A Fundamental Study on Charge Stratification

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ABSTRACT

An experimental study has been conducted to obtain a fundamental understanding of stratified-charge combustion, which is regarded as a promising alternative concept for a spark ignition engine. To reproduce charge stratification, methane was injected into a constant-volume vessel corresponding to a real engine chamber at the top dead center. By using a hot-wire probe technique, temporal and spatial gas properties were measured throughout the vessel with special reference to fuel concentration fluctuation and velocity turbulence. Applying these properties to the combustion models proposed by some researchers, burning rates of stratified charges were estimated.

Results of ignition tests have shown that the stratified charge has a wider range of flammability than that of a homogeneous mixture at the same overall fuel concentration. It has been confirmed that the flame development observed by schlieren photography can be related to the concentration fluctuation and turbulence.

INTRODUCTION

For spark ignition engines, the use of lean-fuel mixtures has been regarded as an alternative concept that could improve thermal efficiency while reducing exhaust gas emissions. In recent years, much attention has been paid to stratified-charge combustion as a possible candidate for lean combustion. It is expected to be a very promising approach since it would allow a higher compression ratio and more flexibility for multifuel use due to its high anti-knock quality, and would require no intake throttle which causes pumping losses. For these reasons, various kinds of practical stratified-charge combustion systems have been investigated(1)~(3). These systems may be broadly divided into two categories: the divided chamber type and the direct-injection type.

This study has focused on a direct-injection stratified-charge combustion system because of its superior features. Although the divided chamber provides better fuel-air mixing by using a gas jet generated in the passage between the two chambers, it inevitably suffers from a reduction in work due to passage throttling and to heat losses across the prechamber wall. By contrast, the direct-injection type is much simpler in design, and yields better fuel economy without such losses. However, this type involves more difficulties in charge stratification, i.e. fuel-air mixture formation, and no principle seems to have been established for optimizing mixture formation and ignition parameters. Primarily for these reasons, such combustion systems have not come into practical use yet.

Thus, in this work, fundamental experiments were conducted to shed more light on mixture formation phenomena and to confirm the prospects for assuring ignition and fast burning in a stratified charge. In addition, the data obtained are also useful in understanding the phenomena in a direct-injection diesel engine which exhibits certain aspects similar to charge stratification.

As for direct-injection combustion systems, there are two fuel injection concepts in terms of injection timing: early injection and late injection. The former offers sufficient time to develop a stratified charge, and the charge is usually ignited after fuel injection. The latter concept offers some possibility for controlling combustion more precisely by means of fuel injection itself. However, both charge stratification and ignition are more difficult to effect, since spark ignition must be done during or immediately after fuel injection. In this study, therefore, the early injection concept has been examined, because it seemed the more feasible approach.

In association with mixture formation in a direct-injection system, the transient concentration and fluctuation of the fuel injected as well as the charge flow velocity and turbulence can play an important role in ignition and combustion. A constant-volume disc-type vessel was used to reproduce charge stratification and combustion in a real engine, and methane was injected as the fuel. The fuel concentration was measured by using a hot-wire sampling probe, and fluid velocity by hot-wire anemometry. From these measurements, time and space-resolved fuel-air mixing phenomena in the vessel were analyzed with special reference to concentration fluctuation and velocity turbulence. Using the data obtained, burning rates were estimated throughout the whole charge on the basis of the combustion models proposed by Spalding and others. Then, ignitability was examined over a range of stratified charges, and the flame development observed by means of high-speed schlieren photography was analyzed in relation to the fluid property measurements.

EXPERIMENTAL

Combustion Vessel and Fuel Injection

One of the most important problems in stratified-charge combustion is to determine the proper conditions for assuring ignition and fast burning in a confined space. To resolve this problem, a constant-volume vessel was used to reproduce charge stratification and combustion at the top dead center of a real engine. As is illustrated in Fig. 1, the vessel has a 115-mm diameter and a 28-mm depth. A flat quartz window is built into one side of the vessel to allow observation of ignition and flame propagation. The opposite side can be replaced with another window of the same type for schlieren photography.

Methane was chosen as the fuel to be directly injected in order to avoid any fuel evaporation effects which could complicate mixture formation. An electromagnetically actuated injection nozzle with a 3.0-mm-diameter needle was used to inject the fuel into the vessel. The orientation, pressure and duration of the fuel injection were changed independently so that different patterns of charge stratification could be obtained. In the present work, the overall equivalence ratio was set at 0.714 to allow comparison with a lean homogeneous mixture at the same ratio. To accomplish this, methane was injected into air with a 60 kPa pressure difference and a 10 ms duration.

Another electromagnetic valve was employed to provide air swirl in order to examine its effects on mixture formation and combustion. With this valve, higher pressure air was injected into the vessel, and 40 ms later a nearly solid body swirl was obtained for any injection pressure.

Thus, stratified fuel-air mixtures with and without swirl could be formed at 300kPa and room temperature.

Measurement of Instantaneous Fuel Concentration

Instantaneous fuel concentration in the vessel was measured by using a hot-wire probe. As is illustrated in Fig 2, the probe has an 80-um-diameter orifice at the tip and a 5-um-diameter tungsten wire downstream of the orifice. By means of this probe a local stratified charge was fully choked and extracted into a reservoir where the pressure was kept constant at a specified low level so that a sonic velocity could be achieved at the wire. A hot-wire anemometer system was used to detect the instantaneous voltage that had to be applied to maintain the temperature of the wire at a predetermined high level. As has been explained by Brown,(4) the anemometer output can be related only to the methane concentration which determines the heat transfer between the wire and the passing gas. Calibration was performed to obtain the relationship between the output and fuel concentration by sampling homogeneous gases with different methane-air ratios. This technique has a sufficiently fast response time to allow measurement of concentration fluctuations occurring in the experiment.

Fuel concentration was measured for various mixture conditions at twenty-five points in the vessel as shown in Fig. 1. Then, high-speed He-Ne laser schlieren photography using 16-mm film was carried out at 2400 frames/s to obtain a full view of the fuel-air mixing jet. Based on the concentration measurements and photographs, spatial and temporal distribution maps of the mean fuel concentration and fluctuation were drawn. Further, velocity measurements were made at the same points in the vessel by hot wire anemometry and distribution maps were drawn in the same manner.

Ignition and Combustion Tests

Ignition tests were performed at some of the twenty-five points in the vessel. Spark ignition location and timing were selected by referring to the concentration maps. A capacity discharge ignition system was used to ignite the charge with a 20 mJ spark energy. Ignitability was roughly determined by observing whether a flame developed or not for ten discharges at a fixed point. Combustion pressure was also monitored by a pressure transducer and flame development was observed by the schlieren photography mentioned above.

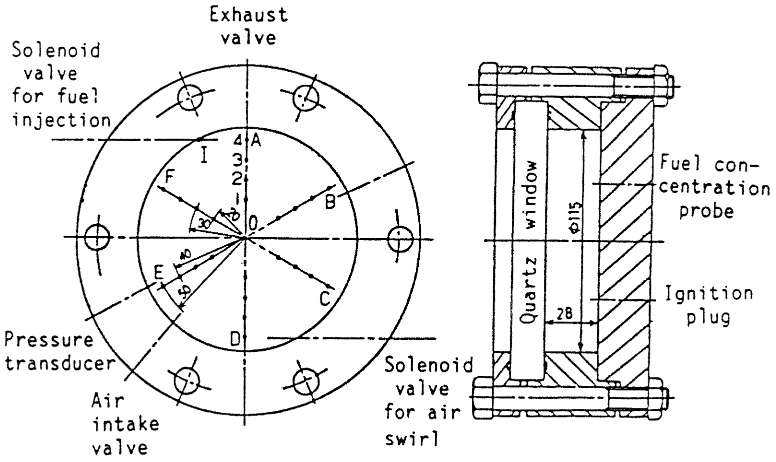


Fig. 1 Constant-volume vessel

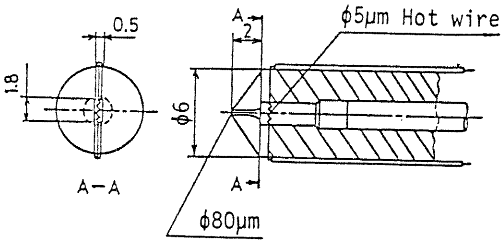


Fig. 2 Hot-wire probe

RESULTS AND DISCUSSION

Fuel Concentration and Fluctuation

In Figs. 3 and 5, time history maps are shown for mean fuel concentrations and fluctuations, respectively. In these cases, the fuel injection nozzle was oriented at an angle of 45 degrees to the normal line at point I in Fig. 1, and the effect of air swirl was examined. In drawing these maps, the following procedure was used. First, for the twenty-five measuring points, mean concentration values and fluctuations were calculated from the data obtained by the instantaneous measurements where the mean values were given by taking a moving average with an 8 ms interval, and the fluctuations were determined as root-mean-square deviations from the mean values. Then, spatial linear interpolations were done for two thousand points, using the data of the four nearest measuring points. For the points upstream of the fuel jet in particular, the boundaries with the air were determined by referring to the schlieren photographs which are capable of indicating differences in gas density.

Figure 4 shows sketches of the schlieren photographs taken under the same conditions. A comparison of Fig. 3 and 4 verifies that the method used for making fuel concentration measurements and interpolations in stratified

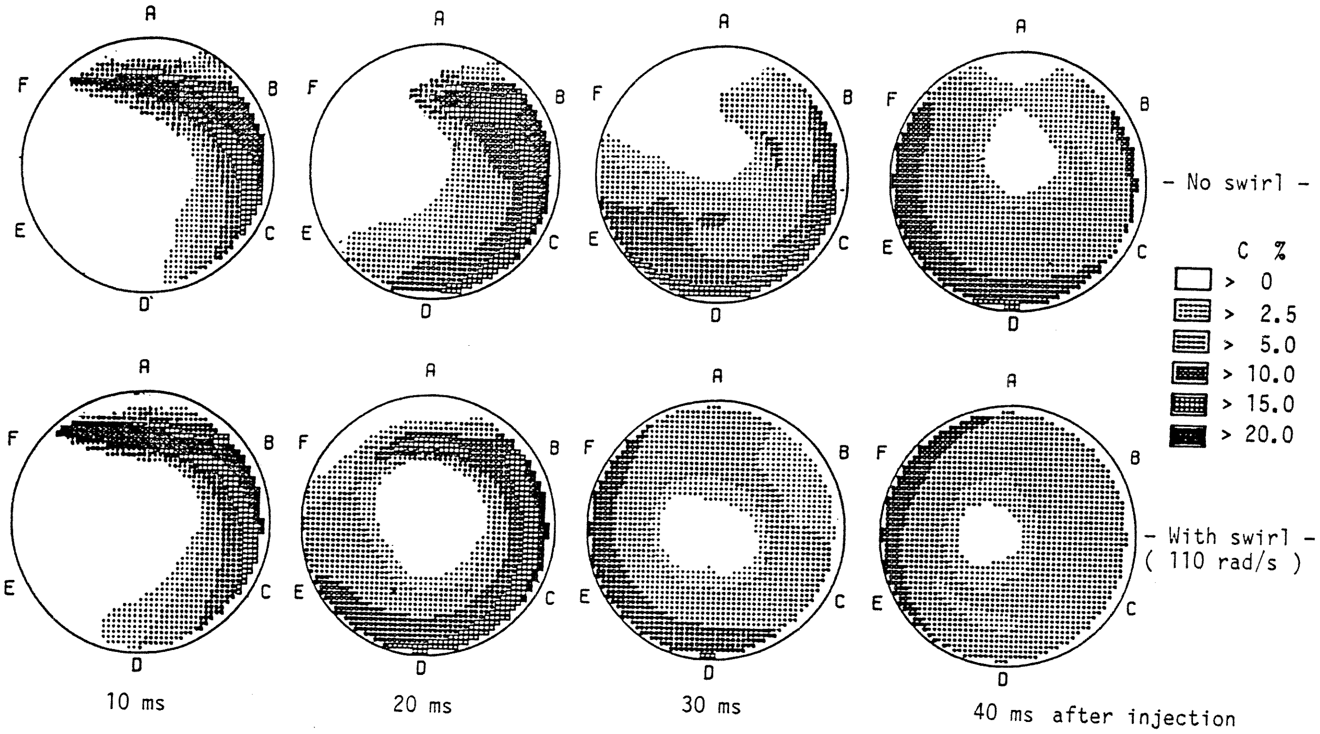


Fig. 3 Time history maps of mean fuel concentration for 45° injection

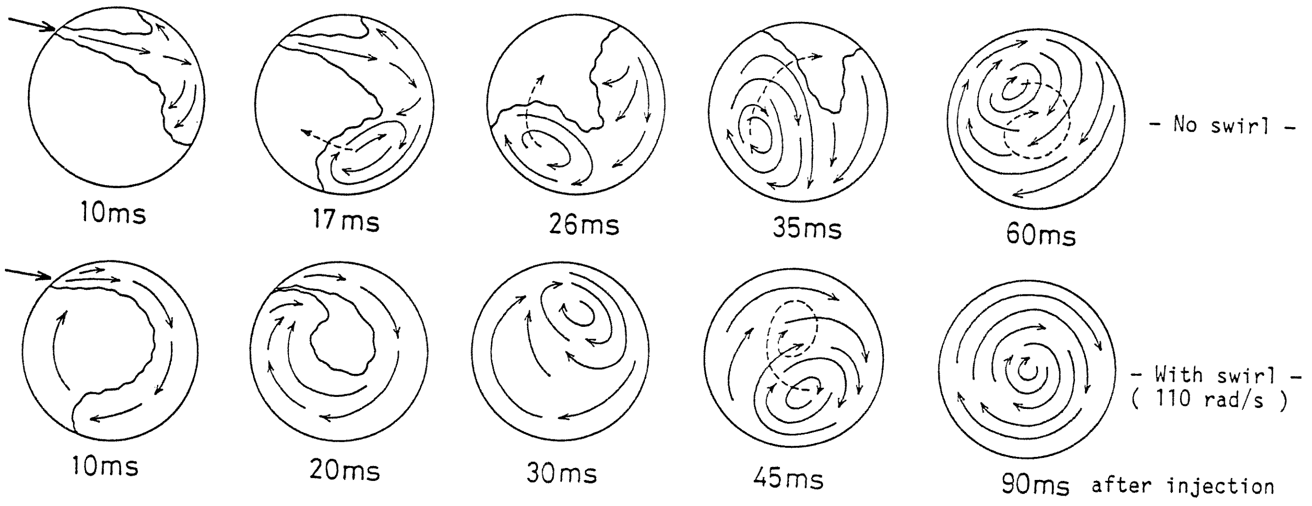


Fig. 4 Scketches of schlieren photographs for 45° injection

charges is valid. These figures indicate that while the jet of injected fuel travels along the chamber wall, fuel concentration is higher near the wall and that the concentration fluctuation is higher near the jet core. The fuel jet forms a swirling flow by its own momentum and the stratified charge tends to become homogeneous with time. Further, air swirl tends to enhance the fuel-air mixing process and leads to a more homogeneous mixture.

Figures 6 and 7 show maps for mean concentrations and fluctuations, respectively, at a 90-degree angle injection without any swirl and with an air swirl level of 110 rad/s. As can be

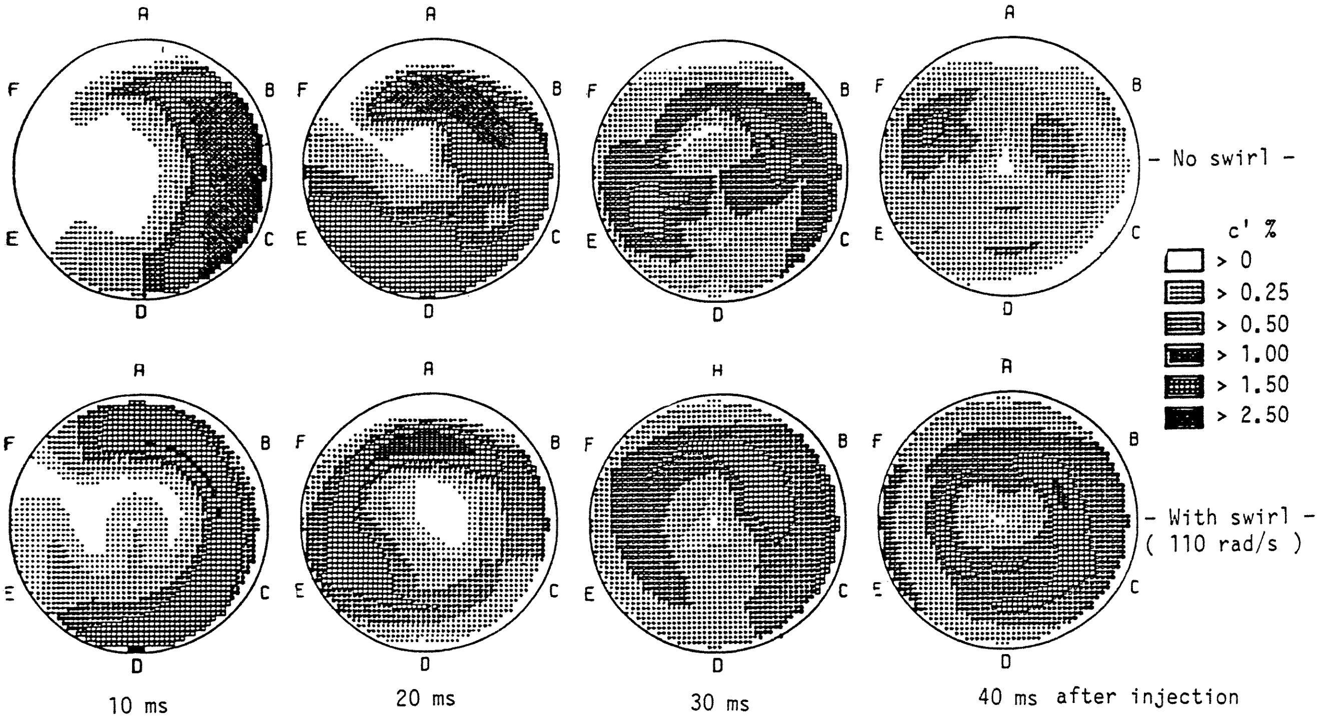


Fig. 5 Time history maps of concentration fluctuation for 45° injection

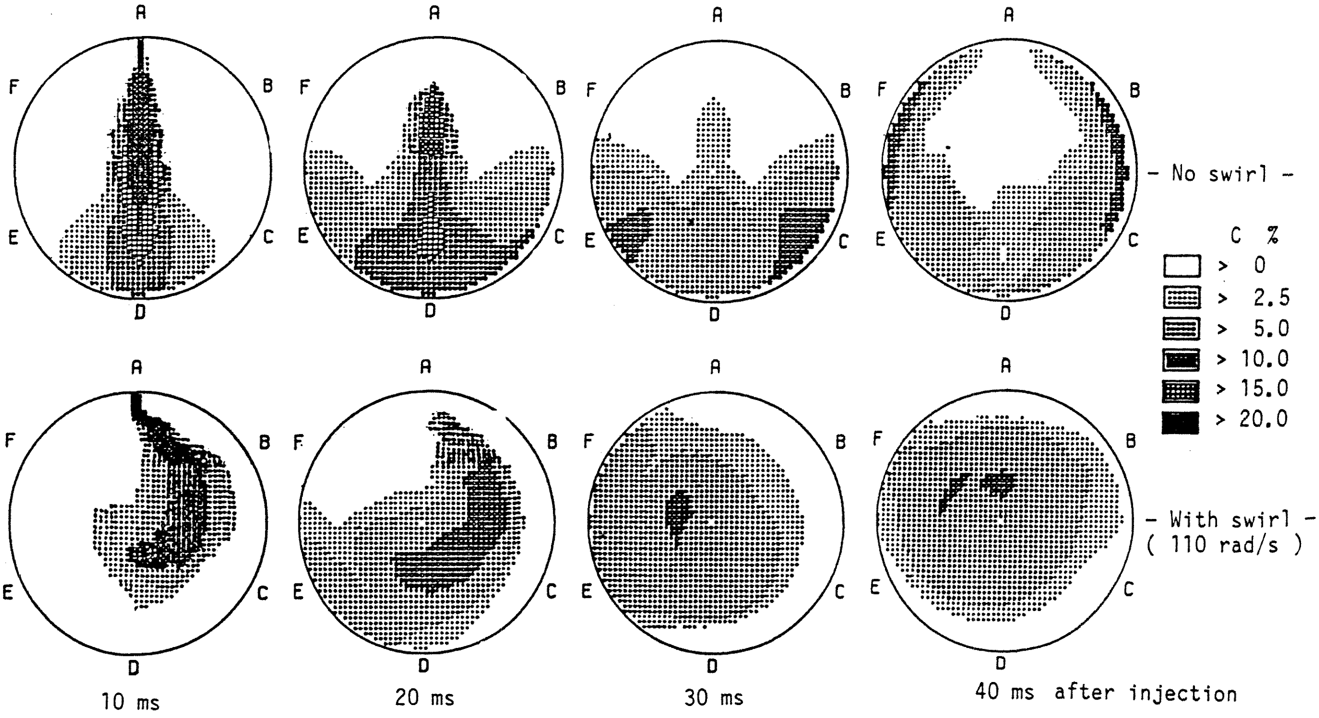


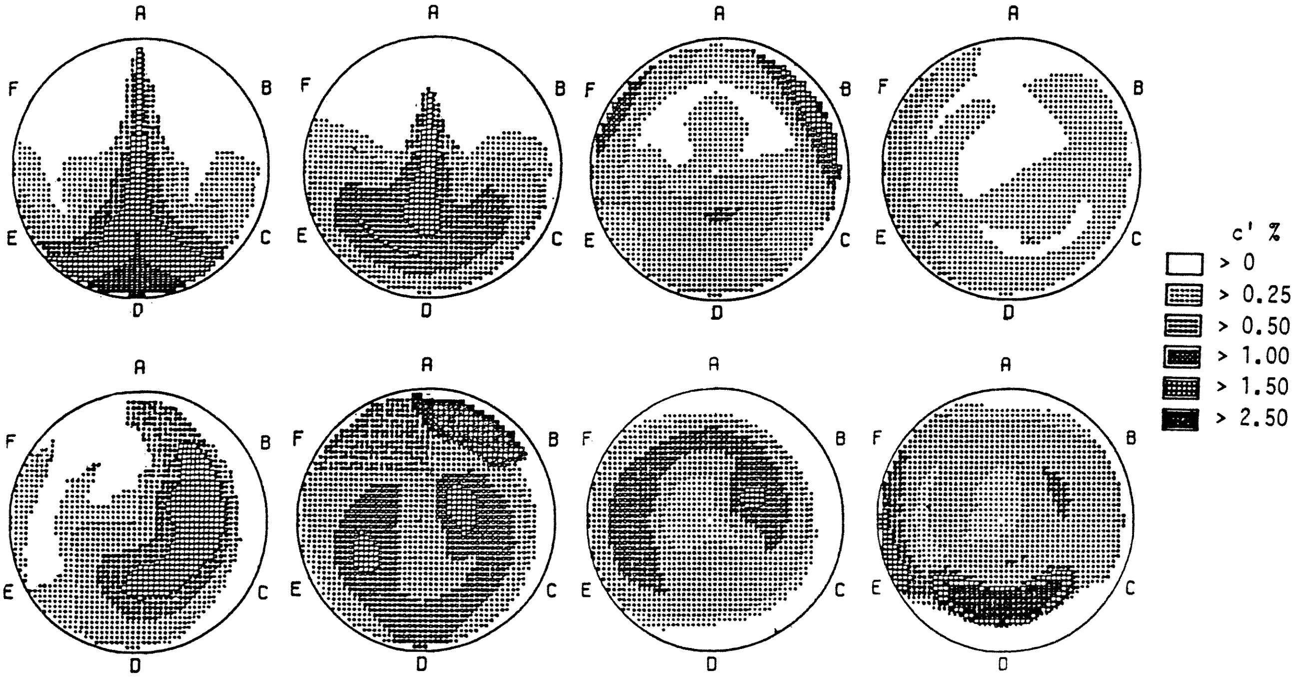
Fig. 6 Time history maps of mean fuel concentration for 90° injection

seen, air swirl deflects the trajectory of the fuel jet and prevents the jet from impinging against the wall.

In this study, the degree of charge stratification, Ds, was defined as the standard deviation from the stoichiometric fuel concentration in the whole charge and expressed as:

$$Ds = \sqrt{(1/n)\ \Sigma\ (Ci - Cs)^2} \qquad (1)$$

where Ci is the fuel concentration for each element of the charge, Cs is the stoichiometric fuel concentration, i.e. 9.5 % and n is the number of elements into which the charge is divided, i.e. 2000. This index was calculated for each condition of charge stratification and the results are shown in Fig. 8. Two nozzle orientations of 45° and 90° are compared in the figure in terms of the values of Ds with different air swirl levels. It is seen that the degree of charge stratification tends to decrease with time and that air swirl enhances the decline especially for the 90° injection nozzle. The 45° nozzle is seen to have a faster fuel-mixing



10 ms 20 ms 30 ms 40 ms after injection

Fig. 7 Time history maps of concentration fluctuation for 90° injection

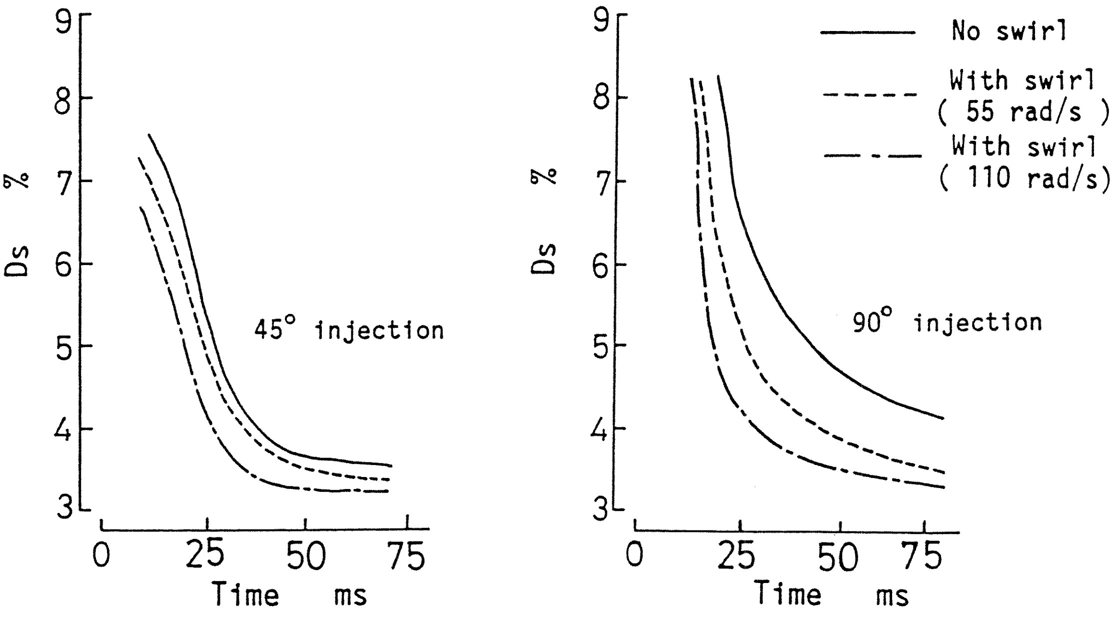
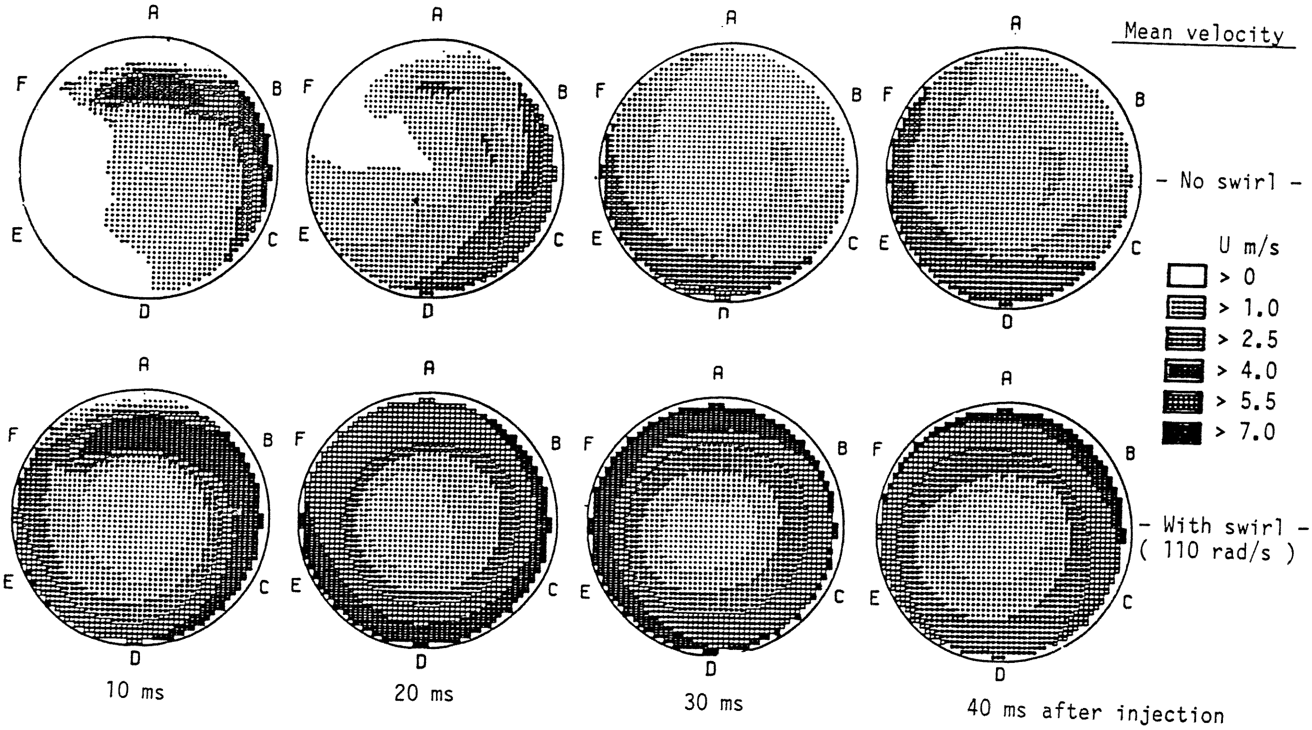


Fig. 8 Comparison of degrees of charge stratification

effect.

Flow Velocity and Turbulence

Figure 9 shows time history maps of the mean velociy and turbulence intensity for the 45_ nozzle with and without swirl. These maps were calculated with the same procedure used to obtain the mean fuel concentration and fluctuation. The fuel jet has a higher velocity and turbulence near the wall since there is less momentum exchange with the surrounding air. Referring to Figs. 5 and 9, it should be noted that the distributions of the fuel concentration fluctuation show some similarity with those of



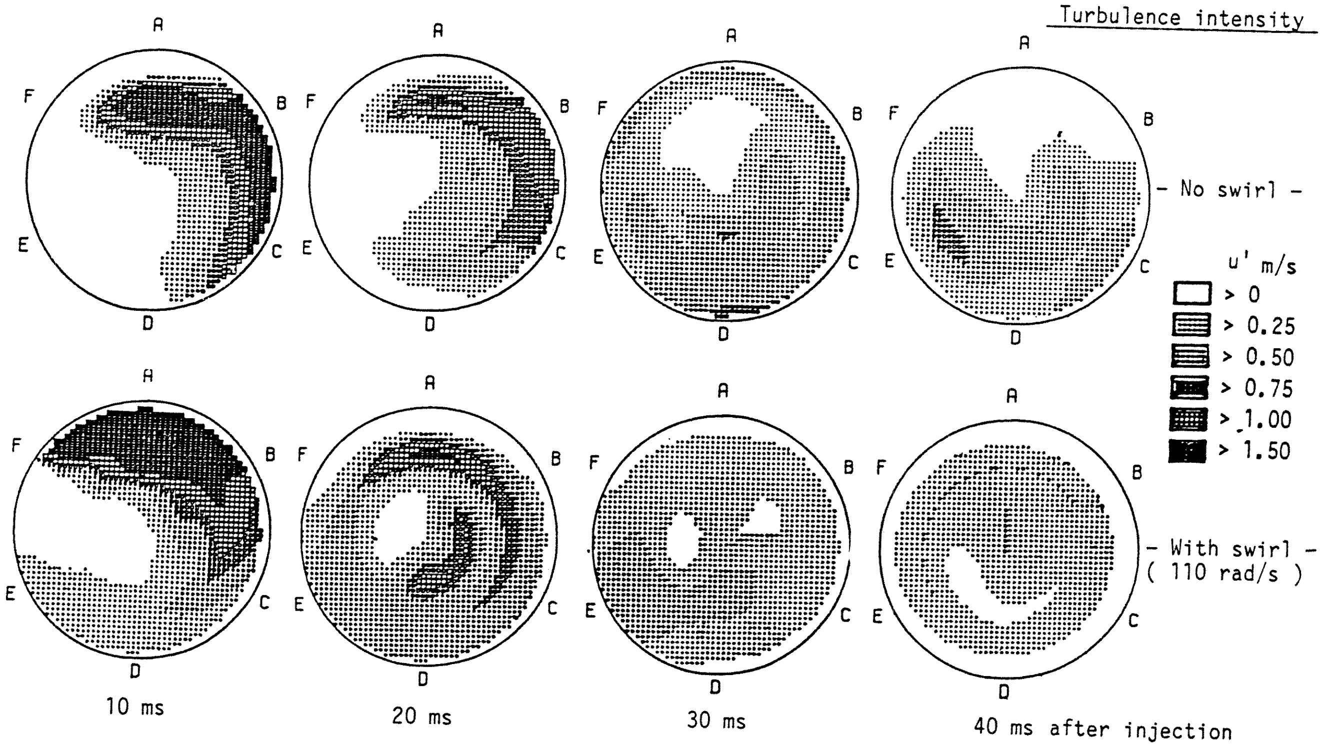


Fig. 9 Time history maps of mean velocity and turbulence intensity

turbulence intensity. As is also seen in these figures, a part of the surrounding air region has a certain velocity level, without any mixing with the fuel, due to the progressive force of the fuel jet. It should be noted that this phenomenon can appear only for a transient jet.

The effects of concentration fluctuation and velocity turbulence on combustion will be discussed later in reference to the combustion models proposed by other researchers.

Ignition and Combustion of the Charge

The results of ignitability tests are shown in Fig. 10, which illustrates the effects of mean fuel concentration, fluctuation and mean velocity measured at the spark location on charge ignitability. These data were collected from the various measuring points and ignition timings. As is seen, an excessive velocity of more than 7 m/s tends to reduce ignitability. A proper concentration fluctuation can improve ignitability especially in leaner mixtures and extend the flammability limits. This may be due to the fact that a fluctuating mixture can instantaneously come within the limits of ignitability during spark discharge even if its mean fuel concentration exceeds the limits. These results suggest that enhancements in spark energy and discharge duration will improve ignitability of a stratified charge. From the combustion pressure measurements, the burning rate or heat release rate was calculated for each condition of charge stratification. Figure 11 compares the burning rates for a 10 % fraction of fuel, which occurred around the spark location where the fuel concentration was measured. The figure indicates that the burning rate is higher at mixtures which are stoichiometric or richer at the mean concentration value. For these mixtures, a maximum burning rate is attained at a certain concentration fluctuation level.

Heat release rates calculated for typical conditions are shown with their fuel concentration maps in Fig 12. A greater heat release rate is obtained with air swirl. Its effect is more remarkable for the 90° injection nozzle due to the reduced wall impingement of the fuel jet. In the case of this nozzle without any swirl, the heat release pattern has two peaks which result from combustion lag occurring between two mixture clouds divided by the wall impingement. Such a pattern is improper for good thermal efficiency.

Exhaust NOx concentrations are compared for each injection nozzle with and without air swirl in Fig. 13, where the concentrations have been normalized by the NOx level measured for a quiescent homogeneous mixture with the same equivalence ratio, 0.714. It is clear that NOx emissions can be reduced by stratified-charge combustion with a specified degree of stratification. This effect is achieved by a relative reduction in quantity of slightly lean mixtures where much NOx forms. In the figure, scatters of NOx for a fixed condition of charge stratification are due to differences in the spark location.

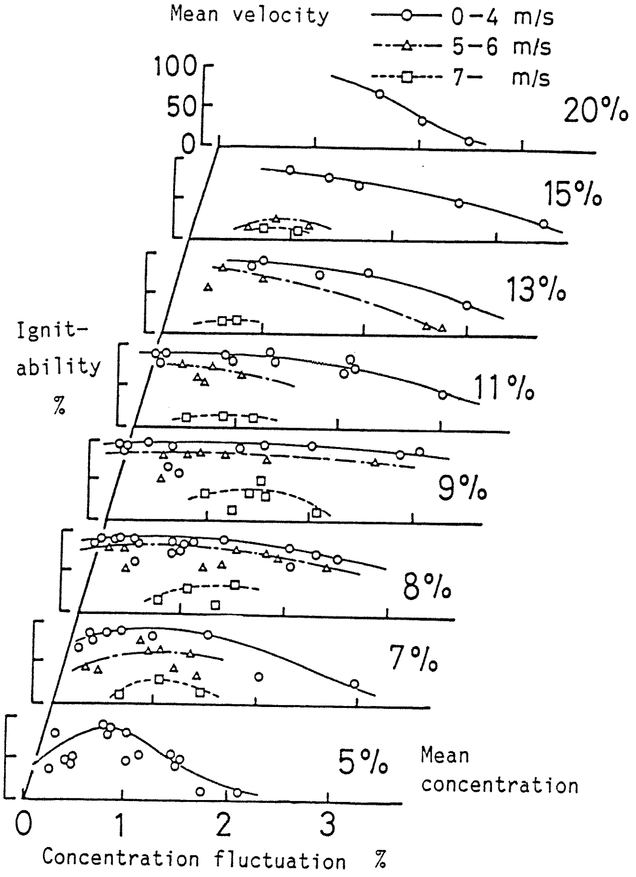


Fig. 10 Effects of mean fuel concentration fluctuation and mean velocity on ignitability

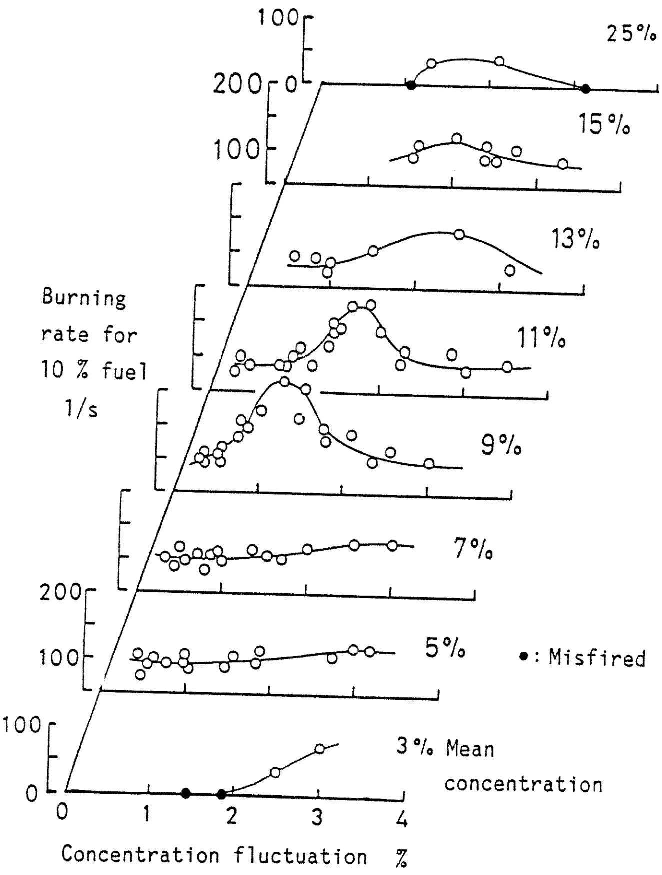


Fig. 11 Burning rates for 10 % fuel fraction burned

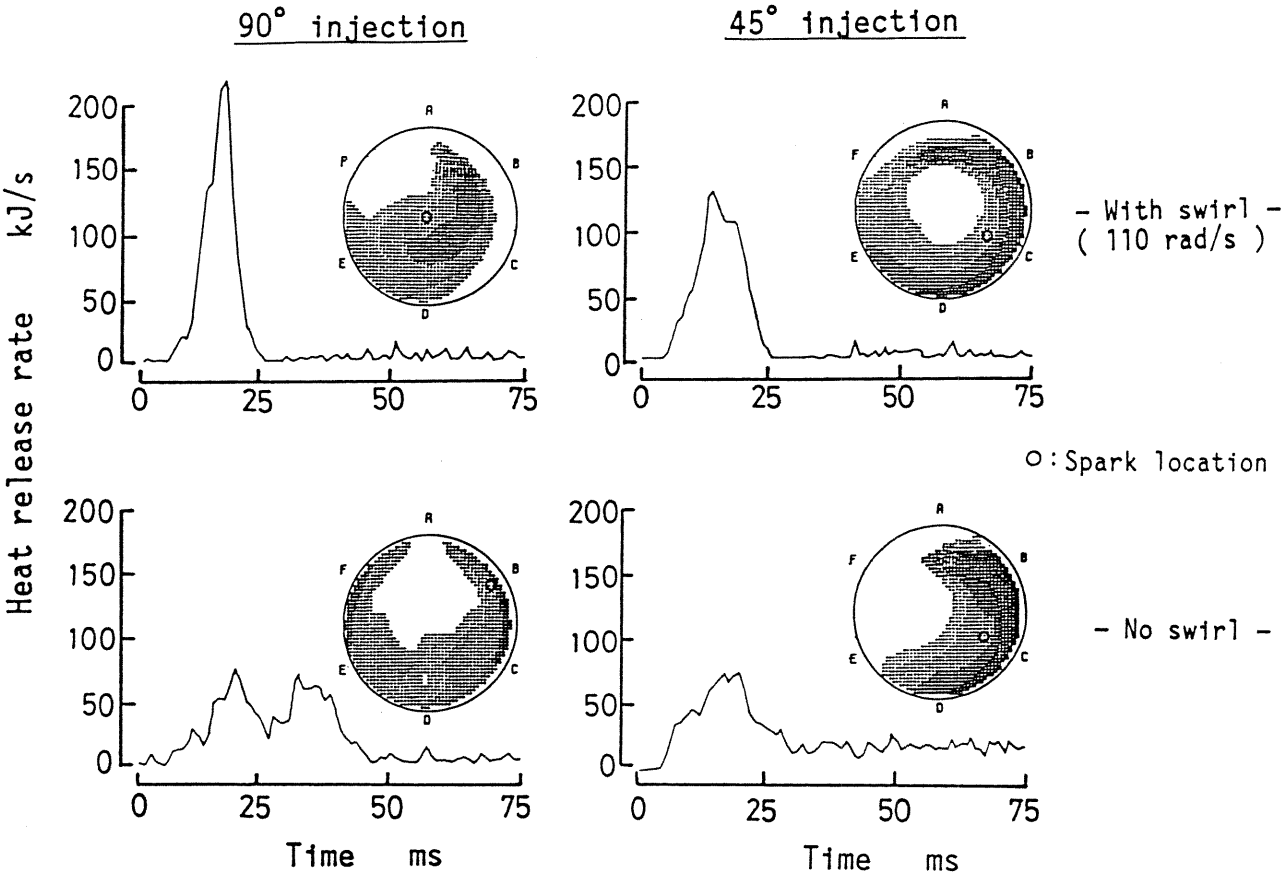


Fig. 12 Heat release rates calculated for typical conditions

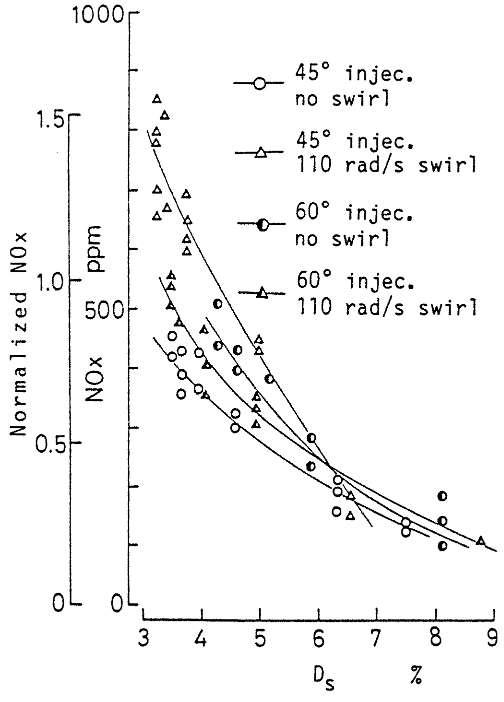


Fig. 13 Exhaust NOx concentrations measured for each condition

Flame Development Compared with Combustion Models

High-speed schlieren photographs were taken for ignition timing at 20 ms and 30 ms after the end of fuel injection and without any swirl. Sketches of the flame development were drawn from these photographs and are presented in Figs 14 and 15 together with the measured fuel concentrations at the ignition timings, combustion pressures and heat release rates calculated from them.

To elucidate the effects of charge stratification on charge combustion, burning rates have been estimated by using three combustion models for unburned local stratified charges in the vessel. The models employed are explained next.

Model 1 assumes that a flame propagates at a turbulent flame velocity of a homogeneous mixture having the same local fuel concentration. According to Karlovitz (5), the velocity, S_T, is expressed by:

$$S_T = u' + S_L \tag{2}$$

where S_L is a methane-air laminar flame velocity determined by the local methane concentration and u' is a turbulence intensity which extends the flame. The local values of S_L and u' are obtained from the measured conentration and velocity, respectively. Model 2 is based on the Eddy-break-up model proposed by Spalding et al (6),(7). In this model, the volumetric burning rate is in the form:

$$R = C_{ebu}\, c'\, \rho\, \varepsilon/k \tag{3}$$

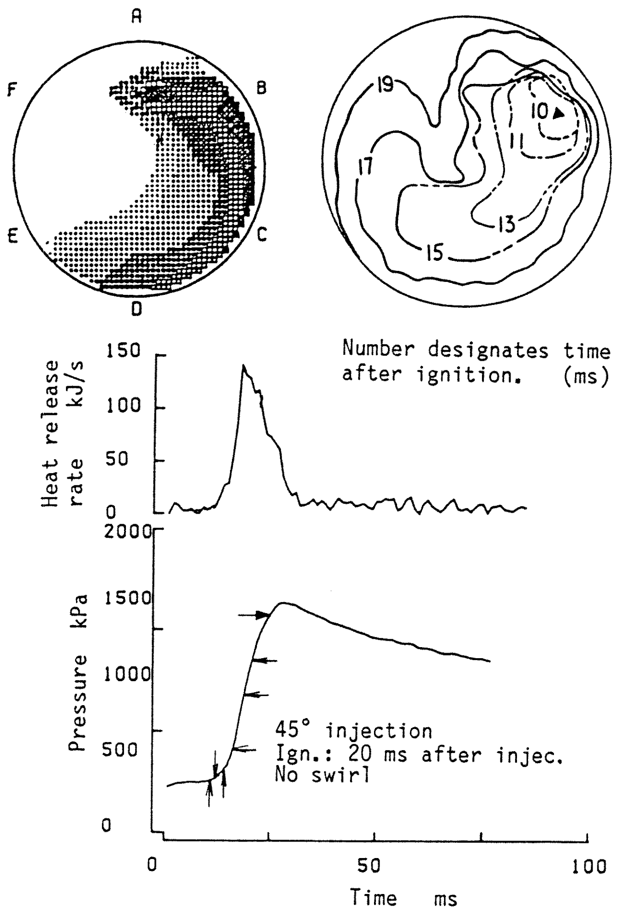


Fig. 14 Flame development for ignition timing 20 ms after injection

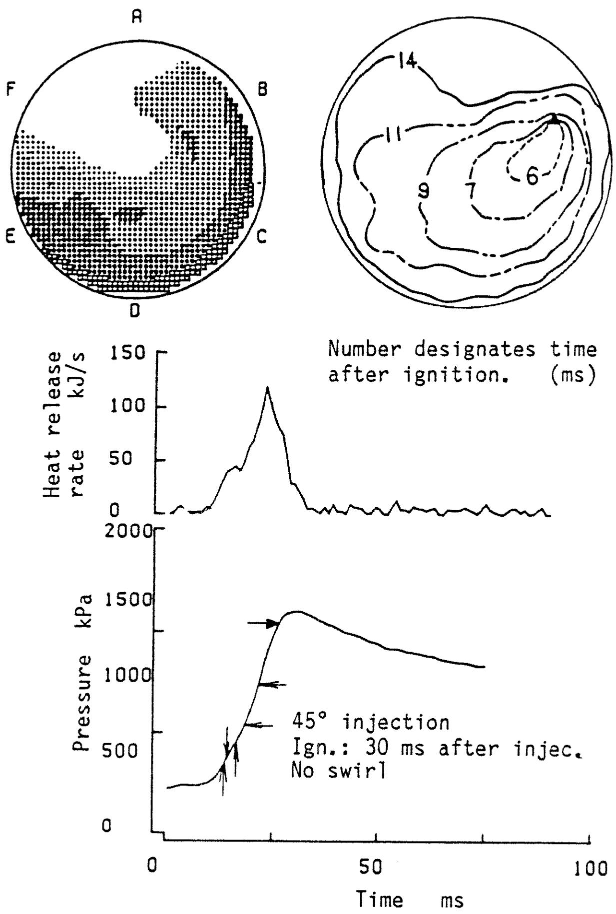


Fig. 15 Flame development for ignition timing 30 ms after injection

where Cebu is a constant, c' a fuel concentration fluctuation calculated by the root-mean-square method, ρ a gas density of the charge, k a turbulence energy and ε a dissipation rate of the turbulence energy. The values of k and ε are given by:

$$k = 3/2\, u'^2 \text{ and } \varepsilon = Ao\, u'^3/Lx \qquad (4), (5)$$

respectively, where Ao is a constant and Lx an integral length scale. All these values are determined from the measured instantaneous concentrations and velocities. This model postulates that the burning rate depends on the rate of break-up of the eddies by turbulent mixing. Model 3 is based on the overall reaction rate applicable to a homogeneous methane-air mixture and the rate is expressed by the Arrhenius type:

$$R = m_f\, m_a\, \rho^2 A \exp(-E/RTm)^{(8),(9)} \qquad (6)$$

where m_f and m_a are the mole fractions of fuel and air, respectively, ρ a gas density, $A=10\times10^{10}$ m³/kgs, E/R =1.84x10 K, and Tm = Tu+0.74x(Tb-Tu), where Tm is a mean temperature at the reaction zone, Tu an unburned gas temperature, and Tb an adiabatic temperature determined by the mean fuel concentration. The burning rate is assumed to be limited by the reaction rate in the flammable mixure with the fuel concentration which ranges from 5.0 to 15.0 %. Using these models, the flame velocities and burning rates were calculated for the same conditions of charge stratification in Figs. 14 and 15. The results are compared in Fig. 16. The results obtained with Models 1 and 2 are quite similar since the fuel concentration fluctuation shows similarity with turbulence as already mensioned. Allowing for the fact that the properties of unburned gases are somewhat changed by burned gases, these models correlate well with the observed flame development. This suggests that stratified-charge combustion is governed greatly by the turbulent fuel-air mixing process. However, Model 3 is not so useful for predicting stratified-charge combustion since it is only applicable to homogeneous mixture reaction. This model should be used in combination with some turbulent mixing model.

CONCLUSIONS

Direct-injection charge stratification was performed in a constant-volume vessel, and measurements were made in terms of the instantaneous local fuel concentration and flow velocity.

The procedure has been demonstrated to obtain space and time-resolved maps for the mean fuel concentration, concentration fluctuation, mean velocity and turbulence on the basis of the results of the instantaneous measurements. The

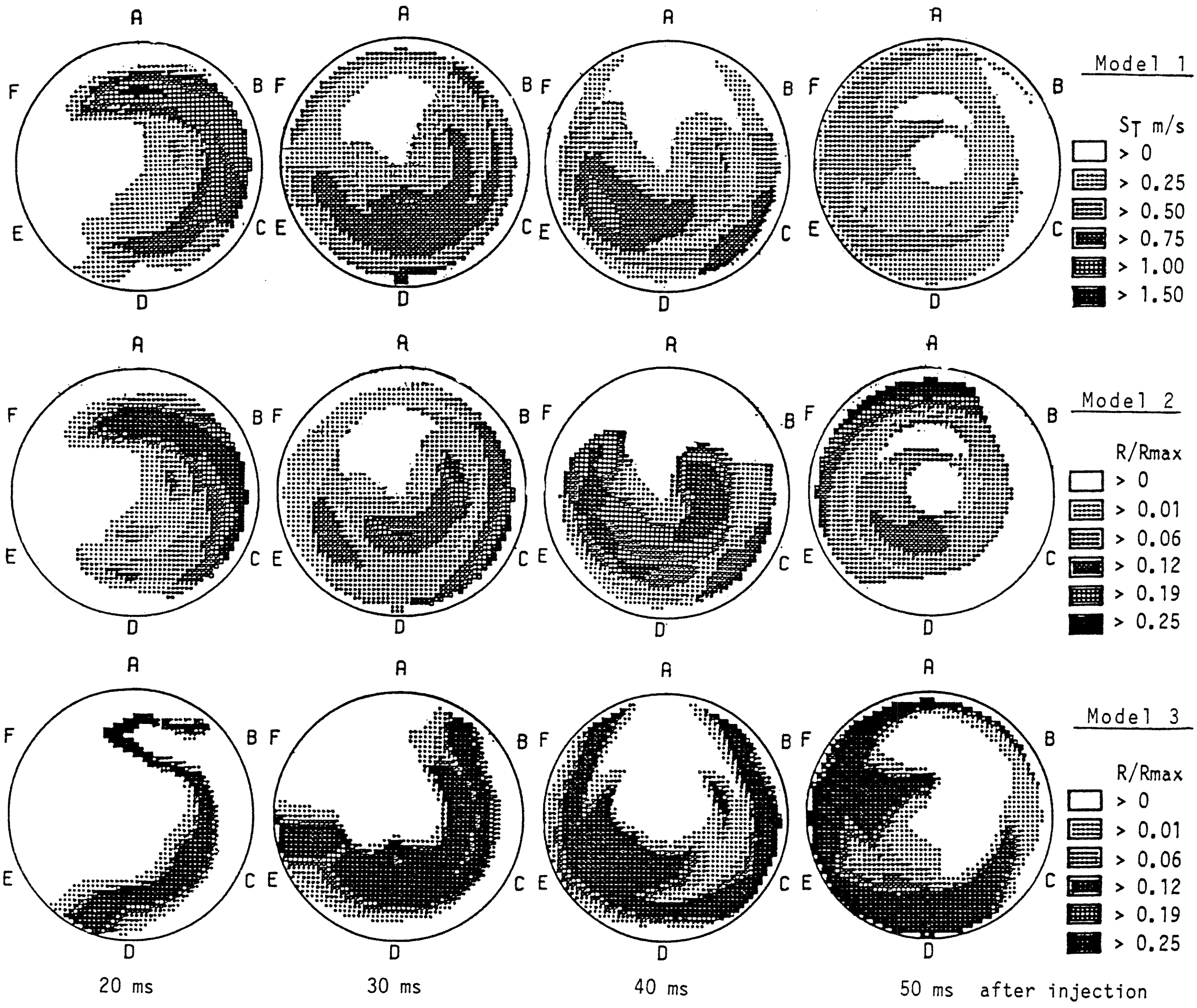


Fig. 16 Comparison of results calculated by three models

maps obtained show that an injected fuel jet induces high concentration fluctuation and velocity turbulence and that they decline with time in a similar manner, and make the charge more homogeneous.

Results of ignition tests indicate that a mixture with a proper fuel concentration fluctuation can be ignited even if its mean concentration exceeds the flammability limits. In a stratified charge, the concentration fluctuation shows similarity with turbulence and these two factors significantly govern the flame development process. This has been supported by high-speed schlieren photography as well as by the results obtained with the turbulent combustion models proposed by some researchers.

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