzle hole diameter

(b)Smaller l_n/d_n with larger nozzle hole diameter

Fig.4 Change in spray cone angle on kinematic viscosity ratio between fuel and ambient

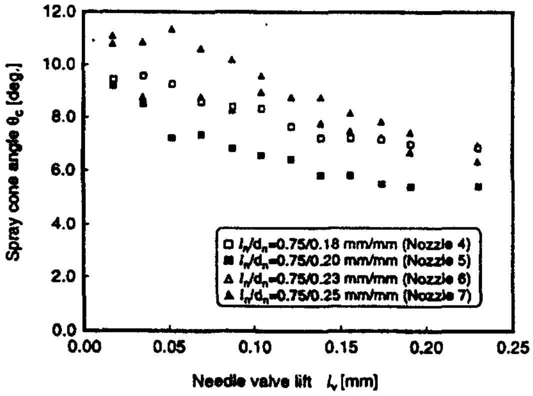
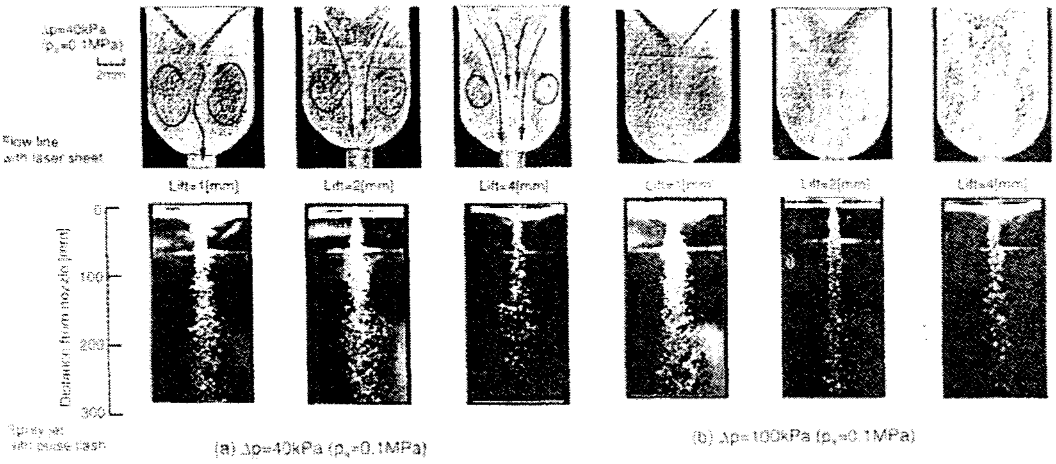


Fig.5 Change in spray cone angle of steady fuel spray with variation of needle lift



(a) Δp=40kPa (p_a=0.1MPa)

(b) Δp=100kPa (p_a=0.1MPa)

Fig.6 Change in nozzle inner flow and ambient jets with planner acrylic model nozzle

nozzle. It is supposed that fuel flow in nozzle would be divided into two macro cases as indicated in figure. From those results, it is concluded that turbulence of fuel flow in nozzle would affect both in discharge coefficient of nozzle C_d and divergence angle θ_c. It is found that the more fuel turbulent, C_d becomes smaller and θ_c increases at near region of nozzle.

Figure 7 shows change in spray angle θ (z > 10-40mm) with ambient kinematic viscosity v_a. In this figure liquid phase divergence angle would be related to v_a. **Figure 8** shows change in θ with both in density and viscosity. In this figure gas phase divergence would be shown as effect of viscosity at a same density.

Figure 9 shows comparison in spray angles with empirical equations which are proposed for liquid fuel sprays(14)(19). Table 1 shows those equations. In this figure, it is shown that spray cone angle θ_c would be represented by Sitkei formula, and spray angle θ by Reitz et. al formula tends to 25 degree constant by Abramovich. That is to say, θ_c represents turbulent liquid surface angle, and θ represents induced and entrained gas angle.

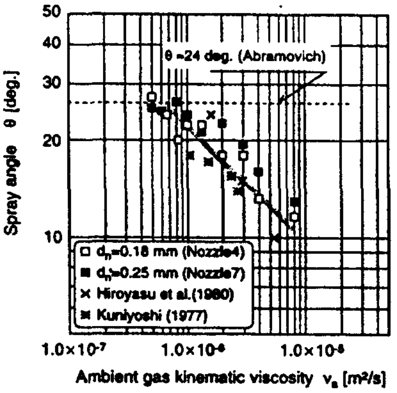


Fig.7 Change in spray angle on ambient kinematic viscosity

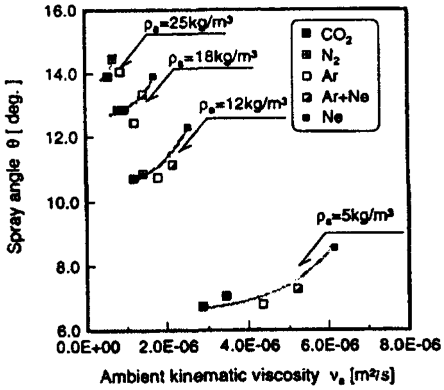
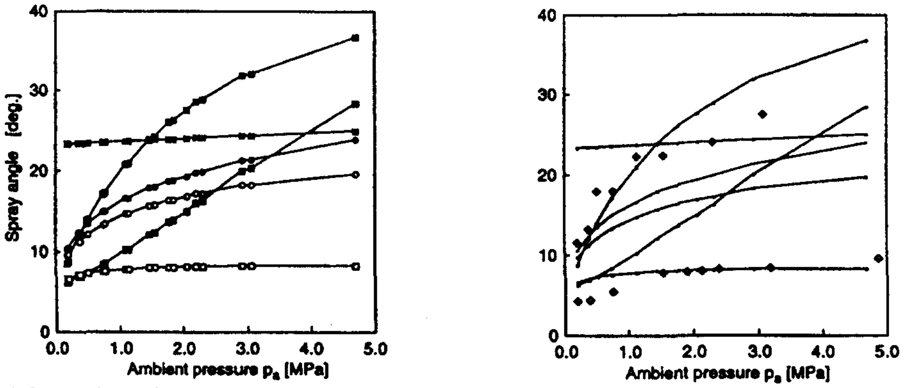


Fig.8 Change in spray angle with ambient kinematic viscosity



(1) Comparison of various empirical equation p_{inj}=18.0MPa (d_n=0.18mm, l_n=0.75mm, C_d=0.60, $u_{inj}=C_d(2\Delta p/\rho_l)^{1/2}$)

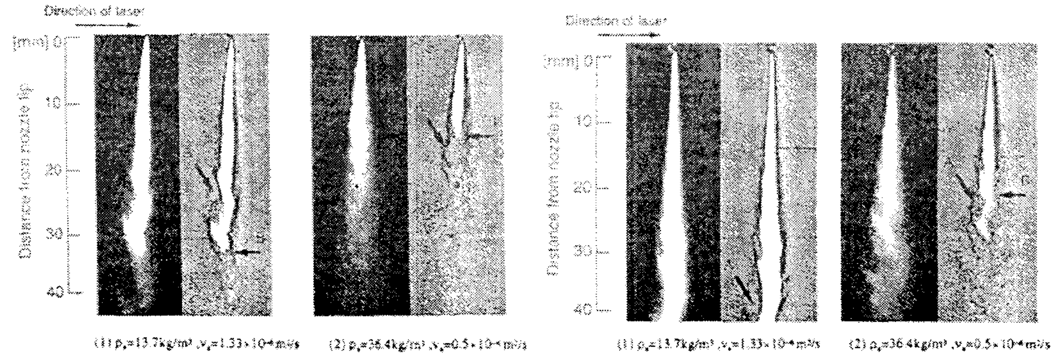
(2) Comparison with experimental data

Fig. 9 Relation between spray angles with previous studies

Table 1 Comparison of empirical equations of liquid spray

<table>
<tr><th rowspan="2">Researcher</th><th colspan="2">Formula of empirical equations</th></tr>
<tr><th>Concept and scope of method</th><th>Experiments and analyses range</th></tr>
<tr><td rowspan="2">Abramovich
(1963)</td><td colspan="2">$b/x \approx 0.27(1+\rho_a/\rho_l)/2 = 0.135(1+\rho_a/\rho_l)$
$db/dx = 0.135(1+\rho_a/\rho_l)$
ρ_a : ambient density, ρ_l : jet density</td></tr>
<tr><td>Momentum conservation theory with *Plandtl*'s mixing length</td><td>High density gas jet into low density gas ambient</td></tr>
<tr><td rowspan="2">Sitkei
(1964)</td><td colspan="2">$\theta=0.03(l_n/d_n)^{-0.3}(\rho_a/\rho_l)^{0.1}Re_l^{0.7}$
l_n : hole length, d_n : hole diameter
Re_l: jet Reynolds number $(=d_n u_{inj}/\nu_l)$</td></tr>
<tr><td>Dimensional analysis due to experimental results
Extracting effective factors by experiments</td><td>——————</td></tr>
<tr><td rowspan="2">Yokota
&
Matsuoka
(1977)</td><td colspan="2">$\theta=0.135(l_n/d_n)^{-\beta}f(\rho_l/\rho_a)Re_l^{0.46}$ $\quad f(\rho_l/\rho_a)=[1-exp\{-(\rho_l/\rho_a)/43.6\}]^{-1.0}$
$\beta=0.0284(\rho_l/\rho_a)^{0.39}$</td></tr>
<tr><td>Dimensional analysis due to experimental results
Difference on physical phase between jet and ambient</td><td>Diesel gas oil JIS#2, N_2 CO_2 He (300K)
$\rho_a=0\sim30kg/m^3$, $\mu_a \approx 15\sim20$ μPa·s
$d_n=0.2\sim0.6mm$, $l_n=1.2mm$
$Re_l=0.5\sim3.5\times10^4$</td></tr>
<tr><td rowspan="2">Reitz
&
Bracco
(1979)</td><td colspan="2">$tan(\theta/2)=(1/A)4\pi(\rho_a/\rho_l)^{0.5}f(T)$, $A=3.0+(l_n/d_n)/3.6$
$T=(\rho_l/\rho_a)(Re_l/We_l)^2$
We_l: jet Weber number $(=\rho_l d_n u_{inj}^2/\sigma_l)$ $\quad \left[\begin{array}{l} f(T)\approx(\sqrt{3}/6)[1-exp(-T/\tau)] \\ \text{where } f(\tau)=0.63f(T)\ (\tau\approx0.1) \end{array}\right]^*$</td></tr>
<tr><td>Theory of jet surface wave
Liquid stability due to nozzle internal geometry and shear force</td><td>Water and glycerol mixture, Air N_2 He Xe
$\rho_a=1.3\sim51.5kg/m^3$, $\mu_a \approx 18\sim23$ μPa·s
$d_n \approx 0.34mm$, $l_n/d_n=0.2\sim85$
$Re_l=0.4\sim4.75\times10^4$, $We_l=2.25\sim9.12\times10^4$</td></tr>
<tr><td rowspan="2">Hiroyasu
&
Arai
(1980)</td><td colspan="2">$\theta=0.0413(\rho_a/\rho_l)^{0.25}(u_{inj}d_n\rho_l/\mu_a)^{0.5}$
u_{inj} : jet issue velocity
μ_a : ambient viscosity</td></tr>
<tr><td>*Wakuri*'s mometum excahnge theory with dimensional analysis</td><td>Fuel oil ($\rho_l \approx 850kg/m^3$), N_2(300K)
$\rho_a \approx 12\sim36kg/m^3$, ($\mu_a \approx 17.8$ μPa·s)
$d_n=0.3mm$, $C_d=0.39$
$u_{inj}=50\sim74m/s$ ($Re_l=0.6\sim0.9\times10^4$)</td></tr>
<tr><td rowspan="2">Shimizu
(1991)</td><td colspan="2">$\theta=83.5(l_n/d_n)^{-0.22}(\rho_a/\rho_l)^{0.26}(d_n/d_o)^{0.15}$
d_o : sac diameter</td></tr>
<tr><td>Dimensional analysis due to experimental results
Observation of fuel flow in nozzle</td><td>Water, Air (300K)
$\rho_a=1.3\sim48kg/m^3$, $\mu_a \approx 18$ μPa·s
$d_n=0.1\sim0.4mm$, $d_n/d_o=0.033\sim0.134$
$u_{inj}=100\sim250m/s$</td></tr>
</table>

* $f(T)$ is increasing function which tends to $(3/6^2)^{1/2}$ at T=1000.
The τ is value of T when $f(T)$ is equal to 63% of $(3/6^2)^{1/2}$.



(1) $\rho_a=13.7\text{kg/m}^3, \nu_a=1.33\times10^{-6}\text{m}^2/\text{s}$ (2) $\rho_a=36.4\text{kg/m}^3, \nu_a=0.5\times10^{-6}\text{m}^2/\text{s}$

(a) Nozzle 4 (d_n=0.18mm)

(1) $\rho_a=13.7\text{kg/m}^3, \nu_a=1.33\times10^{-6}\text{m}^2/\text{s}$ (2) $\rho_a=36.4\text{kg/m}^3, \nu_a=0.5\times10^{-6}\text{m}^2/\text{s}$

(b) Nozzle 7 (d_n=0.25mm)

Fig.10 Inner structure of steady spray by means of laser light sheet incidence with edge enhanced processing

Figure 10 shows the inner structure of diesel fuel spray with 3mm thickness of pulsed laser sheet. A is the half spanwise vortex which was defined as "Vortex-like structure L_f", and B is characteristics length which was defined "Momentum-exchange length L_m". These characteristics have physical meaning of required distance to exchange momentum from liquid jet to surround gas.

<u>Momentum Exchange</u> - **Figure 11** shows the qualitative feature of diesel spray(20). To elucidate of them, numerical calculation should be one of possible methods. **Figure 12** shows calculated results(12)(13) of spray tip penetration with TAB method on KIVA II. With some modification on coefficient in source codes, both in temporal change and atomized droplets diameter would be successfully simulated by KIVA II code. **Figure 13** shows the calculated results of self-similarity profile of induced ambient gases which initially have no motion on k-ε

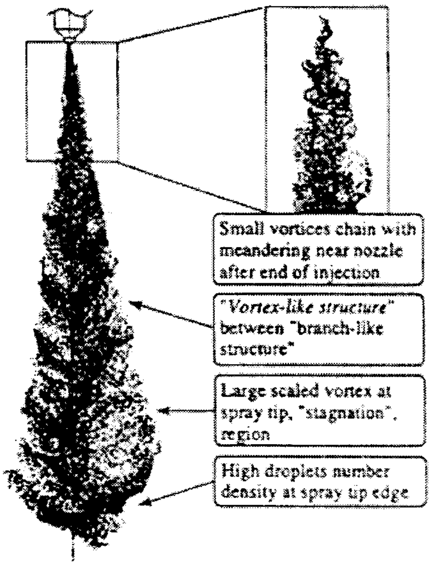


Fig.11 Qualitative physical phenomena of Diesel spray

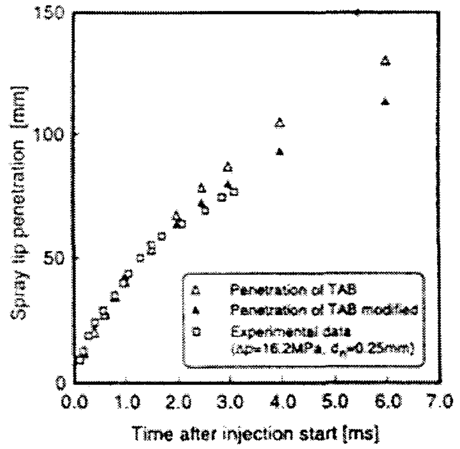


Fig.12 Comparison on penetration with results of KIVA II

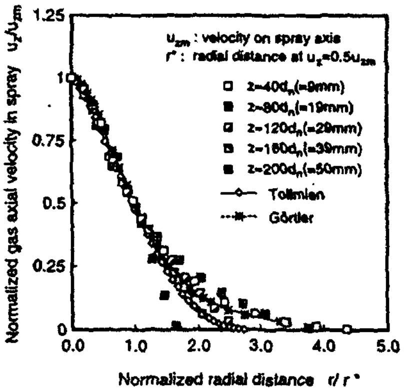


Fig. 13 Selfsimilar profile in induced ambient gas with KIVA II

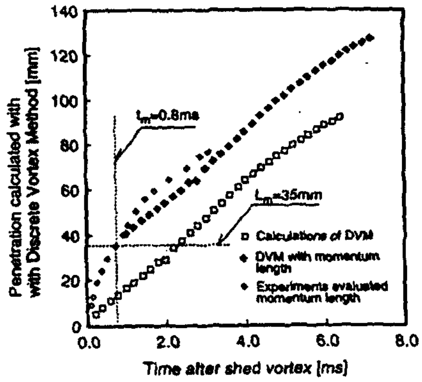


Fig. 15 Comparison on penetration with results of DVM

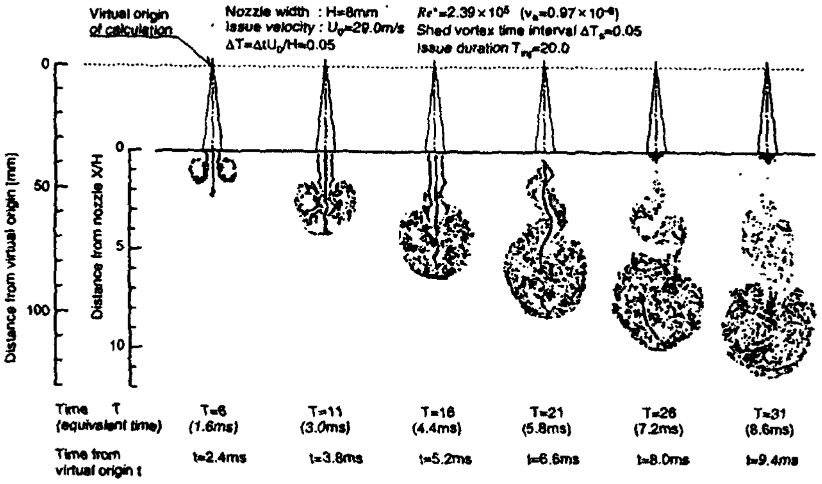


Fig.15 Distribution of tracers injected at different radial position on nozzle outlet

turbulent model. The momentum exchange is successfully simulated in comparison with basic mathematical treatments. But the exchange distance seems to be short compared to photographic assumption. That is with in z=35mm of this conditions, spray axis is dominated by fuel droplets in experiments but simulated gas motion existence. This is caused by DDM assumption and might be modified by Wave Breakup Method of Reitz and Diwakar(1987)(21).

Figure 14 shows the calculated results with Discrete Vortex Method of Kosaka, Kobayashi & Kamimoto(1994)(22). The input and determination of initial parameter on nozzle width H, velocity U_0 and kinematic viscosity ν_a is as same as what it had concluded from experimental analysis. H should be the spray width at momentum-exchange length L_m. And U_0 should be related to have equivalent momentum with liquid jets. And ν_a is essential factor for DVM which is subjected to natural feature of vortices. These detail treatment was noted in paper of authors(13) in respect to Kosaka et. al's treatment(23). **Figure 15** shows comparison of gas jet

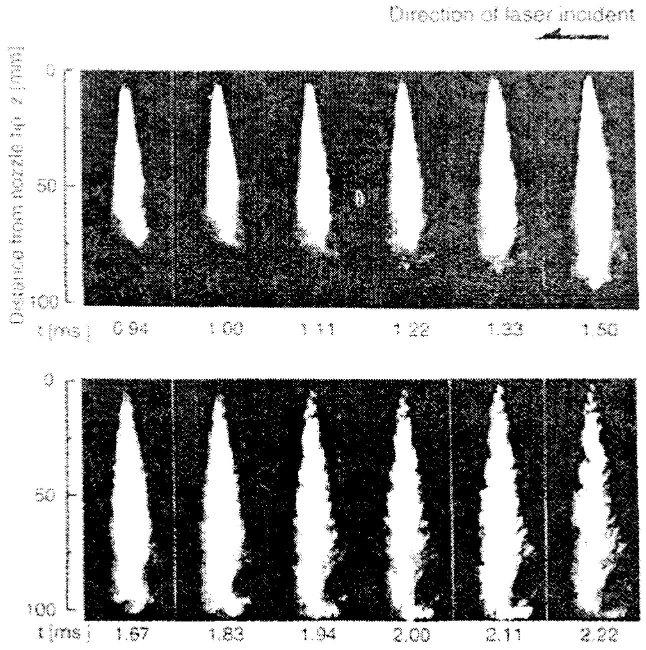


Fig.16 Visualized tip vortex by means of time sequential measurement of laser sheet incidence

penetration with experimental results of fuel spray. And **Fig.16** shows one of typical results which ensure of this methods.

Recent Treatments and Mechanism Proposal

In former section, it is argued with recent treatment on momentum exchange process. And detail mechanism of itself, namely how to exchange, is still not cleared as theorem. Possible factors might be both density and viscosity(11), and possible equation should be drag force treatment(12). In describing with physical formula, it conflict with lack of knowledge in friction. Friction, i.e. shearing, is function of surface profile in solid state contact which is notation of coefficient of viscosity μ_a in fluid state. But contribution of spatial expanse of contacting area is not considered though it is surely effective in practical.

Turns to diesel fuel spray phenomena, liquid jet surface would dominate the momentum exchange process. But this process might be instantaneous phenomena to describe and observe in previous methods. Since the observation of inner structure of diesel fuel spray by Azetsu et al. (1990)(24) drastically altered researcher's perceptions of atomization and dispersion process. In their experiments, the distribution of fuel droplets in dense spray was obtained by means of laser light sheet incidence. The notable is the existence of high number droplets density portions distributed periodically on spray boundary. They appears in 4 to 6mm axial spacing inclined narrow angle toward upstream. It is called "Branch-like structure" of spray at vicinity region from nozzle, *i.e.* within 40mm from nozzle tip. Lately, authors(20)(25)(26) had been investigated the detail feature of inner structure mostly concerned about its possible formation mechanism. From them, it is concluded that the vortices of induced ambient gas will caused this feature.

At vicinity of nozzle, liquid jet makes wedge narrow to downstream surrounded occasional gas vortices(11). And at downstream of spray, those gas vortices gather into large half spanwise vortex(11). These large vortices makes spray angle characterized by gas kinematic viscosity(12). With this turbulent motion, atomized droplets should be classified due to its diameter(12). This mechanism of particle dispersion in turbulent boundary layer is identical to the concept of *Stokes* number proposed by Chung & Troutt (1988)(27). And characteristics of turbulence is quite resemble large-scale spanwise vortex with much smaller vortices in plane mixing layer observed by Brown & Roshko (1974)(28).

Since the drastic change in appearance of diesel spray structure(24) is promoted by shorten the observation time duration from sub-milli seconds (≈20μs) to sub-micro seconds (≈10ns), it would be worth to reconsider the application of theories and equations of fluid dynamics to turbulent flow. Moreover, most kinetic chemical reaction for harmful matters occurs in sub-micro seconds, those heterogeneous aspects of fuel distribution will affect to combustion process. For the cold state spray, it must be clarified the exact criterion of using the theorem related to both time duration and spatial expanse, namely volume. With this evaluation, the propel modification would be deduced both in spray technology and combustion process.

Summary

From experimental analysis and numerical analysis, some propel results for fuel spray structure were obtained. It is not appropriate to conclude the formation mechanism only with above mentioned results. So, it is proposed as "hypotheses in structure formation" of diesel fuel spray as systematized in **Fig.17**.

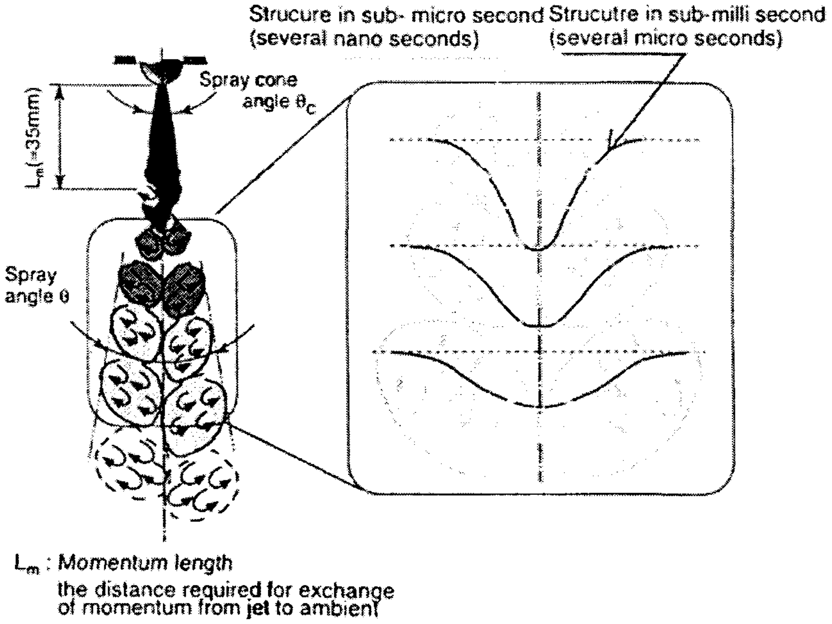


Fig.17 Hypothetical structure and its formation mechanism of Diesel fuel spray

To execute the experimental analyses with fuel spray, there are several important factors which should be noticed with results. They are as follows,

1)Nozzle parameter should be noted not only l_n/d_n (d_n:nozzle hole diameter, l_n: nozzle hole length) but also sac dimensions. For instance, sac diameter d_0 and sac length l_0 (ref. **Fig. 18**).

2)Fuel injection rate should be noted with temporal history. That is, mass injected rate dm_f/dt (m_f : fuel mass) or both injection pressure p_{inj} and needle lift l_v.

3)Ambient gas conditions should be considered as gas amount. That is, both ambient pressure p_a and its temperature T_a with exact property should be noted.

4)Nozzle tip location to closed vessel would be better indicated.

5)Nozzle hole inlet location to sac chamber would be better noticed.

Term 1) is related to estimation in fuel turbulence(11)(19)(29). Term 2) is related to spray growth tendency(23). Term 3) is related to estimation of ambient physical properties(12), such as density ρ_a ($\approx p_a/R^*T_a$, R^*: specific gas constant [J/(kg·K)] in SI unit) or viscosity ν_a ($=f$[species, T_a]). And term 4) and 5) are additional ones which are not clear, but surely effect to spray characters(30)(31).

To execute numerical simulations, essential difference in computation method between such as KIVA and such as DVM should be noticed. KIVA calculates average profile of physical properties with some modeling which orders both in time and space are smaller than averages. Otherwise, DVM calculates small order ones itself with modeling in causing average feature. In usage of them, for instance of ambient gas, KIVA simulate it as fixed *Eulerian* matter which energy is traversed and DVM simulate it as moving *Lagrangian* matter whose interaction is modeled. We should chose of them due to objective. And DVM is on sprout time in its algorithm and some more experimental ensuring should be needed(13).

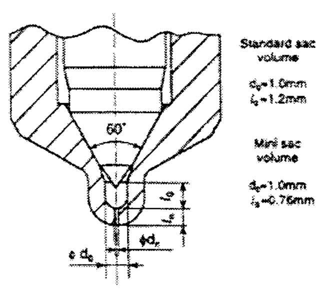


Fig.18 Dimensions of hole-nozzle

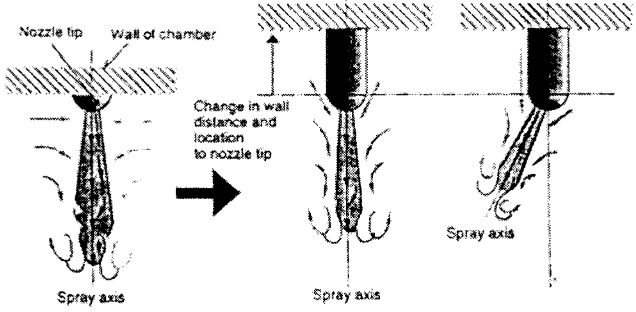


Fig.19 Possible modifications in changing nozzle location

Conclusions

Finally, it is set as one of possible modifications to recent engines due to spray formation as shown in **Fig.19**.

That is change in inducement of gas both its initial located position and efficiency. It will be promoted drastic change in combustion process and exhaust emissions. The gray area in understanding on spray combustion(32) also would be clarified in same manners.

These trials are conducting by many authors(33)(34) and companies(35) which nozzle location is varied from ordinal cylinder head center position to some other sides. And optimized conditions would be exist for each specification of engines. This might be one of break-throughs in developing and constructing internal engines.

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