A Study on the Combustion Control in the Centrifugal Acceleration Environment by Means of Flame Initiation Process

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ABSTRACT

As a scheme for combustion control in a swirling flow of SI engine through flame growing process, the flame behavior which is actively controlled by the convective motion of flame, and the number of flame kernels, are examined in the solid vortex model, the combustion device which rotates with mixture in it. The serial flamelets can be initiated by the electronically controlled multiple spark system when a flame does not attached to the igniter.

From the analysis of the combustion pressure with the simultaneously observed high speed record of flame behaviors, it is noticed that the rate of pressure rise, which exhibits the rate of heat liberation is well controllable by altering the flame initiation timings and the swirl speed.

INTRODUCTION

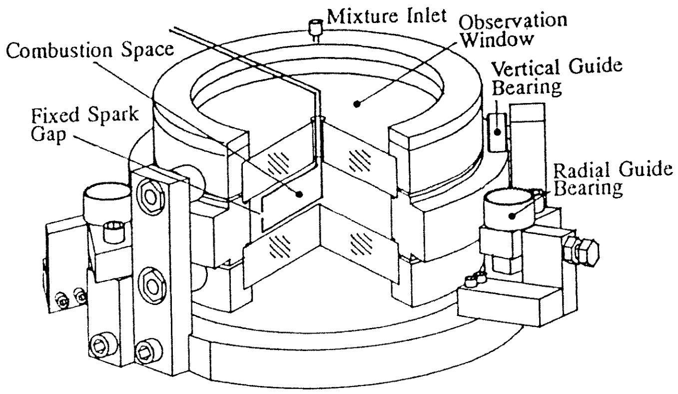
A swirl flow is often used for maintaining a turbulence and/or a momentum of the mixture in a combustion chamber of a spark ignition engine, and the effects on the combustion are usually related to the swirl ratio. Though the turbulence in a swirl is considered to be the real factor directly affecting the flame propagation(1), the swirl speed or the swirl ratio is also important for investigating the effects of a swirling flow velocity (including centrifugal acceleration) on the flame growth(2,3). The convective motion of a flame kernel in both a radial and a tangential direction, and the laminarisation(4,5) of turbulent flame may be the chief effects on the flame propagation. When a flame is initiated near the outer wall of the combustion chamber, the former effects improves the quenching of a flame area by keeping a flame away from the wall, but a rapid transfer of a flame body to the swirl center may cause the latter phenomenon. The laminarisation of turbulence(6) and of the turbulent flame area(4) result in the reduced burning rate. The flame which becomes symmetric with respect to the swirl center after reached the vessel center by the convective motion, suffers from the disturbed propagation(7,8) due to a shearing flow caused by a rapid thermal expansion of flame.

A combustion process in a SI engine is controlled through the mixture formation, the flame initiation process, and the heat release rate (flame propagation process), apart from the definite objectives of control. They are, however, so closely related each other that the separate evaluation cannot necessarily be made. A flame initiation can be made by 1)a conventional electric spark, 2)a flame torch (flame Jet), 3)a plasma jet ignition, etc. The latter two are intended to give not only the flame kernel initation but also the enhanced combustion by the hydrodynamic and the chemical effects. In the former case, a high energy spark, a multi-plug ignition(9,10), etc. have been examined. The multiple flames enhance the heat liberation in the combustion chamber through a reduced combustion time. On the other hand, it may result in the increase of NOx, unless a suitable scheme for equalizing(10) the heat liberation throughout the combustion period is introduced. At the same time, a scheme for reducing a contact area between the burned part and the chamber wall should be taken into consideration in order to reduce a heat loss. Thus the position of flame initiation, the number of flame kernels, and the swirl flow in the combustion chamber are the factors for controlling combustion. In the present study, a scheme for combustion control through flame growing process which is actively controlled by the convective motion of flame and the number of flame kernels, is examined.

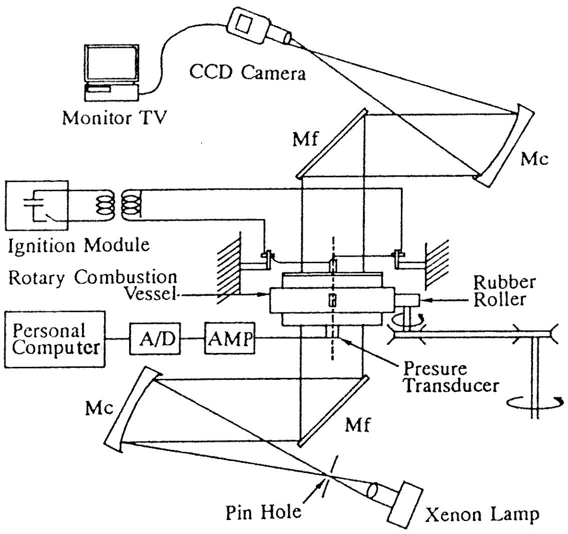
Several flames are successively initiated at a fixed ignition plug by carrying away the flame kernel with swirling flow. The influence of flame initiation intervals and of the swirl speed are chiefly examined. In the present paper, the results obtained from the experiment in a solid vortex are wraped up as the preparation study for the practical applications.

EXPERIMENTAL APPARATUS

To form a solid vortex in a combustible mixture, the rotary combustion chamber made up of a cylindrical vessel of disk type with 200mm in diameter, 35mm in height, which rotates arround its vertical axis with a mixture in it, is used. A schematic view of the chamber is shown in Fig.1-a. For initiating the plural flame kernels, the spark electrodes are fixed in a laboratry cordinate system as shown in (b). The pressure measurements in the rotating chamber is made



(a) Rotary Combustion Chamber



(b)General View

Fig.1 Schematic of Experimental System

using a rotary coupler which tightly connects the pressure transducer to the vessel. The analog signal from the transducer is coverted through A/D converter with the accuracy of 12bits to the digital signal, which is processed by the personal computer. Fig.1-b also shows the optical observation system. A shadow image of growing flame is recorded in the picture memory of 256X256 dot/ frame by the high speed CCD camera with the shutter speed of 1/10000 sec.

Since a spark gap rotates relative to the vessel, the terminals of the electrodes are pulled out of the rotating center of the observation window. The spark gap is located at a distance of 17.5mm apart from the outer wall and on the middle way between the obserbation windows. Fig.2 shows the schematic electrical circuit of the multi-spark ignition module. An electric pulse, P_k turns on the DC power supply, and then capacitances C_1, C_2, $\cdots\cdot$ are charged in a moment. After cutting off of the power supply, a row of serial pulses P_1, P_2, $\cdots\cdot$, the timings of which are programed on the CPU (6803) for the system controller, successively turns on the switching modules S_1,S_2, $\cdots\cdot$. The switching module is constituted of TRIAC thyrister driven by the transistor coupled with a photo signal coupler.

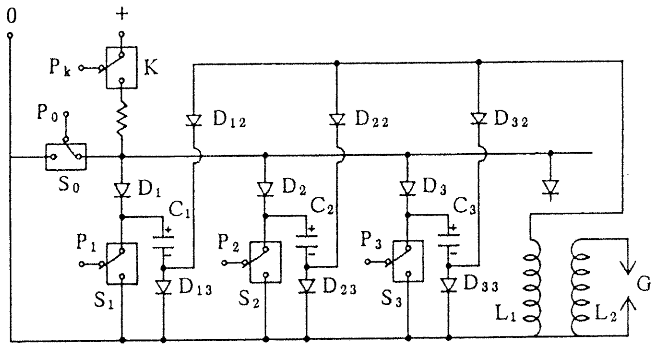


Fig.2 Multi-Spark Circuit

In the present experiment, for the objective of using natural gas in SI engine, the methane-air mixture with equivalance ratio, ϕ = 0.6, is used.

EXPERIMENTAL RESULTS

A flame initiated in a solid vortex at the off-centered position, moves with growing in a kernel size toward the vortex center. In the case of the electrodes fixed relative to the mixture, or rotaing with mixture, a relatively low turbulent flame moves to the vessel center to form an axisymmetric flame, which suffers from disturbed propagation (7,8) due to the shear flow caused arround the flame body by the rapid flame expansion. Even when ignited by the plasma jet(8) which makes turbulent kernel, it also appears. In the case of the 2 symmetrical kernels(7), it appears after growing together as well as the single flame case (see Fig.3). Therefore the appearance of the symmrtrical flame(symmetric about a center axis of the swirling flow, hereafter, designated as center-symmetrical flame) in the early propagation stage should be avoided. The results obtained by the experiment with two successive flames which are initiated from one spark gap fixed to the laboratory system, are discussed below.

Fig.4 shows the typical behaviors of the intermittently initiated flames for different rotation speed of the vessel. In the case of a short spark interval ($\Delta\tau$ ms) and a low rotation speed(ω rad/s), a single flame, though extended a little by double kernels, is formed without separation.

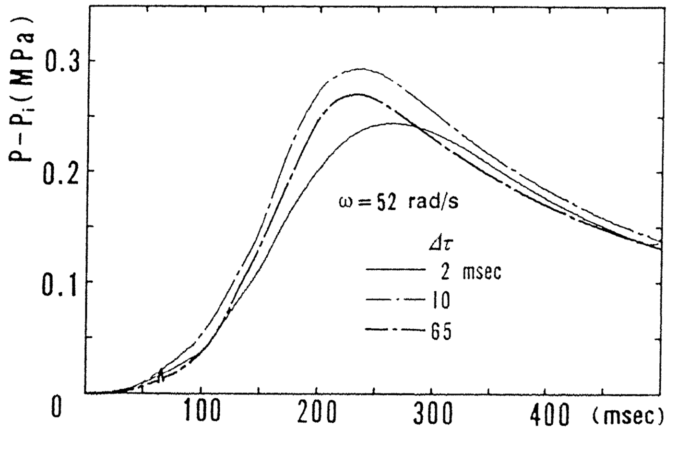
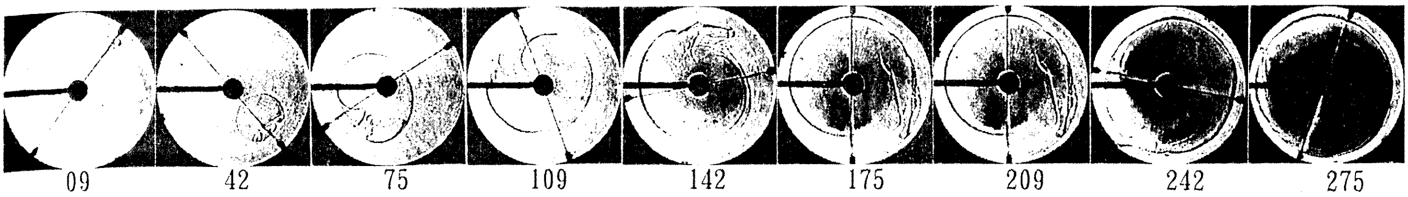
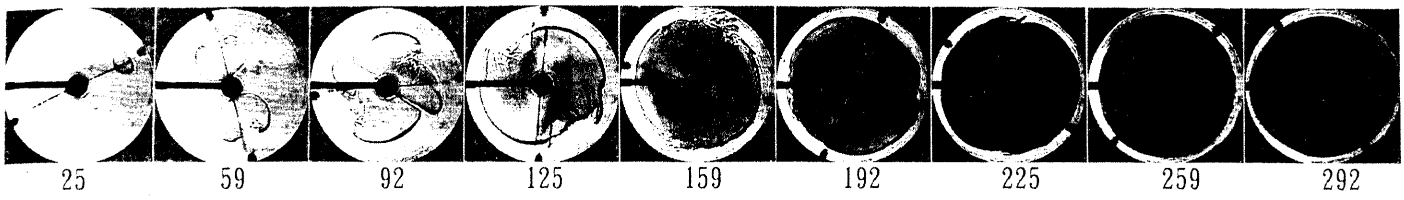


Fig.5 Change of Combustion Pressure with Spark Intervals

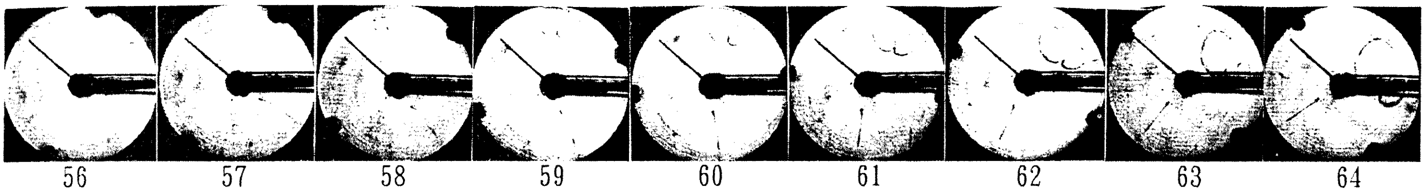


(a) Off-centered Flame ($\omega = 52$ rad/s)

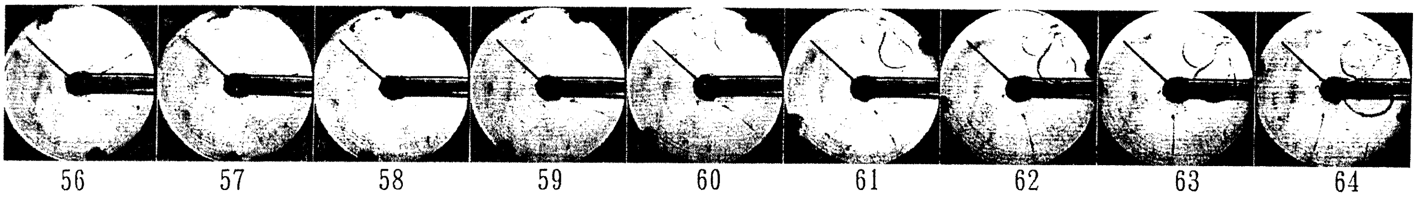


(b) 2 Symmetrical Off-centered Flames($\omega = 52$ rad/s)

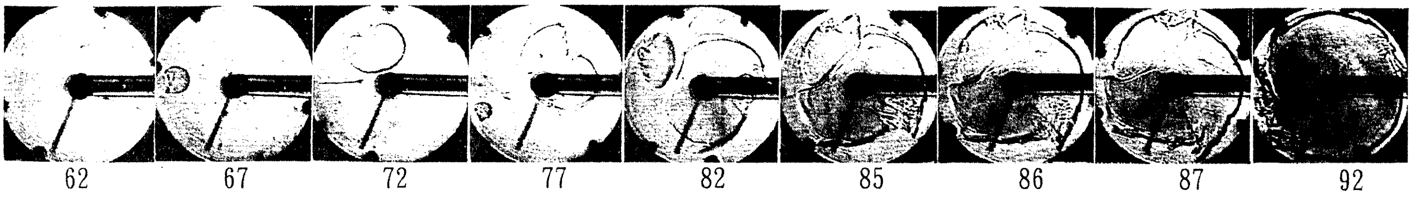
Fig.3 Behaviors of Flames initiated by the Rotating Electrodes
(Numbers indicate the time after ignition in msec)



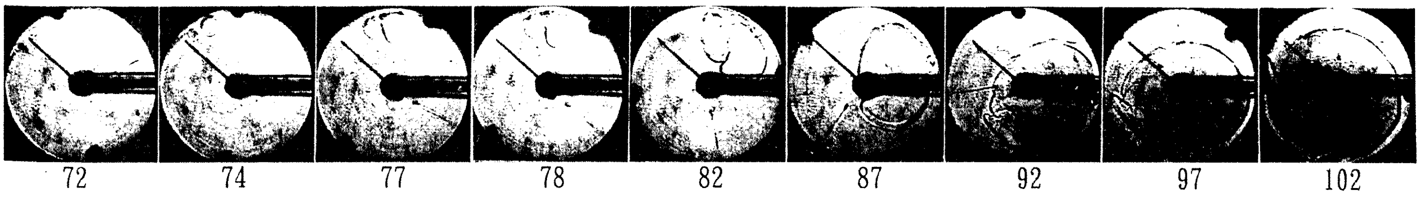
(a) ω = 52 rad/s, $\Delta\tau$ = 2ms



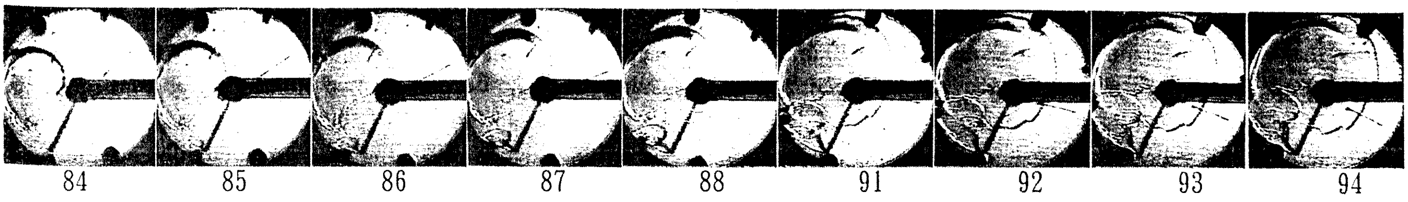
(b) ω = 52 rad/s, $\Delta\tau$ = 10ms



(c) ω = 52 rad/s, $\Delta\tau$ = 65ms

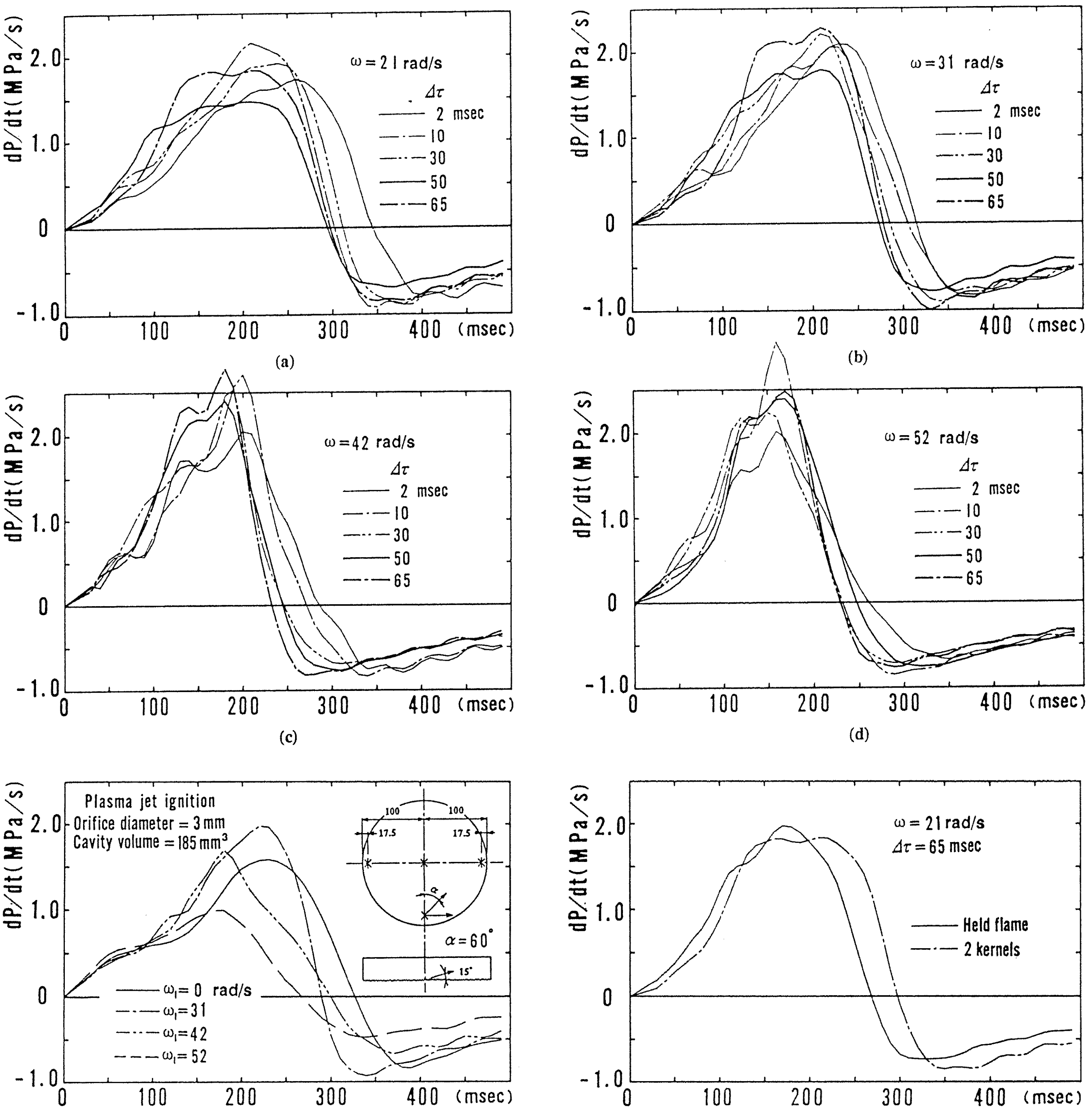


(d) ω = 31 rad/s, $\Delta\tau$ = 10ms



(e) ω = 21 rad/s, $\Delta\tau$ = 65ms

Fig.4 Behaviors of Flames Initiated by Double Sparks
(Number indicates the picture frame counted after arbitrary trigger start, time between neighboring frames: 5.38 ms)



(a) (b) (c) (d) (e) (f)

Fig.6 Rate of Pressure Rise For Various Flames

Since the separation of flames is not sufficient for the short intervals of $\Delta\tau$ = 2ms, even when ω = 52 rad/s(see Fig.4-a), the maximum combustion pressure seems to be low as shown in Fig.5, because the early unification of flame can easily make a center-symmethical flame and the flame may suffer from the disturbed propagation as described above. On the other hand, too large separation also causes the delayed combustion since the growth of the second flame may be suppressed by the fully developed first flame, and different merging process of flames may make a center-symmetrical flame(cf Fig.4-c). The highest maximum pressure can be obtained at a certain interval of $\Delta\tau$. Comparing Fig.4-b with 4-d, a difference in the flame separation and in the distance of flame element from the wall can be noticed. The difference in the flame separtion is not so large that the (dp/dt) in the early stage of flame growth little differs from another.However, the effect of the wall contact soon appears to change the rate before the two flames merge into one.Thus, it contributes to holding of flame area to keep a flame away from the outer wall by the convective motion in the radial direction.

A rate of pressure rise, (dp/dt), calculated from the observed combustion pressure for various experimental conditions is summarized in Fig.6. The experimetal results, shown in the figure, are the average of more than five measurements. Therefore, each progress cannot always coinside with the corresponding photograph. With increase of ω , or a convection speed, the (dp/dt)-curve exhibits the steeper gradient as seen from the figure. By comparing the curves with the photographs of the flame behaviors, it is noticed that a rapid reduction in flame area when two flames merge into one, makes the local peak in the(dp/dt)-curve. The first bulge of the curve roughly corresponds to the timing of the flame unification. The reduction in the (d^2p/dt^2) also appears when a flame element is quenched by the wall. These behaviors changes depending on $\Delta\tau$ and ω . In the case, ω = 21rad/s, for example, (dp/dt) exhibits a low and flat progress when $\Delta\tau$ = 50ms. But with increase of ω (ω = 41,52), (dp/dt) in the later stage gradually becomes steep. Depending on the flame initiation timing, the higher value of (dp/dt) in the early stage can be obtained.

Comparing the effect of $\Delta\tau$ for the case of ω = 52rad/s, the following facts are observed. When $\Delta\tau$ = 2ms, two kernels quickly grows together, and the combustion rate after unification shows the lowest rate. Though the fast combustion is attained for $\Delta\tau$ = 10ms, the rate is again lowered when $\Delta\tau$ = 65ms. These behaviors may be understood by considering the disturbed propagation of the center-symmetrical flame and the growth of 2nd flame as discussed above.

DISCUSSIONS

For the more detailed analysis of the change in the (dp/dt)-curve, the change of the mean flame area is estimated from the observed photograph of flame whose pressure record approximately coincides with the averaged curve. The shadow image on the photogrph indicates the outer edge of flame front projected on the observation plane. In the present analysis, a flame area is estimated by considering the equivalent sphere or cylinder depending on the size of the shadow image. D is defined as the diameter of the equivalent circle which has the same area as the measured shadow area. In the calculation of the flame area, it is assumed that the flame shape is spherical before D exceeds the vessel height, H, and cylindrical when D > H. Results of the analysis are partially shown in Fig.7.

For the case $\Delta\tau$ = 2ms, the flame area changes as virtually same as the single flame case since a flame separation is very little. However, in each case of $\Delta\tau$ grater than 10ms, the increase of flame area originated in two kernels, and also the rapid reduction in flame area caused by unification of flames, are clearly observed in the figure. The latter timings are plotted against ω in Fig.8. In the case of short $\Delta\tau$, they increases with ω ,while they exhibit a tendency to reduction with ω when $\Delta\tau$ becomes a long interval. In a lower ω region, however, it is not observed. These behaviors are understood by considering the flame separation. In a shorter $\Delta\tau$ region, the separation increases with ω to increase the unification timing. In a longer $\Delta\tau$ region, a radial convection may determine the timing. However, in a slow ω region, the flame separation with ω may play a role for the change of the timings of unification. In these regions, they increase with ω .

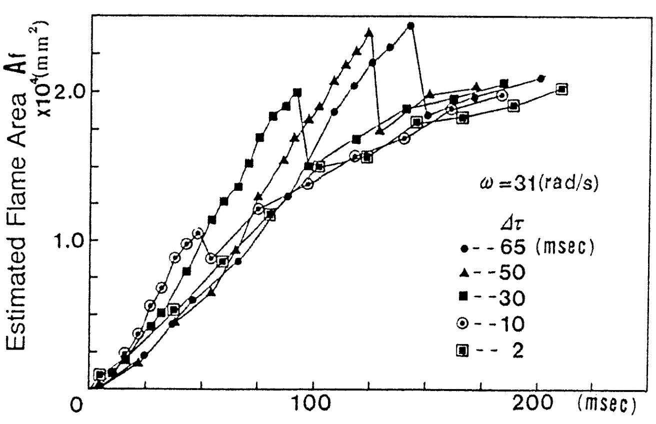


Fig.7 Change of Flame Area with Spark Intervals

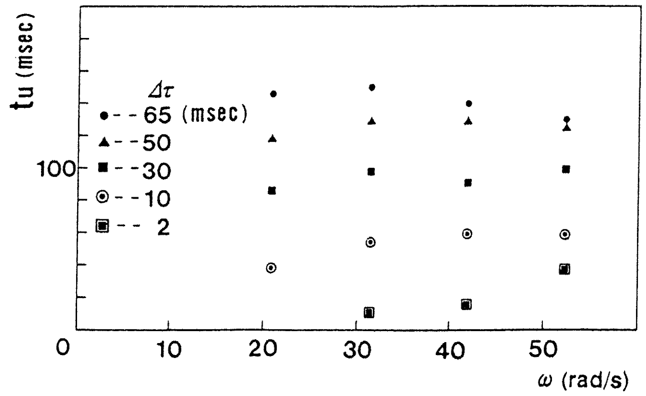


Fig.8 Change of the Flame Unification Timing

The timing of the first bulge appeared on the (dp/dt)--curve, roughly coincides with that for the peak on the curve in Fig.7, though the average curve of (dp/dt) cannot necessarily correspond to the photographic observation. As so far described above, (dp/dt) during combustion period can widely be changd by altering a combination of $\Delta\tau$ with ω .

Under the non flame-holding condition which may be realized in a lean combustion with a high swirl speed, an active control of combustion may become possible by these means. Although only a double flame case is elementally examined in the present study, a means of combustion control by more than 3 flames is also available.

The effect of flame holding on the (dp/dt)-curve is examined with some what richer mixture. In this case, the flame area is extended by the swirl flow to exhibit the higher rate of pressure rise as shown in Fig.4-e and Fig.6-e. When a flame is held on the ignition source, several ignition plug must be installed in a combustion chamber depending on the number of flame initiation. Therefore the flexibility in the combustion control may diminish.

CONCLUSION

As an approach to control a flame growth in a swirl by the flame initiation means, the flame behaviors in the solid vortex model are examined. Results of the experiment shows:

1) When a plural number of flames can be initiated by a single igniter, the rate of heat liberation may be controllable by alterling the initiation interval and the swirling speed. Under the conditions of flame holding, a control of flame growth is also possible in some extent by making use of a plural number of igniters.
2) The timing when an individual flame grows together is determined by the flame separation which depends on the ignition interval and/or the relative approaching speed of flames.
3) The single flame, whether initiated by the single spark or the plasma jet, is apt to grow the center-symmetrical flame to cause the delayed combustion.

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