Effects of Turbulence on Combustion of Homogeneous Mixture of Fuel and Air in Closed Vessel*

By Yoshisuke HAMAMOTO** , Hisao OHKAWA*** ,
Hiroaki YAMAMOTO**** and Ryosuke SUGAHARA*****

The effects of turbulence on the flame propagation in closed vessel were investigated by analyzing the high speed schlieren motion pictures of flames and the pressure changes. Turbulent conditions were prepared by moving a perforated plate quickly once for each experiment, and the characteristics of turbulence were measured by a laser Doppler velocimeter. The main results are as follows:

(1) The flame propagation speed and the rate of pressure rise increase with an increasing intensity of turbulence. The volume enveloped by turbulent flame, however, is larger than that by laminar flame at the same mass fraction burned. This fact suggests that turbulent flame has some "burning zone", which includes unburned gas cloud.

(2) The thickness of burning zone δ_T and the turbulent burning velocity S_T increase with an increasing intensity of turbulence having higher frequency than f_0 , where $f_0 = (S_T/\delta_T)/2$.

Key Words : Combustion, Turbulent Combustion, Turbulent Flame, Burning Velocity, Burning Zone, Turbulent Flame Propagation

1. Introduction

In order to understand the combustion phenomena in spark-ignition engines, many studies on the turbulent combustion of fuel-air homogeneous mixture have been carried out with the closed vessel of constant volume. For instance, A.S. Sokolik, et al.(1) investigated the effects of turbulence on combustion in a closed vessel, in which the turbulence was produced by rotary fans. S.Ono, et al.(2) improved Sokolik's method to produce a nearly homogeneous turbulent field in the central part of combustion chamber, and investigated the effects of intensity and scale of turbulence on combustion. S.Ohigashi, et al.(3) investigated the promotion of combustion and the enlargement of burning zone due to a turbulence which was produced by sudden movement of the perforated plate in the combustion chamber. H.Hiroyasu, et al.(4) investigated the effects of mixture motion on the combustion pressure and the composition of burned gas in a closed vessel. From these experimental results, effective information for the simulation of combustion and exhaust emissions in spark-ignition engines would be obtained(5).

In these kinds of studies, one of the most difficult problems is measurement of turbulence. In previous studies mentioned above, hot-wire anemometers were used for measurement of turbulence. Since a hot-wire anemometer can not determine the turbulence characteristics in a flow field which has no main flow, quantitative discussion is very difficult in the studies mentioned previously.

In this study, from the results of the turbulence measurements by a laser Doppler velocimeter, the flame observations by high speed schlieren photography and the measurements of pressure rise, the effects of turbulence characteristics on the burning velocity and the burning zone thickness of turbulent flame were investigated.

2. Experimental Apparatus

A schematic diagram of experimental apparatus is shown in Fig.1. The combustion chamber is cubic of 80 mm - side, with two facing visual observation windows on its both sides, for taking schlieren pictures of flame and applying a laser Doppler velocimeter (LDV). A homogeneous mixture of methane and air is prepared in the combustion chamber, and a turbulent motion in the mixture is generated by a perforated plate which is pulled down by a rack and pinion gear driven by an electric motor. By action of a solenoid, a motor-driven pinion gear is engages with a rack gear connected to the perforated plate. In this experiment, two kinds of perforated plates, D8 and D12, shown in Fig.1 were used. The mean speed of the perforated plate was about 6.7 m/s. The intensity of turbulence decays with time. The flame in various intensities of turbulence can be observed by igniting the mixture at

* Received 2nd April, 1982.

** Professor, School of Engineering, Okayama University, Tsushima Naka 3-Chome, Okayama City.

*** Engineer, Nissan Motor Co. Ltd., Daikoku-Cho, Tsurumi-Ku, Yokohama City.

**** Engineer, Nippon Steel Corporation, Hirohata-Ku, Himeji City.

***** Engineer, Shimadzu Corporation, Nishinokyo-Kuwabara-Cho, Nakagyo-Ku, Kyoto City.

different times t_1 after pulling down the perforated plate to the bottom of the chamber.

Turbulence characteristics of the mixture were measured by LDV in unburned condition. The laser source is 15 mW, He-Ne, and its wave length is 632.8 nm. Forward-scattering, fringe-mode is adopted. The intersecting angle is set at 0.2023 radians (11.59 degrees). Also a frequency-shifting system is used so that flow direction is identified. Tracker-type device is employed as signal processing system. JIS test dust No.11 (fine red clay) is used as particles for scattering the light.

Flame configuration and flame propagation speed were determined from high speed schlieren motion pictures (4000 frames/sec.). Also a pressure transducer of semi-conductor type is attached to measure the pressure during combustion, and a small ion-gap was provided at the point of 22.5 mm horizontal distance from spark gap.

In this experiment, various values of mixture ratio of methane and air were used, and initial pressure was set at 0.101 MPa (1 atm). In order to ignore effects of combustion chamber wall on flame propagation, especially to ignore effect of heat loss to wall, experiments were limited to the range from ignition to about 30 mm radius of flame, that is initial stage of combustion which is smaller than about 1.5 % mass fraction burned.

Fig.1 Experimental apparatus

3. Characteristics of Turbulent Motion of Mixture in Combustion Chamber

Measuring point of gas velocity is located at a diagonal distance of 22.5 mm from spark gap on a horizontal plane of 40 mm height. Figure 2 shows examples of measured values of velocity, where LDV and HW indicate the results obtained with a laser Doppler velocimeter and a hot-wire anemometer of constant temperature type, respectively. Both data were obtained at the same time, but the measuring position of HW was 1 mm higher than that of LDV. A tungsten wire of 5 μ m diameter and 1.2 mm length was used as hot-wire. Optics of LDV was so arranged as to determine a vertical component of velocity. The positive and negative signs of velocity represent upward and downward flows, respectively, and t_1 indicated the elapse time after pulling down the perforated plate to the bottom of the combustion chamber.

It is understood from the result measured by LDV that the flow inside the chamber is likely to have no "main flow". Consequently, the measured velocity itself was treated as "turbulence". It is also understood from the results shown in Fig.2 that HW is not fit for determining such as turbulent flow field having no "main flow", because that HW can not identify the flow direction.

Three orthogonal components of an instantaneous velocity vector are represented with u_1 , u_2 and u_3 , where u_1 is a vertical component. The values of u_1 and u_2 were measured 30 times, and ensemble average of u_1^2 and u_2^2 , u_1^2 and u_2^2 , respectively, were obtained. Assuming that $u_2^2 = u_3^2$, the intensity of turbulence, TI , is determined as follows:

$$TI = \sqrt{(\overline{u_1^2} + 2\overline{u_2^2})/3}$$

In the experimental results, a linear relationship between t_1 and $TI^{-4/5}$ was recognized. Figure 3 shows the decay of turbulence intensity TI against the elapse time t_1 after pulling down the perforated plate to the bottom of the chamber.

Although the phenomenon was unsteady, a spectral analysis was performed. In the time intervals of t_1 of 10.0 ~ 22.8 ms, 20.0 ~ 32.8 ms, 50.0 ~ 62.8 ms and 100.0 ~ 112.8 ms, power spectrums of LDV-output

Fig.2 Examples of velocity measurements (Comparison between LDV and HW)

were obtained. Data sampling interval was 0.2 ms and upper limit of frequency on the spectral analysis was 2500 Hz. The power spectrum of turbulence in the combustion chamber, E , is expressed as follows:

$$E = (E_1 + 2E_2)/3$$

where E_1 and E_2 indicate the power spectrums of vertical and horizontal components of velocity, respectively. And then, the power spectrum density of turbulence, F , is expressed as follows:

$$F = E/TI^2$$

where TI^2 is mean square of turbulence intensity in each time interval.

Autocorrelation function of turbulence, $R(\tau)$, is expressed approximately by the following equation (6).

$$R(\tau) = e^{-\tau/L_t}$$

where τ is time and L_t is integral time scale. Consequently, the power spectrum density of turbulence is expressed as follows:

$$F = 4 \int_0^\infty R(\tau) \cos 2\pi f \tau d\tau = 4L_t / \{1 + (2\pi f L_t)^2\} \quad (1)$$

where f is frequency. The square of turbulence intensity in the frequency interval between a certain frequency f_0 and the maximum frequency $f_{\max}$, $(TI^2)_{f_0}^{f_{\max}}$, is expressed as follows:

$$(TI^2)_{f_0}^{f_{\max}} = \int_{f_0}^{f_{\max}} E df = 2TI^2 (\tan^{-1} 2\pi L_t f_{\max} - \tan^{-1} 2\pi L_t f_0) / \pi \quad (2)$$

Because $f_{\max} = 2500$ Hz, $\tan^{-1} 2\pi L_t f_{\max} \approx \pi/2$, it is possible to assume approximately that $f_{\max}$ is infinity in Eq.(2). Consequently, turbulent intensity TI_{f_0} and its square $(TI^2)_{f_0}$ at the frequency more than f_0 are expressed as follows:

$$(TI^2)_{f_0} = (2TI^2/\pi) \{(\pi/2) - \tan^{-1} 2\pi L_t f_0\} \quad (3)$$

$$TI_{f_0} = \sqrt{(TI^2)_{f_0}} \quad (4)$$

Experimental and calculated values of $(TI^2)_{f_0}$ are shown in Fig.4. In Eq.(3), the measured values shown in Fig.3 were used for TI , and the values of L_t were so determined as to obtain a good fit between the calculated and the experimental values. If the values of TI and L_t are known, the turbulence intensity, TI_{f_0} , at the frequency more than f_0 is able to be calculated by Eqs.(3) and (4), where f_0 is not high frequency. The values of TI_{f_0} used in the following chapter were calculated from Eqs.(3) and (4), where L_t was determined for the change of t_1 and the measured values of TI were used.

4. Burning Zone Thickness and Burning Velocity of Turbulent flame

4.1) Burning zone thickness

Examples of schlieren photographs of flames are shown in Fig.5, where TI_1 is the turbulence intensity at the moment of spark ignition. In the case of small value of t_1 , the high frequency component of turbulence is still in existence at the time of combustion. Then the spatial frequency of the surface roughness of flame becomes high with an increase of turbulence intensity, i.e. the smaller value of t_1 .

Since turbulent flame is not a perfect sphere because of the perturbation due the existence of turbulence, the flame radius r was determined by radius of a circle having the same area as that of the projected flame picture, and the flame propagating speed was determined as one at $\dot{r} = dr/dt$.

Fig.3 Decay of turbulence intensity

Fig.4 $(TI^2)_{f_0}$

The pressure measurement in the combustion chamber and the photographic observation of flame were carried out synchronously. Figure 6 shows the relations between the pressure p and the flame radius r in various conditions of turbulence intensity, where $\Delta p = p - p_i$ and p_i is 101.3 kPa of initial pressure of the mixture in the combustion chamber. Although the rates of flame propagation and pressure rise increase with an increase of turbulence intensity, at a constant radius of flame, the pressure becomes low with an increase of turbulence intensity. Then, this fact suggests that the mass of burned gas included in turbulent flame is less than that in laminar flame ($Tl_i = 0$) having the same radius as that of the turbulent flame. That is to say, a large amount of unburned gas exists inside the turbulent flame. It seems that such unburned gas exists in the zone near the flame front as shown schematically in Fig. 7. In this paper, the mixing zone of burned gas and unburned gas is called the turbulent burning zone.

In a spherically propagating turbulent flame as shown schematically in Fig. 7, r_T and δ_T are radius and burning zone thickness of turbulent flame, respectively. In a coordinate system attached to the flame front, the mass fraction of burned gas in a spherical shell with the small width $d\eta$ at the distance η from the front is assumed to be an error-function of η given by the following equation.

$$n_b = \frac{6}{\sqrt{2\pi}\delta_T} \int_0^\eta \exp\left\{-18\left(\frac{\eta'}{\delta_T} - \frac{1}{2}\right)^2\right\} d\eta' \quad (5)$$

By integrating Eq. (5) from $\eta = 0$ to δ_T , the value of n_b becomes 0.9973, but the small

Fig. 5 Schlieren photographs of flames (methane-air mixture, $\phi=1.0$, D8)

Fig. 6 Relation between flame radius and pressure rise

difference between 0.9973 and 1.0000 is neglected and it is assumed that $n_b = 1$ in the range of $\eta > \delta_T$.

Turbulent flame is thought to have both burned and unburned clouds in a certain width of turbulent burning zone, of which boundaries are "elementary zone of combustion" where actual combustion reaction takes place. It is not clear whether this "elementary zone of combustion" exists continuously within the turbulent burning zone, discretely spreads or is just like an enlarged combustion zone of laminar flame. The question is not taken up here. It is assumed here that the average fraction of burned gas in the spherical shell having a width of $d\eta$ changes with η like Eq. (5).

Given the radius r_L of laminar flame sphere of which mass fraction burned is equal to that of turbulent flame sphere of radius r_T as shown in Fig. 7, the following relation on the mass enveloped by flame front is obtained.

$$3 \int_0^{\delta_T} (r_T - \eta)^2 n_b d\eta = r_L^3 - (r_T - \delta_T)^3 \quad (6)$$

The thickness of turbulent burning zone is determined as δ_T satisfying Eq. (6). Pressure has the same value for both turbulent and laminar flames in a closed vessel of constant volume when mass burned is equal for them. Therefore δ_T is obtained by reading a couple of radii r_L and r_T at the same pressure in Δp - r diagrams and putting them into Eq. (6).

4.2) Burning velocity

The radius of turbulent flame sphere as shown in Fig. 7 changes from r_T to $r_T + \dot{r}_T \Delta t$ during the minute time interval Δt , where $\dot{r}_T$ is a propagating speed of turbulent flame front. By considering the mass balance of unburned gas in the flame sphere, we obtain the following relation.

$$\begin{aligned} & \int_0^{\delta_T} 4\pi\rho_u(1-n_b)(r_T - \eta)^2 d\eta \\ & + \int_0^{\delta_T} 4\pi\rho_u S_T (r_T + \dot{r}_T \tau)^2 d\tau - \int_0^{\delta_T} \dot{M}_b d\tau \\ & = \int_0^{\delta_T} 4\pi\rho_u(1-n_b)(r_T + \dot{r}_T \Delta t - \eta)^2 d\eta \end{aligned}$$

where S_T represents the entrainment velocity of unburned gas against the flame front, i.e. the turbulent burning velocity, and $\dot{M}_b$, ρ_u and τ represent the

Fig. 7 Schema of burning zone in turbulent flame

rate of mass burned in the total flame sphere, the unburned gas density and the time, respectively. And the changes of δ_T , ρ_u , S_T and r_T during the minute time interval Δt are ignored. Each term in the above equation is divided with Δt , and determining the limitation of $\Delta t \rightarrow 0$, we obtain the equation of S_T as follows:

$$S_T = (\dot{M}_b / 4\pi r_T^2 \rho_u) + (2\dot{r}_T / r_T^2) \int_0^{\delta_T} (1 - n_b)(r_T - \eta) d\eta \quad \dots (7)$$

The mass burned M_b can be determined from the following equation using the measured value of pressure (7).

$$M_b = \{ (p - p_i) V + M \bar{c}_{vu} (\bar{x}_b - \bar{x}_u) \times (\bar{T}_u - T_{ui}) / [(\bar{x}_b - 1)h + (\bar{x}_b - \bar{x}_u) \bar{c}_{vu} \bar{T}_u] \} \dots (8)$$

where V , M , T , h , c_v and κ represent the volume of combustion chamber, the temperature of gas, heat of combustion of the mixture, the specific heat in constant volume and the ratio of specific heats, respectively. The subscripts i , u , and b refer to the ignition timing, the unburned gas and the burned gas, respectively, and $-$ expresses the spatial average. $\dot{M}_b$ is the time rate of change of M_b . The values of r_T and $\dot{r}_T$ are determined from flame photographs, and the values of ρ_u and $\bar{T}_u$ are obtained on the assumption of adiabatic compression of unburned gas.

4.3) Experimental results

Determining the radius r_T of turbulent flame sphere of which the pressure is equal to that of laminar flame sphere of radius r_L , and assuming the distribution of mass fractions of burned gas in burning zone, n_b , as Eq.(5), the thickness of burning zone δ_T was determined by Eq.(6). Examples of δ_T are shown in Fig.8. After the flame develops to a certain size, the value of δ_T hardly changes under the conditions of experiments in Fig.8, in which the pressure change in combustion chamber is about 10 kPa. Further, to determine the value n_b , the following equation was used instead of Eq.(5).

$$n_b = \eta / \delta_T$$

The results were almost same as those shown in Fig.8.

If a pair of electrodes (ion-gap, see

Fig.8 Burning zone thickness δ_T

Fig.1) imposed with d.c.voltage is inserted into the flame, an ion-current occurs. As turbulent flame is thought to consist of many elementary zones of combustion where actual combustion reaction occurs, the ion-current has several peaks while the flame passes through the ion-gap. The value of δ_{ion} defined in the following relation is a measure of the turbulent burning zone thickness(3).

$$\delta_{ion} = \tau_{ion} \dot{r}_T$$

where τ_{ion} is the time interval between the growth of an ion-current and the appearance of the last peak. As shown in Fig.9, there is a direct proportional relation between δ_{ion} and δ_T . Then it is seen that the value of δ_T determined by the method mentioned above is reasonable. The value of δ_{ion} shown in Fig.9 is a mean value of 10 measurements.

The burning velocity S_T and the burning zone thickness δ_T of CH₄-air turbulent flame were determined under several conditions of turbulence. Figs.10 and 11 show the results obtained in the conditions that the equivalence ratio $\phi = 1$ and the perforated plates of D8 and D12 were used. In the figures, S_L is a laminar burning velocity (reference (8)), and S_T , δ_T and TI are expressed with average of 3 values at the times corresponding to r_L of 17.5, 20.0 and 22.5 mm. The values of S_T and δ_T increase with an increase of turbulence intensity. From this fact, it is suggested that the entrainment speed of unburned gas to the burning, i.e. the turbulent burning velocity increases with an increase of turbulent intensity, but the increase of average reaction rate in burning zone is less than the increase of entrainment speed of unburned gas, and then a thick burning zone becomes necessary for a perfect reaction of entrained unburned mixture. In the case of using different kinds of perforated plates, different values of S_T and δ_T are obtained in spite of the same intensity of turbulence. The reason is a difference in spectrum of turbulence generated with different kinds of perforated plates. It is likely that the low frequency turbulence hardly affects the combustion. Consequently, for the expression of turbulence, the intensity of turbulence having higher frequency than

Fig.9 Correlation between δ_T and δ_{ion}

Fig. 10 Relation between S_T and TI Fig. 11 Relation between δ_T and TI Fig. 12 Relation between S_T/S_L and TI_{f_0} Fig. 13 Relation between δ_T and TI_{f_0}

f_0 , i.e. TI_{f_0} , is reasonable.

It is assumed that the very slow fluctuation of velocity as compared with the characteristic reaction time in burning zone, δ_T/S_T , has no influence on combustion. It is also assumed that the critical frequency of turbulence affecting sufficiently combustion, f_0 , is proportional to the value of S_T/δ_T as seen from the following relation.

$$f_0 = (S_T/\delta_T)/2$$

The intensity of turbulence having higher frequency than f_0 , TI_{f_0} , was obtained from Eqs. (3) and (4). The data on S_T and δ_T were rearranged by using TI_{f_0} . The results are shown in Figs. 12 and 13. By using TI_{f_0} as turbulence intensity, a unique relation between TI_{f_0} and S_T or δ_T is obtained independently of the spectrum of turbulence.

Figures 14 and 15 show the experimental values of S_T and δ_T obtained for various values of mixture ratio. The values of S_T/S_L in a lean mixture have a tendency to be larger than those in a rich mixture. Effect of ϕ on δ_T is not remarkable. In the range of experimental conditions, f_0 was 100 - 150 Hz.

The relations between S_T/S_L and δ_T are shown in Figs. 16 and 17. Under the condition of constant ϕ , a linear correlation between S_T/S_L and δ_T holds independently of the turbulence characteristics. The influence of ϕ on the correlation between

Fig. 14 Relation between S_T/S_L and TI_{f_0} Fig. 15 Relation between δ_T and TI_{f_0}

Fig.16 Relation between S_T/S_L and δ_T Fig.17 Relation between S_T/S_L and δ_T

S_T/S_L and δ_T is not remarkable under the condition of weak turbulence (i.e. in the case of small δ_T in Fig.17), but the influence of ϕ becomes remarkable in the strong turbulence (i.e. in large δ_T). Under the condition that $\phi=1.3$ in Fig.17, the value of δ_T is larger than that for other values of ϕ at the same value of S_T/S_L . If the mixture is made richer or leaner than under this experimental condition, it is expected that δ_T will become larger at the same value of S_T/S_L .

5. Conclusions

Turbulence was generated by rapid movement of a perforated plate in a

methane-air mixture inside a closed combustion chamber, and the effect of turbulence on burning velocity and burning zone thickness near spherically propagating turbulent flame was investigated. The main results are as follows:

- (1) The power spectrum density of turbulence inside a closed vessel is expressed approximately with Eq.(1). Consequently, the intensity of turbulence having higher frequency than f_0 , Tf_0 , can be calculated from Eqs.(3) and (4).
- (2) The rates of pressure rise and flame propagation increase with an increase of turbulence intensity. Under the condition that the volume of flame sphere is the same, however, the pressure rise becomes low with an increase of turbulence intensity.
- (3) The burning zone thickness and the burning velocity of turbulent flame increase with an increase of turbulent intensity. Under a different condition of the spectrum of turbulent fluctuation, even if the turbulence intensity is the same, different values of S_T and δ_T are obtained. But, if the value of Tf_0 is the same, the same value of S_T or δ_T is obtained, when $f_0 = (S_T/\delta_T)/2$ (f_0 is about 100 - 150 Hz in this experiment). Namely, the turbulence having lower frequency than f_0 hardly affects combustion.
- (4) There is a linear correlation between S_T/S_L and δ_T , and the correlation is hardly affected by the equivalence ratio in weak turbulence.
- (5) The burning zone thickness δ_T determined by the measurements of flame radius and pressure rise of laminar and turbulent combustion has a linear correlation to the value of δ_{ion} determined by analyzing the ion-current.

Reference

- (1) Sokolik, A.S., et al., Combustion, Explosion and Shock Waves, Vol.3, No.1 (1967-4), p.36.
- (2) Ono, S., et al. Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.41, No.349 (1975-9), p.2724.
- (3) Ohigashi, S., et al., Bull. Japan Soc. Mech. Engrs., Vol.14, No.74 (1971), p.849.
- (4) Hiroyasu, H., et al., Trans. Soc. Autom. Engrs. Japan (in Japanese) No.7 (1974), p.3.
- (5) Hiroyasu, H. and Kadota, T., 15th Int. Symp. on Comb., (1975), p.1213, The Combustion Inst.
- (6) Wakisaka, T., et al., Bull. Japan Soc. Mech. Engrs., Vol.26, No.212 (1983-2), p.254.
- (7) Lavoie, G.A., et al., Combust. Sci. Techn., Vol.1 (1970), p.313.
- (8) Lewis, B. and von Elbe, G., Combustion, Flames and Explosions of Gases, 2nd ed., (1961), p.389, Academic Press.