

A Study of Spray Direction against Swirl in D.I. Engines

S.Kono, H.Kudo and T.Terashita

*Yokohama Research Center
Mazda Motor Corp.
2-5, Moriya-cho
Kanagawa-ku, Yokohama 221
Japan*

ABSTRACT

Spray formations of three injection directions against swirl have been investigated by means of a 3D numerical calculation and a visualization of spray at an engine operating condition. In-cylinder flow, more over, has been measured by using a LDV system for the purpose of studying in-cylinder flow phenomena and obtaining initial flow conditions of calculations. Comparing analytical results of 3D calculations, etc. with engine performances data; a fuel consumption, emissions, and a cyclic variation, effects of spray directions against a swirl direction and relations between spray formations in a combustion chamber and engine performances have been cleared.

INTRODUCTION

A spray formations of D.I. engines controls its combustion and effects strongly on its performances; a fuel consumption and emissions. Because applications of in-cylinder flow on a spray formation is important, a lot of studies of spray formations in swirl have been done. (1),(2) Though a relation between injection and swirl directions is important for the purpose of an application of swirl on a spray formation, the relation in a practical engine has not been investigated sufficiently yet.

In this study, a direct injection type engine which has a single hole nozzle and a spark plug, has been operated, and three injection directions; a forward (same) direction, a reverse one, and a right-angled (central) one against a swirl direction, have been selected. Spray formations in 3D cylinder flow have been investigated by using a 'KIVA' code. Initial conditions of in-cylinder flow are based on data which have been measured in three dimensional by a LDV system under a motoring operation. Analysis results of spray formations by numerical calculations, etc. can explain well data of engine performance tests qualitatively, and some interesting results have been obtained.

MEASUREMENT

Test Engine and Test Condition

A test single cylinder engine which has a single hole type nozzle and a spark plug has been

operated. The combustion chamber is a bowl-in-piston type. Main engine specifications are summarized in Table 1. In order to investigate effects of injection direction against swirl on a spray formation and engine performances, three spark plugs (F,C,R) have been settled to locate their electrodes at a same distance from a nozzle hole location of a injection nozzle (I) as shown in Fig.1. Each injector, of which nozzle hole is settled to inject fuel toward each electrode, has been prepared. Three injection directions, a forward (same) one, a reverse one, and a right-angled (central) one against a swirl direction, then, have been selected. Inlet and exhaust valves are made small, and are set at a left hand side of a cylinder bore in order to enlarge a free area for setting spark plugs and an injector.

Injection timings and spark ignition timings are selected at a MBT under each test and operating condition. A fuel consumption, emissions, and a combustion stability are estimated in each test. A pressure transducer (a quartz and watercooled type one made by KISTLER; type 701A) is settled at one of plug holes to measure in-cylinder pressure. A combustion stability is estimated by analyzing a fluctuation of an indicated mean effective pressure (IMEP). Main operating conditions are summarized in Table 2.

Measurement of In-Cylinder Flow

In-cylinder is visualized by using an extended cylinder block, in which a cylinder liner made of glass is settled, and by using an extended piston for the purpose of measuring the whole of 3D in-cylinder flow.(3) A 2-colors, 4-beams type LDV system (made by DANTEC) and a forward scattered method have been selected. A 4W Ar+ laser and a counter type signal processor have been used. A block diagram of this system is shown in Fig.2. An aerosol liquid of water and glycerin is used for seeding, and piston ring made of plastic is used for operating under a non-lubricated condition, because of preventing that a glass cylinder liner is scratched and is stained.

Five horizontal cross sections in an axial direction and 16 points at each cross section are selected for measuring points as shown in Fig.3. A total measuring point is 80. Laser beams have been made incident in a cylinder from two directions, which are right angled each other,

at every measuring point to obtain 3D flow data. A time averaging method, in which an averaging time travels every 10°(CA), is applied in order to analyze a mean velocity and a turbulent intensity. An engine motoring speed is 500 rpm, and a throttle is wide opened.

Table 1 Main Engine Specifications

Bore * Stroke	86.0 * 86.0 (mm)
Compression Ratio	13.0
Top Clearance	0.5 (mm)
Combustion Chamber	52.0 * 17.6 (mm) (Bowl in Piston type)
Injection Nozzle	Single Hole Nozzle
Nozzle Diameter	φ 0.25 (mm)

Table 2 Main Operating Conditions

Engine Speed	1000 (rpm)
Charging Efficiency	83.0 (%)
Amount of Fuel	10.0 ~ 20.0 (mm3/str)
Swirl Ratio	3.8
Injection Timing	M.B.T.
Ignition Timing	M.B.T.

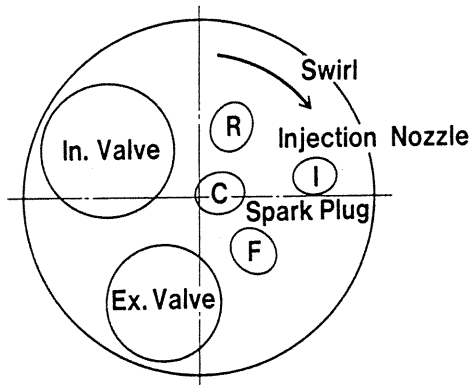


Fig.1 Layout of Cylinder Head

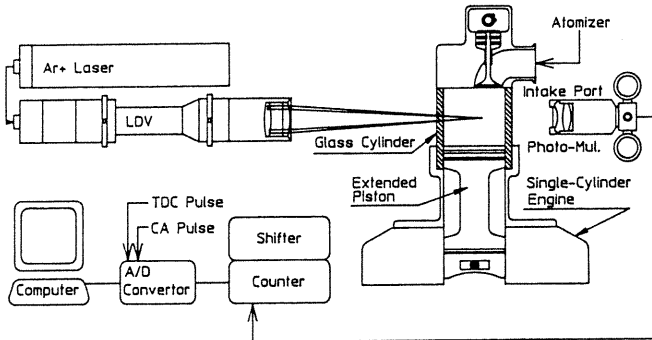


Fig.2 Block Diagram of a LDV Measuring System

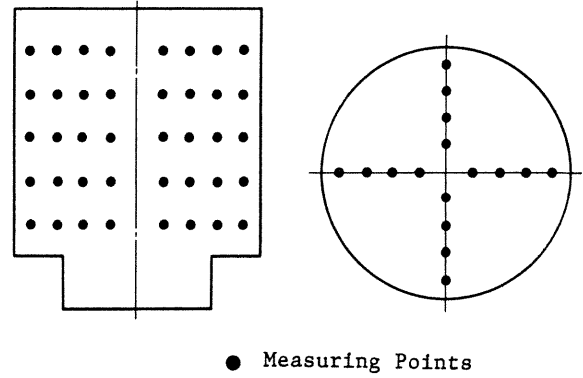


Fig.3 Flow Measuring Points in Cylinder

Visualization of Spray

A combustion chamber has been visualized in a bottom view type method by using an extended cylinder block and an extended piston as shown in Fig.4. A spray formation of each injection direction against a swirl direction has been taken a photograph by a high speed camera. A 5W xenon lamp has been used and a light scattering method has been applied. Engine operating conditions submit to Table 2. A camera speed is set at 3000 frame/sec.

CALCULATION

Spray formations in three dimensional flow have been investigated by calculations of which code is based on a 'KIVA' code developed by Los Alamos National Laboratory.(4) The code has been run on a super computer SX-2, and graphical treatments have been done on a computer ACOS-610.

Basic Equations

A conservation equation of mass under consideration of spray is given as follows.

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \underline{u}) = \nabla \cdot [\rho D \nabla (\rho_m / \rho)] + \dot{\rho}_s \delta m_l \quad (1)$$

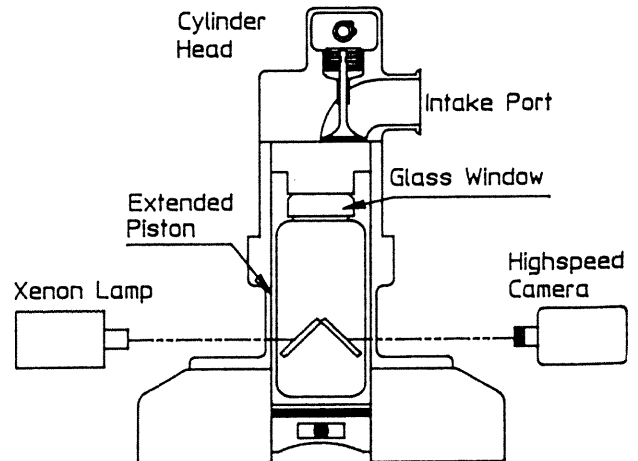


Fig.4 Visualization of Spray (Bottom View Type and Light Scattering Method)

where the 1st and the 2nd terms of the right hand side describe diffusion of species and spray including vaporization respectively, and where D refers to a diffusion constant.

Assuming incompressible and viscous flow, Navie-Stokes equation under consideration of spray momentum for an external force term is given as follows.

$$\frac{\partial}{\partial t} (\rho \underline{u}) + \nabla \cdot (\rho \underline{u} \underline{u}) = -\nabla P + \nabla \cdot \underline{\sigma} + F_s \quad (2)$$

where the 1st, the 2nd, and the 3rd terms of the right hand side describe a pressure gradient, a shear stress of flow, and an external term respectively. Calculations of flow during an induction stroke is impossible, because only momentum of spray is taken an account for an external term.

A conservation equation of energy under consideration of a spray and a turbulence terms is given as follows.

$$\frac{\partial}{\partial t} (\rho I) + \nabla \cdot (\rho I \underline{u}) = -P \nabla \cdot \underline{u} + \underline{\sigma} : \underline{\nabla} \underline{u} - \nabla \cdot \underline{J} + \dot{Q}_s + \dot{Q}_t \quad (3)$$

where I and J describe an internal energy and a heat flux, and the 4th and 5th terms of the right hand side refer to spray and turbulence respectively.

Each physical quantity is calculated by using conservation equations mentioned above and state equations. A turbulent term is calculated by a SGS turbulence model, and a log-law is selected for a boundary condition.

Initial Condition

Initial condition of in-cylinder flow. Because a 'KIVA' code cannot calculate flow of an induction stroke, as mentioned before, a solid swirl is assumed and is settled as an initial condition of in-cylinder flow after an inlet closed timing. A practical flow, however, is not flow which can be assumed a solid swirl, it's hopeful that initial data which is based on measurement flow are set for an initial condition.(5)

In this study, an initial velocity at each calculation mesh has been obtained by making a linear interpolation the 3D flow data which are measured by LDV to satisfy the conservation equations.

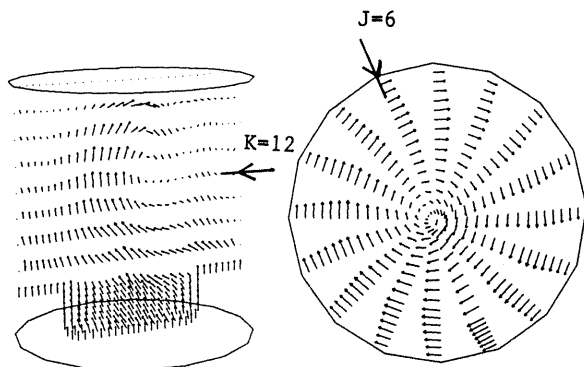


Fig. 5 Initial Condition of Flow Velocity (BTDC 120°: Left hand shows a J=6 cross section, and right hand shows a K=12 one.)

Fig.5 shows a distribution of in-cylinder flow at 120° (BTDC) calculated by the above method. A clear tumble motion (a vertical vortex) can be observed, and in-cylinder flow can be seen not to be like a simple solid swirl.

Initial condition of spray. A discrete-particle model is applied to a spray model. An initial injection velocity, a spray angle, a droplet Sauter mean diameter, etc. have to be prepared for an initial condition. Because it's hopeful that these numerical values are based on measurement data, these numerical values have been obtained by visualization of spray mentioned before and by referencing experimental equations and data of Hiroyasu, et al.(6) A location of injection point, an injection direction, etc. are selected to agree with a practical operating condition.

RESULTS AND DISCUSSIONS

Analysis of In-Cylinder Flow

An intensity of induction swirl has been changed in three stages by an intake port which can incline an induction flow and change a swirl intensity. Each steady flow swirl ratio has been measured by an impulse type swirl meter. The results are summarized in Table 3.

A transition of swirl in a motoring operating condition has been calculated with every local velocity datum obtaining by LDV. Each swirl transition of three swirl ratio is plotted in Fig.6. A swirl ratio is calculated by an average of angular velocity at each measuring cross section assuming a solid swirl. Each swirl ratio at BDC agrees well with a steady flow swirl ratio as shown in Table 3.

Table 3 Steady Swirl Ratio in Three Cases

	a	b	c
Swirl Ratio	0.7	3.8	8.9

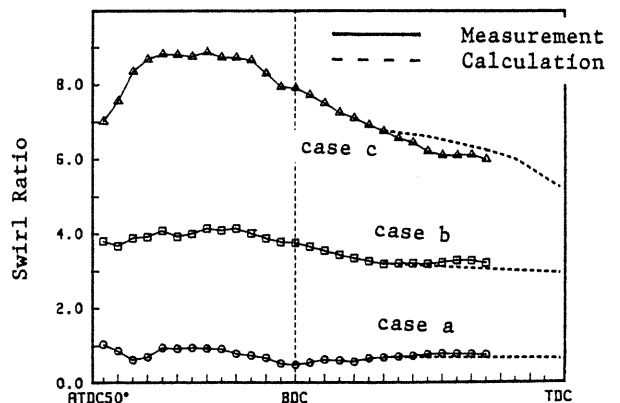


Fig.6 Transition of Swirl Ratio (Solid lines indicate measurements and dotted lines indicate calculations.)

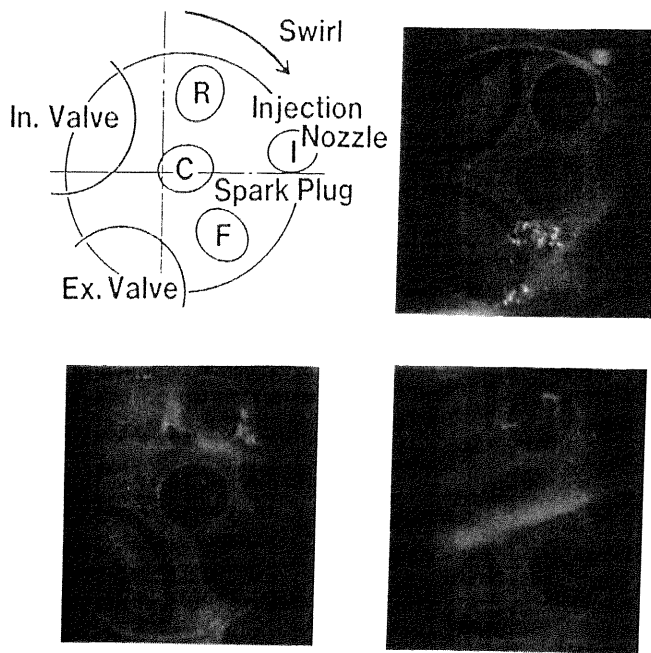


Fig.7 16mm Films of Three Type of Injections
(Left of top; Layout of spark plugs and an injector, Right of top; Forward direction (F) injection, Left of bottom; Reverse direction (R), Right of bottom; Central direction (C))

A transition of a total angular momentum obtained by calculations in which the initial condition is based on a distribution of flow at 120° (BTDC) measured by LDV. Each transition curve is plotted making a value at 120° (BTDC) as a base point in Fig.6. Dotted lines show each calculated swirl ratio, which is obtained by means of assuming a solid swirl, from 120°(BTDC) to TDC.

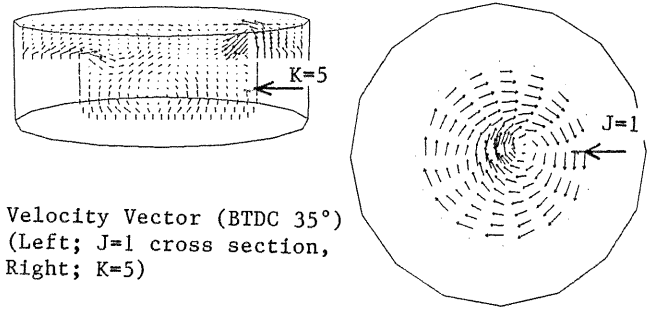
Visualization of Spray

Fig.7 shows a photograph of each spray injection at 5° (CA) after an injection start. Enough information cannot be read from these films owing to lack of light. However, it can be seen that spray conflicts with an electrode, and spray disperses and flows in swirl. In calculation, an existence of a spark plug is not considered, and then the phenomenon that a spray conflicts with an electrode cannot be predicted.

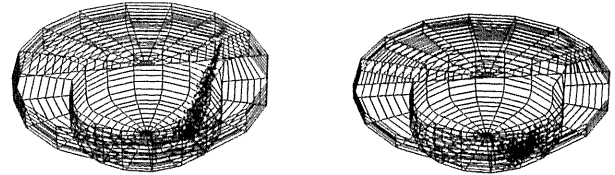
Results of Calculation

Spray formations of each injection direction, a forward (same) direction, a reverse one, and a right-angled (central) one against a swirl direction, have been investigated under an operating condition as shown in Table 2. An amount of injection fuel is 15 (mm³/str), and fuel is C8H18.

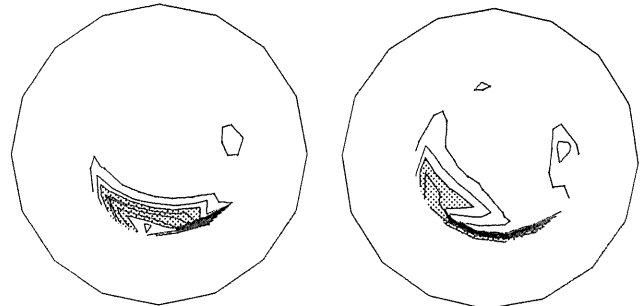
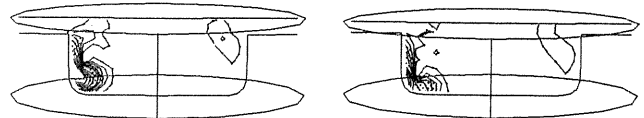
(1) Forward direction (F). In case that a spray is injected toward a forward (same) direction against swirl, flow in a combustion chamber, a spread of spray, and a distribution of fuel density are shown in Fig.8. They are described by a graph of velocity vector at 35° (BTDC), a perspective of spray (liquid) distribution at 30° and 20° (BTDC), and a density contour at 20° and 15° (ATDC).



Velocity Vector (BTDC 35°)
(Left; J=1 cross section, Right; K=5)



Distribution of Spray (Liquid)
(Left; BTDC 30°, Right; BTDC 20°)

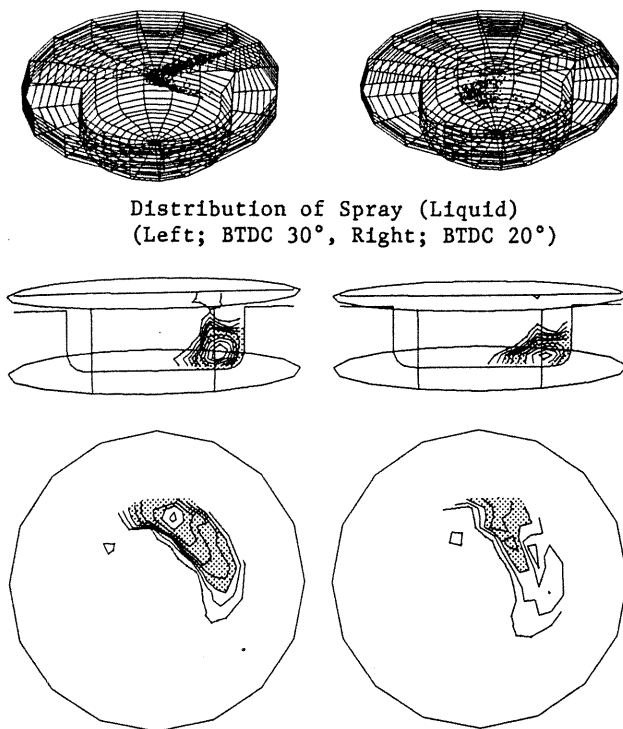


Distribution of Fuel Density
(Left; BTDC 20°, Right; BTDC 15°, Top; J=5 cross section, Bottom; K=5, Hatching area is a combustible mixture zone.)

Fig.8 Spray Formation in case of Forward Direction (F)

A tumble motion (a vertical vortex) cannot be seen clearly at 35° (BTDC), however, a strong shearing swirl is formed. A rich fuel zone is appeared on the vicinity of a cavity wall and an electrode of a spark plug, and a plenty of fuel sticks on a wall comparatively. A lean mixture zone is spread down by swirl as shown in Fig.8 (distributions of fuel density). According to this result, a hydrocarbon emission is expected not to be so well.

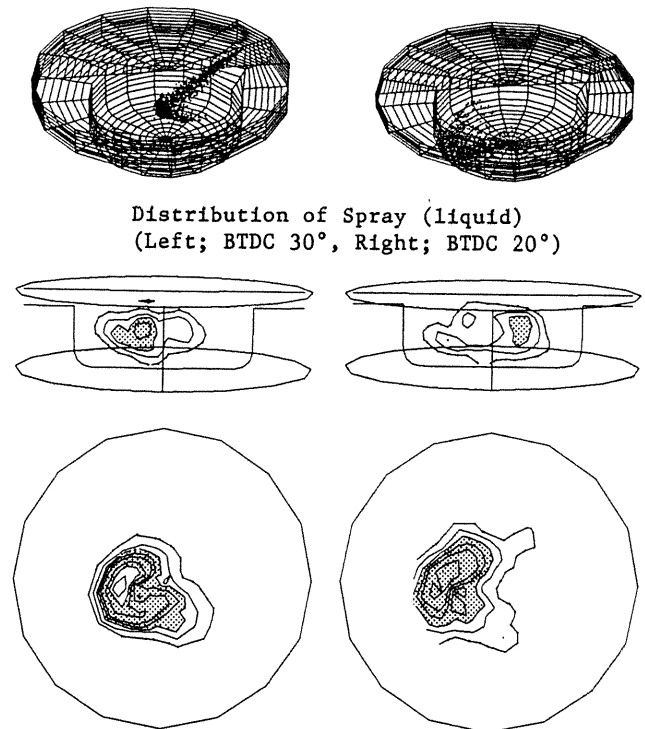
(2) Reverse direction (R). Fig.9 shows a distribution of spray and a fuel density in case of a reverse direction. The tip of spray is crushed and is spread by swirl. A rolling of spray toward the bottom of cavity can be observed.



Distribution of Spray (Liquid)
(Left; BTDC 30°, Right; BTDC 20°)

Distribution of Fuel Density
(Left; BTDC 20°, Right; BTDC 15°,
Top; J=4 cross section, Bottom; K=5,
Hatching area is a combustible mixture zone.)

Fig.9 Spray Formation in case of Reverse Direction (R)



Distribution of Spray (liquid)
(Left; BTDC 30°, Right; BTDC 20°)

Distribution of Fuel Density
(Left; BTDC 20°, Right; BTDC 15°,
Top; J=5 cross section, Bottom; K=5,
Hatching area is a combustible mixture zone.)

Fig.10 Spray Formation in case of Central Direction (C)

A dispersion of spray is comparatively small and mixture distributes at a circumference of an electrode. A better performance data, then, can be expected in case of this direction.

(3) Central direction (C). Fig.10 shows a distribution of spray and a fuel density in case of a central injection. Spray is not influenced by swirl so much, and a tip of spray is spread down by swirl in the vicinity of a cavity wall which locates the other side of an injector. Because an injector locates comparatively far from the cavity wall, an amount of fuel sticking on a wall is comparatively small. Mixture, however, distributes at the left side of a cavity, enough thick density of mixture does not form at an electrode location. A stability of ignition may not be so well.

Results of Operating Test and Discussions

A fuel consumption (ISFC), emissions (ISHC), and a cycle variation (a fluctuation of IMEP) against an amount of fuel (10, 15, 20 mm³/str) have been estimated in each injection direction case. The results are summarized in Fig.11, 12, 13 respectively.

(1) Forward direction (F). A fuel consumption and a hydrocarbon emission deteriorate in each amount of fuel, comparing in case of others injection direction. A fluctuation of IMEP indicates that an ignition and combustion are not stable.

Calculations shown in Fig.8 can explain these results as follows; a fuel stick on a wall in the vicinity of a spark plug, a fuel stick on an electrode, and a dispersion of lean mixture down the swirl cause those deteriorations.

(2) Reverse direction (R). Comparing others direction, a good fuel consumption and a stable combustion are obtained in each amount of fuel. The reason of this is thought to be that a fuel mixing is comparatively well and a fine mixture locates in the vicinity of an electrode because of a spray colliding with swirl, as shown in Fig.9.

(3) Central injection (C). A fuel consumption is worse than that in case of a reverse direction, however, an exhaust of hydrocarbon is equal to that in case of R in every amount of fuel. This can be explained that fuel stick on a wall is little as shown in Fig.10 because of injection fuel toward a bore center, and that a dispersion of fuel is small because of being not affected strongly with swirl. Mixture formation at a circumference of an electrode, however, is difficult, an ignition and a combustion stability, then, are not hopeful. A fuel consumption is worse than that in case of a reverse direction.

As mentioned above, differences of engine performances in three cases, that is, three injection directions against swirl, can be explained qualitatively by calculation data.

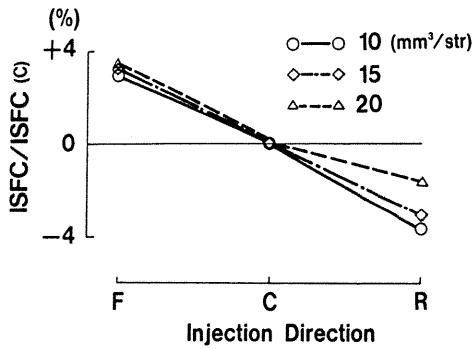


Fig.11 Comparison of a Fuel Consumption (F; Forward direction, R; Reverse one, C; Central one)

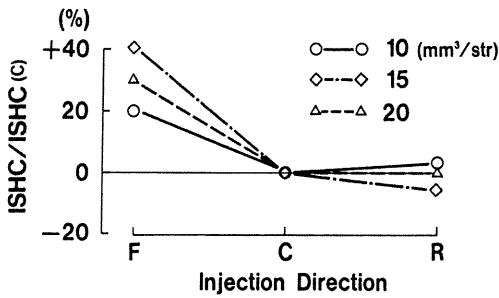


Fig.12 Comparison of a Hydrocarbon Emission (F; Forward direction, R; Reverse one, C; Central one)

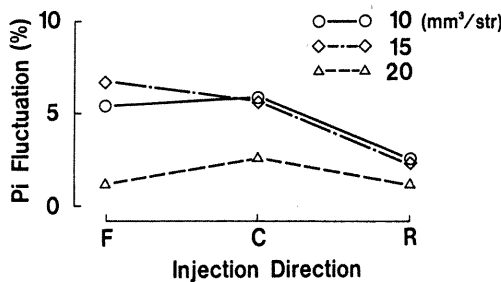


Fig.13 Comparison of a Combustion Stability (F; Forward direction, R; Reverse one, C; Central one)

3. In case of a reverse one, a comparatively good fuel consumption and a stable combustion are achieved by a good mixing and a mixture location in the vicinity of an spark plug (an electrode).

4. In case of a central one, a hydrocarbon emission is equal to that in case of a reverse one, because a fuel stick on a wall and a dispersion of mixture are little. A combustion stability, however, is not hopeful owing to an insufficient mixture formation in the vicinity of a spark plug.

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CONCLUSIONS

Spray formations of three injection directions, a forward one, a reverse one, and a central one against swirl have been investigated by a 3D numerical calculation, a visualization of spray, and a measurement of in-cylinder flow. Comparing these analysis data with engine performances data, following conclusions have been obtained.

1. Analysis results of spray formation, etc. obtained by a numerical calculation can explain well qualitatively engine performances data, that is, a fuel consumption, a hydrocarbon emission, and a combustion stability data.

2. In case of a forward injection direction, a fuel stick on a wall and an over mixing deteriorate engine performances.