A Study on the Shaped Combustion System Using Diesel Spray Impinged on a Wall

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In modern small compact combustion chambers of diesel engines with high speed injection spray, the wall impaction of spray is encountered. A number of combustion systems have been developed which deliberately employ wall impaction as a means of breaking up the fuel spray and/or directing it in a desired direction. As a link of this, in a further type of geometry, which has been presented by Park et al. cut-off pips were provided for a number of sprays directed not only straight down into combustion chamber centre but also across and down into the bowl in the normal radial direction. The sizes of the pips and their positions were tested for axi-symmetrical shape, and their results were analyzed. The further type was simulated in here by using 3D non-orthogonal spray engine code. The simulation results show that the further type is much better than general conventional shapes, i.e. well mixing of fuel vapour and spray high qualified droplet atomization, etc. Thus the improvement of the engine performance is expected by the shaped engine.

Key Words: Spray, Diesel Engine, Impaction

1. Introduction

The application of diesel engines has been wider in the small vehicle with compact engine. The spray impaction on the piston wall may not be avoided, and it gets an undesirable phenomenon because of fuel deposition on the wall. Thus more efforts have been given to optimize the combustion chamber with using spray impinged on a wall.

In the middle of the nineteen eighties new geometries for optimizing the combustion chamber shape were proposed by Kroeger (1986) and Kato and Onishi (1987). These chamber designs include a piston with a bowl and a small projection in the middle of the bowl.

Kroeger applied it for direct injection diesel engine (Caterpillar) using neat methanol. The basic geometry has a pip near the centre of piston bowl, onto which a fuel spray impacts. Also nine other sprays are injected in a normal pattern radially and slightly downward from the injector. Kato and Onishi developed a direct injection stratified charge engine. All of the fuel is sprayed onto the raised piston impingement area from a single orifice.

In both cases the intent of the pip in the chamber is to enhance the fuel injection process by directing the fuel to be injected onto the pip. Also the impacted spray provided a centrally located cloud of fuel drops and fuel vapour, in a region in which fuel and vapour are not expected for conventionally supplied direct-injection diesel engine.

A little later Naber, Enright and Farrell (1988) tested similar geometries in a rig consisting of a constant volume bomb. The chamber was designed with a flat land for impaction very near the injector (15 nozzle orifice diameter) in the centre of the bomb.

A number of times Kato and Onishi reported the development of their new chamber. In their earlier reports (1987, 1988, 1990a), similar geome-

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tries were shown with a raised land on the piston bowl of the methanol and gasoline spark ignition engine.

In another report (1990b) they applied it to a diesel engine (OSKA-D). Also a single hole fuel injection nozzle was located in the cylinder head to make the fuel jet impinge against the centre of the impingement part in the centre of the piston bowl. Two inlet valves were employed with straight inlet port. They compared the results with a conventional multi-hole injection system.

Lastly, a varied geometry of the impinging land was reported in their papers (1991, 1992) for spark ignition chamber and diesel engine piston bowl respectively. In the previous reports (1987 ~ 1990) the impinging part was installed in the centre of the piston, but in these later reports it is installed on the cylinder head in order to eliminate the variation of the distance between the injector and the impingement point.

A multi-impingement-wall head diffusion combustion system was proposed by Ogura et al. (1994). In this system fuel injected from a multi-hole injector is impinged onto the multi-impingement-wall head which is located in the centre of the combustion chamber and is attached to the cylinder head.

The experimental results has shown that the combustion performance and the fuel consumption have been improved, the NOx, HC and smoke densities of the exhaust gas of a diesel engine have been reduced, the maximum rate of pressure rise has been decreased significantly, and the fuel has been burned quickly after the injection start.

Park, Wang and Watkins (1993) proposed a further type of geometry of Diesel engine piston bowl. That is one in which cutoff pips are provided for a number of sprays, directed not only straight down into the bowl centre but also across and down into the bowl in the normal radial direction. They computationally examined spacings and sizes of the pip, using an axi-symmetric cylindrical orthogonal grid code. This is discussed more fully in Park (1991). They have shown the spray distributions for 10 cases at 1.0 ms after the start of injection, and these are compared with the result when there is no pip. For very thin pips only a part of the spray is interrupted, and it continues to flow down toward the bomb bottom, around the pip. For slightly wider pips the spray on impact divides into two distinct parts. Some of the spray still fails to strike the pip at all and continues down the side of the pip. The other part of the spray is formed by drops that strike the land and then move outward across the middle part of the bomb. As the size of the pip increases, the former spray region diminishes and then disappears completely, leaving only the later part. For larger values of pip radius, there is no movement of the droplets toward the bottom of the bomb after impact on the pip. The dispersed spray volumes, and SMD were analyzed to look for the optimum pip size. From these analyses of the size of land upon which the spray was impacted, they reported that the pip radius should be about 1.4 ~ 1.8 mm, and that the pip land should be placed at most 10 mm from the injector. This is used as a base on which the present study for optimizing the piston bowl shape is built.

2. Mathematical Model

The gas phase is modelled in terms of the Eulerian conservation equations of mass, momentum, energy and fuel vapour fraction, and turbulent transport is modelled by the k-ε turbulence model in a form for highly compressed flows. The droplet parcel equations of trajectory, momentum, mass and energy are written in Lagrangian form. The droplet parcel is containing many thousands of drops assumed to have the same size, temperature, velocity components, etc. The actions of the gas phase on the liquid phase are accounted for through the shear terms in the liquid phase momentum equations and the heat transfer terms in the liquid phase energy and fuel mass conservation equations. The efforts of the liquid phase on gas phase is given as sources or sinks in mass, momentum and energy equations in the gas phase.

The equations are transformed into general non-orthogonal curvilinear coordinates ξ^i with general tensor notation.

$$\frac{\partial}{\partial t}(\theta\rho\Phi)+\frac{1}{\sqrt{g}}\frac{\partial}{\partial\xi^i}\left(\theta\rho U^i\Phi-\frac{\theta\Gamma_\Phi q_{ij}}{\sqrt{g}}\frac{\partial\Phi}{\partial\xi^j}\right)$$
$$=\theta S_\Phi+S_\Phi^d \quad (1)$$

The normal flux components U^i to a coordinate surface on which ξ^i is constant is defined by

$$U^i=P_{ij}u^j \quad (2)$$

where u^j are the Cartesian components of a vector field $\bar{V}$, and P_{ij} are the Cartesian components of the area vector which are given as ;

$$P_{ij}=\sqrt{g}\frac{\partial\xi^i}{\partial x^j} \quad (3)$$

and Jacobian Determinant $\sqrt{g}=|J|$ is defined by

$$\sqrt{g}=det(J_j^i) \quad (4)$$

which is referred to as the infinitesimal volume element at interest point, especially if $\Delta\xi^i=1$, $\sqrt{g}$ is the volume of the cell.

The geometric relations q_{ij} are defined by

$$q_{ij}=\bar{A}^i\cdot\bar{A}^j \quad (5)$$

and $\bar{A}^i$ is the area vector normal to the surface of the control volume.

The source terms are given as follows ;

The momentum sources for $u^k(k=1, 2, 3)$ are given as

$$\sqrt{g}S_{u^k}=-P_{jk}\frac{\partial P}{\partial\xi^j}+\frac{\partial}{\partial\xi^l}\left(P_{li}\mu_{eff}\frac{P_{jk}}{\sqrt{g}}\frac{\partial u^i}{\partial\xi^j}\right)$$
$$-\frac{2}{3}P_{jk}\frac{\partial}{\partial\xi^j}\left(\rho k+\mu\frac{1}{\sqrt{g}}\frac{\partial U^m}{\partial\xi^m}\right) \quad (6)$$

The energy source term is

$$\sqrt{g}S_e=-P\frac{\partial U^m}{\partial\xi^m} \quad (7)$$

The kinetic energy source term is

$$\sqrt{g}S_k=\sqrt{g}G_t-\sqrt{g}\rho\varepsilon \quad (8)$$

The kinetic dissipation rate source term is

$$\sqrt{g}S_e=\sqrt{g}\frac{\varepsilon}{k}[C_1G-C_2\rho\varepsilon]$$
$$+C_3\rho\varepsilon\frac{\partial U^m}{\partial\xi^m} \quad (9)$$

and

$$G=G_t-\frac{2}{3\sqrt{g}}\frac{\partial U^m}{\partial\xi^m}\left(\rho k+\mu_{eff}\frac{1}{\sqrt{g}}\frac{\partial U^m}{\partial\xi^m}\right) \quad (10)$$
$$G_t=\frac{\mu_{eff}}{\sqrt{g}^2}\left[2\left(P_{li}\frac{\partial u^i}{\partial\xi^l}\right)^2+\left(P_{mk}\frac{\partial u^j}{\partial\xi^m}\right.\right.$$
$$\left.\left.+P_{mj}\frac{\partial u^k}{\partial\xi^m}\right)^2\right] \quad (11)$$

The transformed formulations are discretised by the finite volume manner. Within this process, Euler implicit method is used for the transient term and a hybrid upwind/central difference scheme is used as the approach to approximating the convection term.

The wall impaction model is given as follows ;

For $We<80$

$$\bar{V}_a^n=-\alpha\bar{V}_b^n \quad (12)$$
$$\bar{V}_a^t=\bar{V}_b^t \quad (13)$$
$$D_{da}=D_{db} \quad (14)$$

For $We>80$

$$(\bar{V}_a^n)^1=(\bar{V}_a^n)^2=-\alpha\bar{V}_b^nR_{xx} \quad (15)$$
$$(\bar{V}_a^t)^1=\bar{V}_b^t+\bar{V}_{scattering}^t \quad (16)$$
$$(\bar{V}_a^t)^2=\bar{V}_b^t-\bar{V}_{scattering}^t \quad (17)$$
$$D_{da}=C_wD_{db} \quad (18)$$
$$(N_{da})^1=(N_{da})^2=\frac{N_{db}}{2C_w^3} \quad (19)$$

Where the subscripts a, b stand for after, before, t, n for tangential, normal and 1, 2 for two small parcels after impaction respectively, and $(N_{da})^{1,2}$, N_{db} are the number of drops in the parcel after and before impaction respectively. The energy coefficient α is obtained as ;

$$\alpha=\sqrt{1-k\cos^2(\beta)} \quad (20)$$

with β the impinging angle to the normal.

C_w is designed to account for the droplet shattering in high incident Weber number case.

And $\bar{V}_{scattering}^t$ is the scattering velocity which are given randomly (Fig. 1) as ;

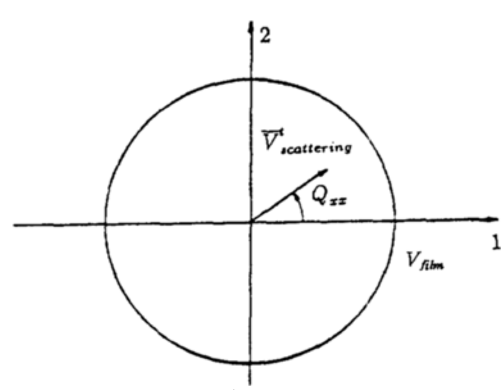


Fig. 1 Scattering velocity in the transformed plane

$$\bar{V}^t_{scattering} = V_{film} P_{xx} \bar{Q}_{xx} \tag{21}$$

Where P_{xx} is a random variable uniform in [0, 1], $\bar{Q}_{xx}$ is an unit vector in the angle distributed uniformly in [0°, 360°]. The film velocity of the thin front of the droplet around the dome is given by differentiation of the equation of the radius which is the evolution of the radius of the thin front of the droplet. (see Wachters et al)

$$V_{film} = 0.835(3.096 - 2\chi)\, V^n_b \tag{22}$$

where χ is a function of V^n_b.

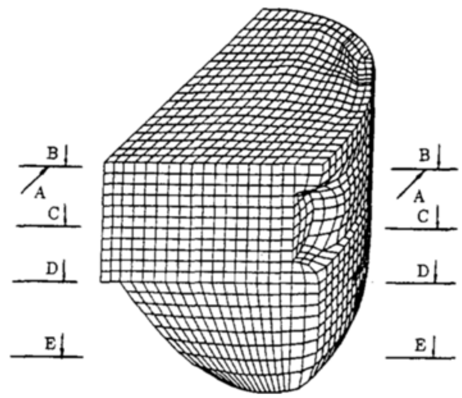
3. Simulation

From the analysis of the size of the land upon which the spray is impacted, Park et al (1993) reported that the pip radius should be about 1.4 ~ 1.8 mm, and that the pip land should be placed at most 10 mm from the injector. Thus the central pip in the centre of combustion chamber is placed at 10 mm from the injector and 1.5 mm as the pip radius is selected in this work. The other pips are placed on the side wall at 15 mm from the injection spray axis to avoid the collision between the spray impacted on the central pip and that on the side pip, because for the case of pip radius 1.5 mm and pip distance 10 mm, the spray radius spreaded out until 1.0 ms is about 13 mm from the axis. And the land size of the side pips is enlarged in proportion to the distance from the injector, also modified in consideration of the spray injection angle. Thus the land has an elliptical shape and the radii are 2.25 mm for the short distance and 3 mm for the long distance.

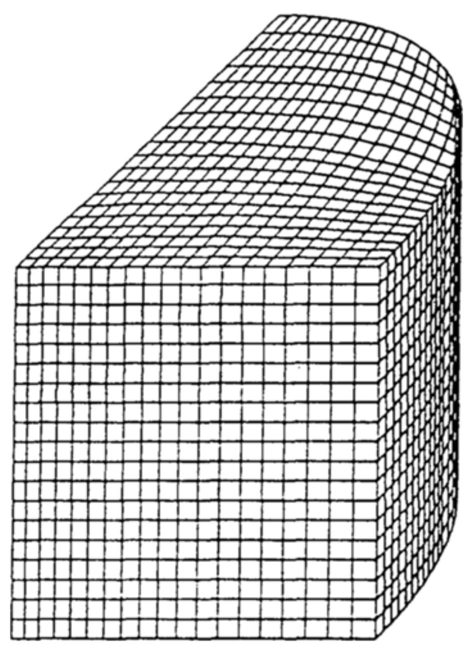
To analyse the optimized combustion structure, two other chambers are introduced, which are one

Table 1 Test cases

Test cases	N15	N17.5	N20
Bowl volume(mm³)	17500	23000	25100
Bowl diameter(mm)	35	40	40
Bowl depth(mm)	20	20	20
Central pip dist.(mm)	10	10	no-pip
Side pip dist.(mm)	15	17.5	no-pip
Central pip radius(mm)	1.5	1.75	no-pip
Side pip radius1(mm)	2.25	2.6	no-pip
Side pip radius2(mm)	3.0	3.0	no-pip
Trap press.(MPa)	1.5	1.5	1.5
Trap temp.(K)	773	773	773
Inj. Press.(MPa)	14.0	14.0	14.0
Nozzle dia.(mm)	0.3	0.3	0.3
Inj. duration(ms)	1.0	1.0	1.0



(a) Shaped chamber (N15)



(b) Cylindrical shape (No-pip)

Fig. 2 Grids used for simulation

is the case of enlarging the size of the optimized structure without any deformation and the other is no-pip case which is conventional simple cylindrical shape. These sizes are given in Table 1 with test conditions.

A $20\times20\times20$ grid is used for the three cases. The grid lines do not follow the boundary shape but the spray movement to reduce the error caused by the inclining of grids for sprays. To generate this grid, the calculation domain is divided into several parts by the pips. The quarter of the grids for the calculation domain are shown in Fig. 2.

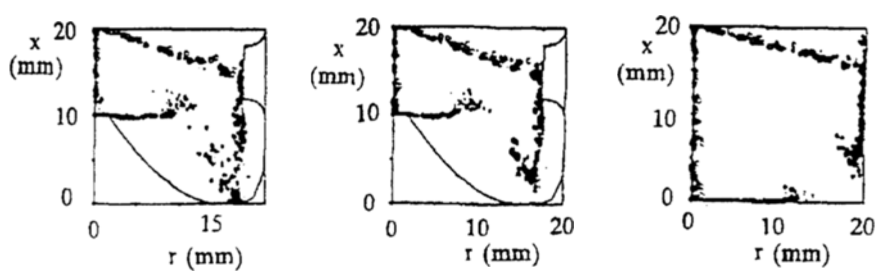
4. Results and Discussion

The Fig. 3 shows the comparisons of the spray development in sectional view. In the case of the new combustion system (N15) the five injection spray are impinged on the pips provided. The droplets impacted on the central pip spread out into the concave region of the spray impacted on the side pip which is placed at 5 mm higher than the position of the land of the central pip and at 15 mm from the axis of the central spray injection which is slightly wider than the distance 13 mm expected that the spray impacted on the centre pip reach until 1.0 msec. Also the end of the spray turns up and draws back by the gas flow back to the injection position, which does an important role to fill up the vacant space between the injection sprays in the middle of the chamber.

On the other hand the spray impinged on the side pips spread out into the bottom and fill the corner area. Its end gets diffused into the vacant space under the spray impacted on the centre pip. These are shown in the sectional view of spray development in Fig. 3. Thus the whole space of the combustion chamber is filled with spray.

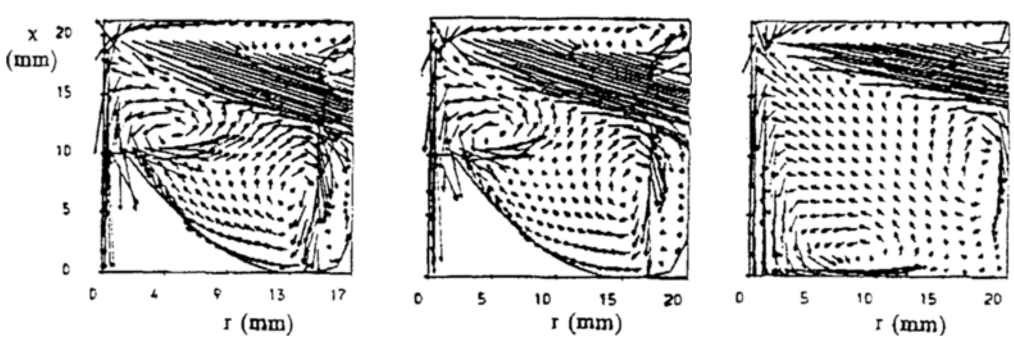
An other combustion system enlarged in radial direction (N17.5) has a similar tendency to the N15 case, but there are some unsatisfied regions because of the too wide position of the side pips.

In the case of no-pip (N20) the all injection sprays impinge on the wall directly and spread out just on the wall. Thus there is no spray at all



(a) Shaped chamber (N15) (b) Shaped chamber (N17.5) (c) Cylindrical shape (No-pip)

Fig. 3 Spray development at 1.0 msec after injection (Section AA)

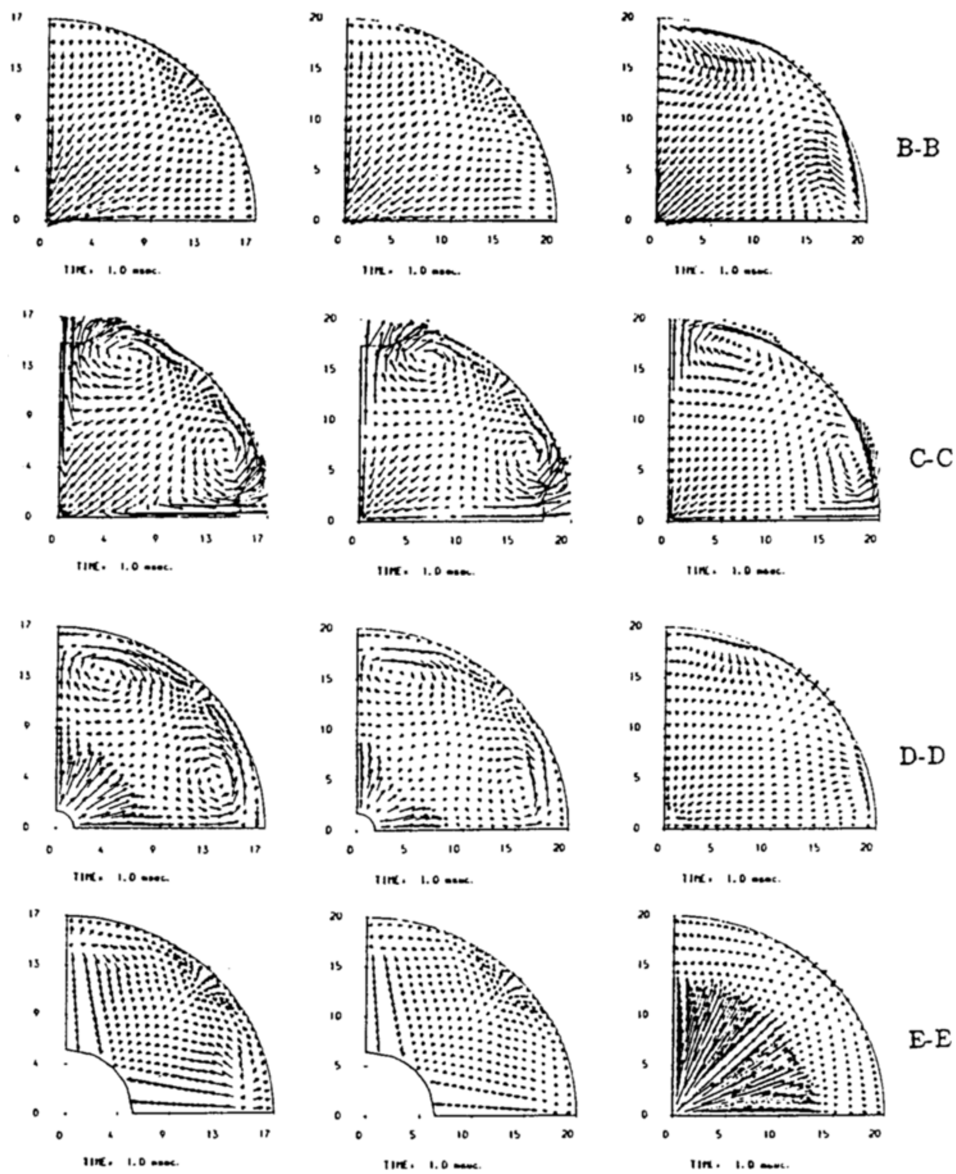


(a) Shaped chamber (N15) (b) Shaped chamber (N17.5) (c) Cylindrical shape (No-pip)

Fig. 4 Gas flow at 1.0 msec after injection (Section AA) in the middle of the chamber, which is quite different from the new shape of the combustion chamber.

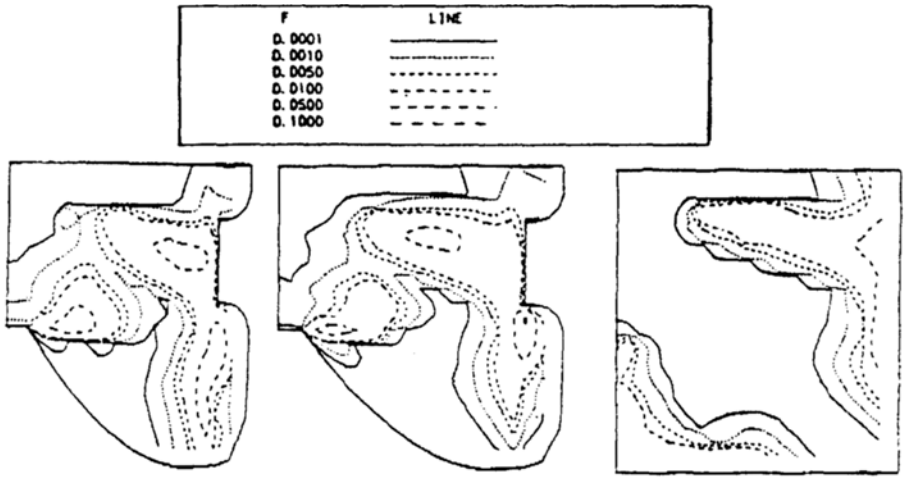
The gas flow fields are compared in the Figs. 4 and 5. The positions of the checking sections are shown in Fig. 2. In the case of new chamber system a number of swirls caused by the pips are shown in the figures, and those diffuse the sprays and fuel vapour in the whole region of the chamber. But the gas flow in the case of conventional simple cylindrical shape remains just near by wall surface. These flows show good agreements on the spray development.

As shown in the Figs. 6 and 7, the shapes of vapour contours have big differences between new systems (N15, N17.5) and conventional system (N20). It shows that most of the chamber in the new systems (N15, N17.5) is occupied by fuel



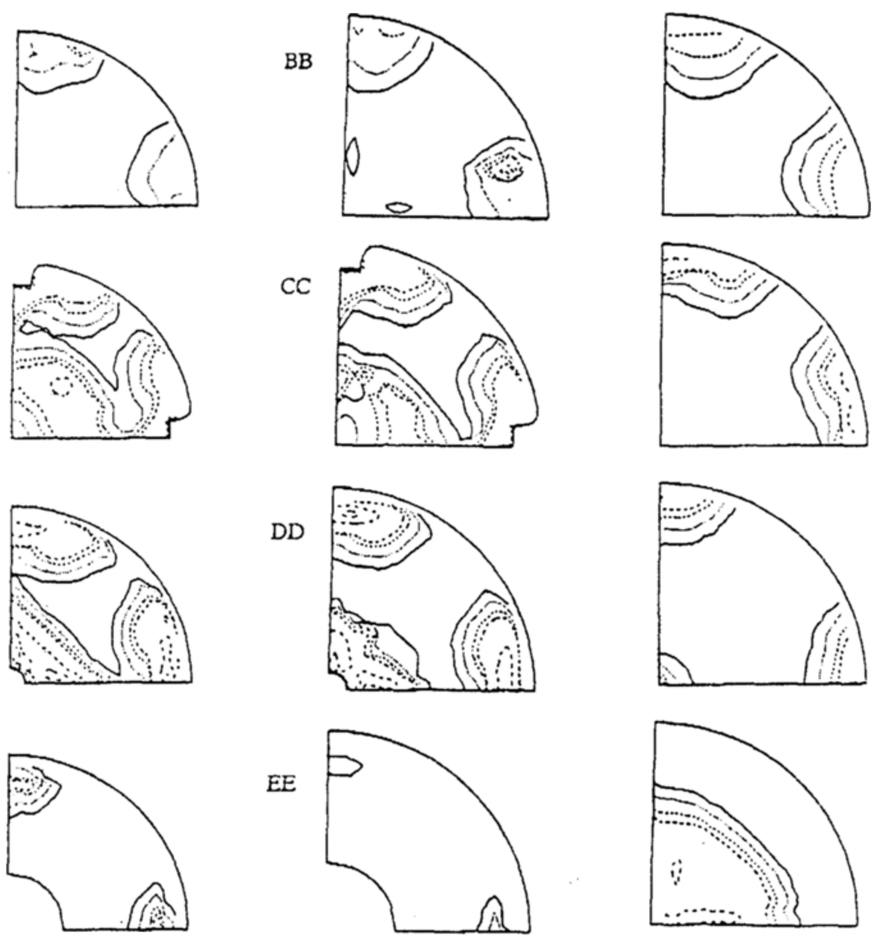
(a) Shaped chamber (N15) (b) Shaped chamber (N17.5) (c) Cylindrical shape (No-pip)

Fig. 5 Gas flow (Section BB, CC, DD, EE)



(a) Shaped chamber (N15) (b) Shaped chamber (N17.5) (c) Cylindrical shape (No-pip)

Fig. 6 Fuel vapour Contour at 1.0 msec after injection (Section AA)



(a) Shaped chamber (N15) (b) Shaped chamber (N17.5) (c) Cylindrical shape (No-pip)

Fig. 7 Fuel vapour contour (Section BB, CC, DD, EE) vapour but there is no fuel vapour in the middle of the conventional chamber without pip.

A fuel vapour contour is one of the most important factor for the combustion. The surface area and the volume occupied by the fuel vapour contours of six different values of fuel vapour mass fraction (FVMF) are compared each other.

To analyse the fuel vapour development in more detail, the calculation domain is divided into a number of horizontal section. And the surface rate is introduced for appropriate compar-

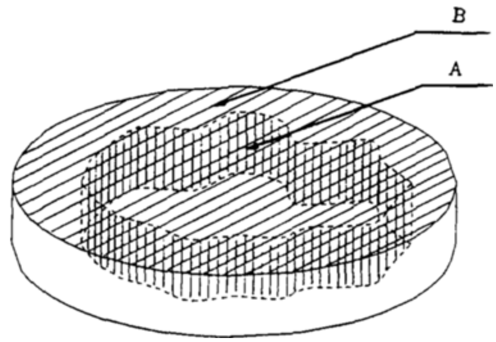


Fig. 8 Coefficients A and B

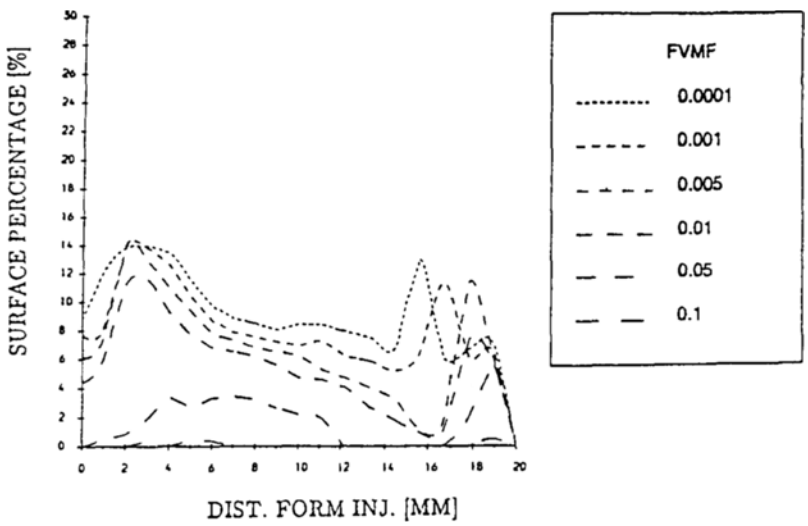


Fig. 9 Surface rate of fuel vapour (N15)

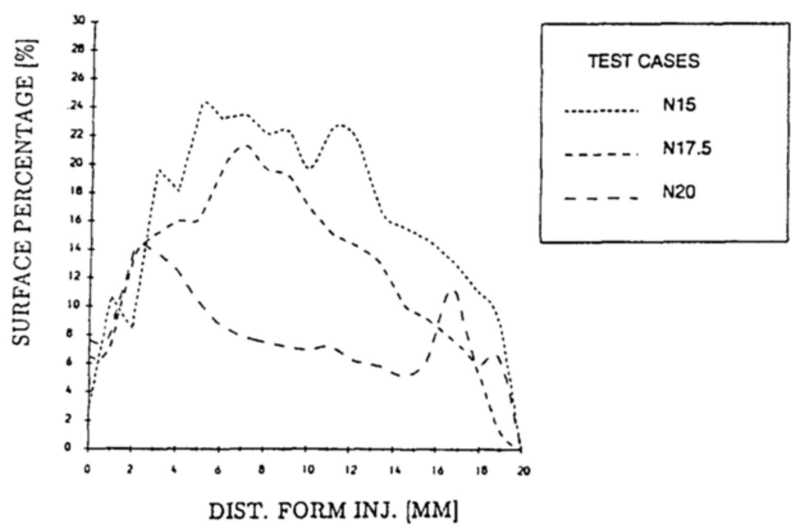


Fig. 10 Surface rate of fuel vapour (N17.5)

ison with the results of three different cases, which is defined by ;

$$SR = \frac{SA_{occupied}}{SEA} = \frac{A}{B} \tag{23}$$

Where SR, SA and SEA stand for the surface rate, the surface area and sectional area respectively, and the A, B are given in Fig. 8.

In the case of the new combustion system (N15) the whole chamber except near wall of the top and bottom is filled with fuel vapour, especially the middle of the chamber between the centre of the side pips and the land of the centre pip is filled so much as 24%, which is shown in Fig. 9.

In the enlarged case of the new combustion system (N17.5) the whole shape of the fuel vapour distribution is similar to that of N15 case, but the amount of surface rate is a little less, which is shown in Fig. 10.

On the other hand the no-pip case (N20) is very different from the others, the vapour development shape is reversed. A lot of vapour is distributed in the area close to the top and bottom wall surface, instead there is very rare or vacant in the large middle area which is filled with lots of fuel vapour in the cases of N15 and N17.5. Those are

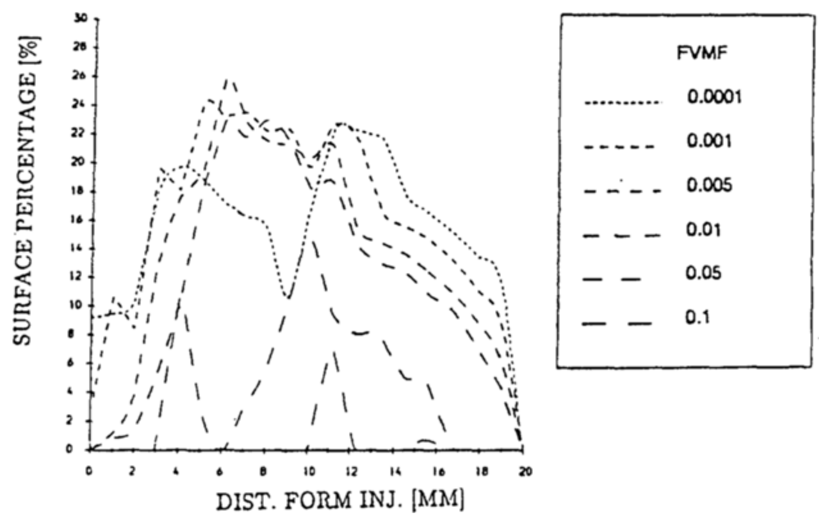


Fig. 11 Surface rate of fuel vapour (N20)

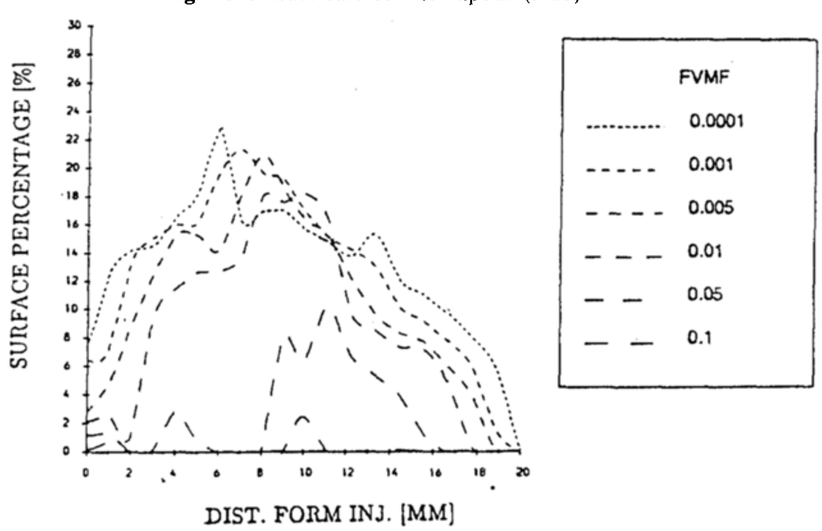


Fig. 12 Surface rate of fuel vapour at FVMF=0.001

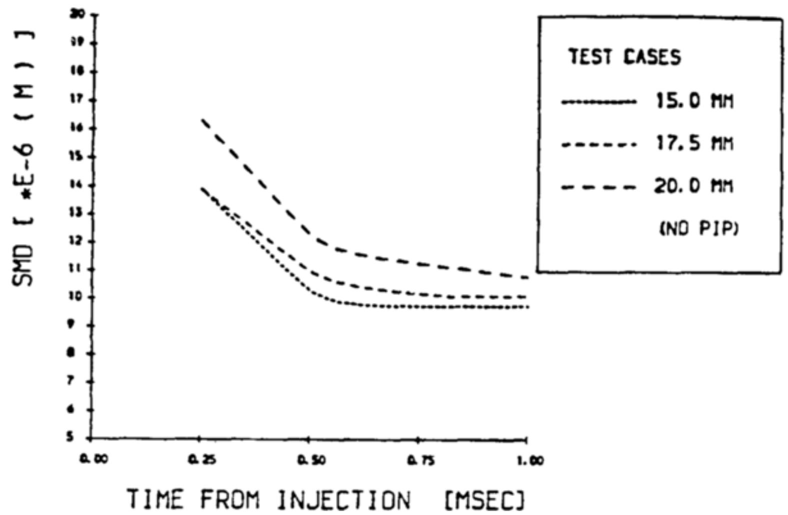


Fig. 13 SMD vs time from injection

shown in Fig. 11.

The Fig. 12 shows that the surface rate in the optimized shape (N15) is higher than that in the enlarged case (N17.5), also the rates of these two cases are much higher than that of the no-pip case (N20) at fuel vapour mass fraction=0.001.

As shown in Fig. 13, the size of SMD is reduced with the increasing of time from injection for all the three cases (N15, N17.5 and N20). In the case of the optimized system with more closed land for the impingement of the spray, the size is reduced rapidly and remains in lower level than that of N17.5 case. And the sizes in the two optimized shapes (N15, N17.5) are much smaller than in the no-pip case.

5. Conclusion

In this study, a novel direct injection combustion system is tested, in which cutoff pips are provided for a number of injection spray, directed not only straight down into the bowl centre but also across and down into the bowl in the normal radial direction. This geometry has been designed with suitably sized and positioned pips. The simulation results for the optimized geometry are compared with those for the slightly larger size chamber or the conventional simple cylindrical shape without any cutoff pip.

For the small engine which can not get away from the impingement of injection spray on the bowl wall, it is desirable using the spray wall impaction to avoid fuel deposition on the wall. Here the optimized combustion chamber system has been proposed, and it has a lot of benefit. The fuel vapour fills the new chamber much more than the conventional chamber with simple cylindrical shape. That means the new D.I. diesel combustion system looks much more like premixed gasoline engines. Therefore it may make the combustion efficiency better.

The two shaped chamber systems have much rather wide spray distributions and mixing with the air differently from the chamber without pips. However there is no significant differences between those two shaped chambers, that means the most important is not the distance of pips but the effect of spray impingement on a raised pip.

One of the important thing is the shape of the fuel spray and fuel vapour distribution which have developed a lot in the middle of the chamber not in the near wall area of the top and bottom of the chamber in the optimized combustion system. It is an appearance to the contrary with the conventional system, in which the fuel spray and fuel vapour have developed in the near wall area of the top and bottom of the chamber.

Thus for compact combustion involved spray wall impaction, a lot of soot problem is expected in the conventional combustion system without any pip by the spray sticked on the wall, however the optimized combustion system which the spray and vapour developed in the free space in the middle of chamber not near the wall may avoid the soot problem.

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