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Effects of Turbulence on Flame Propagation in Closed Vessel*

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The effects of turbulence on the flame propagation in the propane-air mixture in a closed vessel were investigated by analyzing the high speed motion pictures of flame, the ion-currents due to combustion and the change of the gas compositions in combustion zone. In the combustion chamber, the uniform turbulent conditions were produced by moving suddenly a perforated plate which was driven by the spring and the electro-magnetic control system. The main results are as follows:

(1) The combustion zone of turbulent flame may be composed of a lot of flame elements which are similar to laminar flame, and the apparent burning velocity is increased by enlargement of combustion zone due to turbulence.

(2) During the early stage following ignition, the flame speed is affected by both factors of mixture strength and intensity of turbulence. With further development of the flame, however, the intensity of turbulence becomes a dominant factor determining the flame speed.

1. Introduction

The combustion phenomenon in a gasoline engine cylinder may be considered, from a simplified view point, as a turbulent flame propagation initiated by a spark ignition in premixed gas in a closed vessel. At present, it seems impossible to express quantitatively the effect of aerodynamic conditions on the development of combustion in actual internal combustion engines. This situation arises from the difficulty of measuring the characteristics of turbulence in the combustion chamber and from the cycle-to-cycle variation of combustion. As a consequence, the effect of turbulence on the development of combustion has been investigated in the constant volume vessel in which the turbulence is given to the combustible mixture by various methods^{(1)~(4)}.

The aerodynamic conditions in the combustion chamber of a 4-stroke cycle engine were investigated by E.S. Semenov⁽⁵⁾, using a hot-wire

anemometer. The combustion chamber of the test engine was flat disc type having no squish area, and the inlet valve was ordinary type without shroud. And the experiments were made in motoring conditions. The experimental results show that uniform turbulence exists and no directional flow does in the combustion chamber at the neighbourhood of top dead center. The combustion in actual engine develops in an almost constant volume at the neighbourhood of top dead center.

In order to investigate the effect of such a uniform turbulence in combustible mixture on flame propagation, in this study, the uniform turbulent conditions were produced in a propane-air homogeneous mixture in a constant volume combustion chamber of disc type by moving suddenly a perforated plate which was driven by the spring and the electro-magnetic control system. By analysing the high speed motion picture, the ionization current and the gas composition in combustion zone, the effect of turbulence on flame propagation was investigated.

2. Experimental procedure

As shown in Fig. 1, the combustion chamber of disc type, having diameter of 80 mm and

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height of 8 mm, has a visual observation window equipped with spark gap in its center. The uniform turbulence is produced in the propane-air mixture by moving suddenly a perforated plate made of bakelite, as shown in Fig. 2, from the top of combustion chamber to the bottom before the ignition. In the combustion chamber before combustion, the average value of gas flow velocity $\bar{U}=0$, and there is the fluctuating component of gas velocity u' alone. The intensity of turbulence ΔU is expressed by the root mean square of u' , i.e., $\Delta U = \sqrt{\bar{u'^2}}$. Since ΔU decays with the elapsing time from the dropping of perforated plate, the combustion in the variable conditions of turbulence intensity can be set up by varying the ignition timing. For changing the scale of turbulence, three kinds of perforated plates, i.e., $D_p=3, 5$ and 7 mm in Fig. 2, were used. The intensity of turbulence ΔU was measured by a hot-wire anemometer in the air of the same pressure and the same temperature as the combustible mixture before ignition, i.e., 4 kg/cm^2 and room temperature, respectively, and ΔU was expressed with the average of measured values in the time interval corresponding to the total combustion time in the stoichiometric

Fig. 1 Schematic diagram of combustion chamber

Fig. 2 Perforated plate

mixture. The diameter and length of hot-wire were 5μ and 1 mm , respectively, and the constant temperature method was adopted. The hot-wire was placed at the point of 10 mm in radial direction from the chamber center and at 4 mm from the upper wall of chamber, i.e., the middle point of height of chamber.

Propane and air were supplied separately into the combustion chamber. For preparing a homogeneous mixture of propane and air, the perforated plate was moved in several times. The mixture ratio was determined from the partial pressures of supplied propane and air, and confirmed by analyzing the composition of mixture before ignition with a gas-chromatograph. The total pressure of the combustible mixture before ignition was 4 kg/cm^2 in all tests.

Figure 3 shows a schematic diagram of the experimental apparatus. The perforated plate is located at the top of combustion chamber by the force of the fixed magnetic field. When a strong electric current is supplied instantaneously to the inverse magnetic coil, the fixed magnetic field is eliminated and the perforated plate is moved to the bottom of chamber by the spring force. The average dropping speed of the perforated plate is about 5.5 m/sec . After a certain delay time from the perforated plate arriving at the bottom of chamber, the breaker point of spark ignition equipment is made to open and the combustion is initiated. Various delays are given by the delay circuit. The high speed motion pictures (5000 frames per second) of the flame development and the combustion pressure records were taken simultaneously.

Further, to investigate the characteristics of turbulent flames, the ionization phenomenon in

Fig. 3 Schematic diagram of experimental apparatus

the flame was utilized. When a pair of electrodes (ion-gap) added with electric voltage is located in the reaction zone of hydrocarbon flame, an electric current (ion-current) due to ions and electrons occurs, and then the existence of reaction zone is detected by the ion-current. The ion-gap as shown in Fig. 4 was located at the point of 20 mm from the chamber center and at 4 mm from the upper wall of chamber. In order to observe in detail the wave form of ion-current, the sweep of cathode ray oscilloscope was initiated at the time that the flame arrived near the ion-gap.

To investigate the change of gas composition from unburned to burned region, a small type electro-magnetic gas sampling valve as shown in Fig. 5 (a) was used. In this test, the ignition gap was located at the peripheral wall of the combustion chamber, and the gas sampling valve was located at the point of 50 mm from the ignition point, as shown in Fig. 5 (b). The position of the flame at the time of gas sampling was detected by the ion-gap which was located at the point shown in Fig. 5 (b). In the preliminary test by high speed motion pictures of the flame development, it was recognized that the flame arrived in the same time at both positions of the ion-gap and the gas sampling valve. The opening and closing signals of the gas sampling valve, which were produced by utilizing the contact point of the valve and the valve seat as a switch, and the ion-current were displayed simultaneously on the cathode ray oscilloscope. The time interval, t , between the beginning of ion-current and the middle point of opening and closing signals of the gas sampling valve, and the flame speed, w_f , were measured. Thus, tw_f expresses the distance between the

Fig. 4 Ion-gap

gas sampling position and the flame front. The opening period of gas sampling valve is 0.5~0.8 msec, and the amount of sampled gas is about 0.5 cm³ at atmospheric condition. The concentrations of N₂, O₂, CO₂ and CO in the sampled gas were determined with gas-chromatograph.

3. Observation of flame

3.1 Observation of flame by means of high speed motion pictures

Figure 6 shows the high speed motion pictures of the flames. The experimental conditions are as follows: The mixture ratio of propane and air is stoichiometric (equivalence ratio $\phi=1.0$), $D_p=7$ mm, the intensity of turbulence $\Delta U=1.37, 1.00, 0.31, 0.15, 0.10$ and 0 m/sec. It was confirmed in preliminary test that the flame developed in circular form in all values of ΔU , i.e., that the propagation of turbulent flame is uniform. This result suggests that the turbulence field in combustion chamber is almost uniform.

(a) Electro-magnetic gas sampling valve

(b) Locations of gas sampling valve and ion-gap
Fig. 5 Electro-magnetic gas sampling valve and its location

Consequently, by using the information from photographs of a part of flame, the whole

configuration of flame can be known.

The results of the photographic observations are as follows:

(1) In the quiescent mixture ($\Delta U=0$), the laminar flame develops in circular form with thin luminous zone, and is hardly disturbed up to the peripheral wall of combustion chamber. On the other hand, the turbulent flame has a complicated irregular front, and the width of luminous zone increases with an increasing ΔU .

(2) In the case of the weak turbulence, for example when $\Delta U=0.10$ m/sec, the profile of the flame front at the initial stage of combustion is similar to that of a laminar flame. When the diameter of flame develops to several millimeters, however, the flame front is distorted by the turbulence, and the distortion of the flame front due to turbulence becomes strong with the development of flame. On the other hand, in a strong turbulence, for example when $\Delta U=1.37$ m/sec, the flame front is distorted even at the initial stage of combustion.

(3) The profile of a strong turbulent flame in this study is similar to the flame photograph taken from an actual gasoline engine⁽⁷⁾. The intensity of turbulence in the combustion chamber of a 4-stroke cycle engine had been determined by E. S. Semenov⁽⁵⁾ in motoring condition. According to his result, $\Delta U=1$ m/sec at the neighbourhood of top dead center in compression stroke. Consequently, it is considered that the combustion similar

Film speed is 5000 frames per second, $\phi=1.0$, $D_p=7$ mm, t =Time from beginning of spark

Fig. 6 High speed motion pictures of flames

to that in an actual gasoline engine occurs in this experimental apparatus.

3.2 Observation of flame by means of ion-current

Examples of the records of ion-currents in the laminar flame ($\Delta U=0$ m/sec) and the turbulent flame ($\Delta U=1.0$ m/sec) are shown in Fig. 7 (a) and (b). In the case of laminar flame, the ion-current has one peak. This result indicates that the reaction zone passes through the ion-gap, because the production of ions concentrates in the reaction zone. On the other hand, in the case of turbulent flame, the ion-current has several peaks. This result indicates that several reaction zones pass through the ion-gap, and suggests that the turbulent combustion region includes several reaction zones (elementary zones of combustion). The wave form of ion-current in turbulent flame is very complicated, and the number of peaks, the height of peak and the appearing times of peaks fluctuate widely, because of statistical characteristics of turbulent flame.

The width of reaction zone in a laminar flame, δ_r , is expressed⁽⁸⁾⁽⁹⁾ by

$$\delta_r = t_r w_f$$

where t_r is the elapsing time between the rising of ion-current and the appearing of its peak as shown in Fig. 8 (a), and w_f is flame speed determined by high speed photography. The measured value of δ_r at the point of 20 mm from

(a) $\Delta U=0$ m/sec (b) $\Delta U=1.37$ m/sec $\phi=1.0$
Fig. 7 Examples of records of ion-currents

$\delta_r = t_r w_f$ (a) Laminar flame
 $\delta_1 = t_1 w_f$ $\delta_m = t_m w_f$ (b) Turbulent flame
Fig. 8 Schematic diagrams of ion-currents

the ignition gap was about 1.4 mm in the stoichiometric mixture. Such a measured value of δ_r may be larger than the true value of reaction zone width, because of the flame quenching effect of the electrodes. However, according to the experimental results of K.P. Vlasov⁽¹⁰⁾, there is a good correlation between the change of ion-current and the change of temperature. And then, it may be considered that such a measured value of δ_r represents qualitatively the width of reaction zone. In the wave form of ion-current of turbulent flame as shown in Fig. 8 (b), t_1 and t_m are measured and δ_1 and δ_m are determined. Here, t_1 and t_m express the time required for elapsing from rising of ion-current to appearing of the first peak and the last peak, respectively, and δ_1 and δ_m are expressed by the following equations.

$$\delta_1 = t_1 w_f,$$

$$\delta_m = t_m w_f.$$

Figure 9 shows the values of δ_1 and δ_m which are determined in the stoichiometric mixtures. When $\Delta U=0$, $\delta_1 = \delta_m = \delta_r$. δ_m represents the width of turbulent flame region. Although the measured values of δ_m fluctuated widely in every test, larger values of δ_m appeared frequently with an increasing ΔU . When $\Delta U=1.0$ m/sec, the maximum value of δ_m was larger by about 5.5 times than δ_r . Such an enlargement of combustion region due to turbulence also can be estimated by the photographic observation of flame. On the other hand, although the value of δ_1 tends to increase slightly with an increasing ΔU , the values of δ_1 being equal to δ_r were detected frequently. Consequently, it is likely that the width of "elementary zone of combustion", δ_1 , in turbulent combustion region

$\phi=1.0$, $D_p=7$ mm
Fig. 9 Width of combustion region

is almost equal to the width of reaction zone, δ_r , of laminar flame, although δ_1 tends to increase slightly due to the high frequency component of turbulence. Assuming that the reaction in "elementary zone of combustion" in turbulent combustion region is the same as that in laminar flame, the wave form of ion-current corresponding to the "elementary zone of combustion" in turbulent combustion region may be equal to one in the reaction zone of laminar flame. The ion-current in turbulent flame, which has several peaks, may be obtained by random superimposing of the ion-currents in "elementary zone of combustion". Here, the wave form of the ion-current corresponding to the ionization zone and the recombination zone of the laminar flame is approximated by a triangle. This triangle may be considered as the wave form of the fundamental ion-current in turbulent flame. As shown in Fig. 10, the wave form of the ion-current in turbulent flame is obtained by superimposing several triangles which are fundamental

Table 1 Maximum gradients of O_2 -concentrations in combustion region

	$\phi=1.00$	$\phi=1.39$
$\Delta U=0$ m/sec	-1.2%/mm	-0.9%/mm
$\Delta U=1.0$ mm	-6.8%/mm	-3.3%/mm

Fig. 10 Examples of composing the wave forms of turbulent ion-currents by superimposing fundamental ion-currents

ion-currents. Since the peak values of ion-currents fluctuate even in laminar flames, the heights of the triangles are not always constant, but the values of δ_1 are constant all the time.

A clue to elucidating the mechanism of turbulent flame may be found in the result mentioned above. The combustion region of turbulent flame is enlarged by the turbulence. A great number of small burning parts are included irregularly in the turbulent combustion region. The chemical reaction in the small burning part is similar to that in the reaction zone of the laminar flame. It may be supposed that the chemical reaction rate in the "elementary zone of combustion" is not much affected by the intensity of turbulence, while the apparent burning velocity increases heavily due to the enlargement of combustion region by the turbulence.

3.3 Change of gas composition across combustion region

Figure 11 shows the changes of weight fractions of O_2 , CO_2 and CO across combustion region. The abscissa of the figure, X , is the distance between the flame front and the gas sampling point. The experimental conditions are as follows: $\phi=1.0$ or $\phi=1.39$, and $\Delta U=0$ or $\Delta U=1.0$ m/sec. The gradient of concentration in laminar flame ($\Delta U=0$ m/sec) is steeper than that in turbulent flame ($\Delta U=1.0$ m/sec). This result suggests the enlargement of combustion region due to the turbulence. Table 1 shows the maximum gradients of O_2 -concentrations in the combustion region. The ratio of the maximum gradient of O_2 -concentration in the turbulence of ΔU of 1.0 m/sec and that in the quiescent mixture is about 5.7 when $\phi=1.0$, and when $\phi=1.39$, the ratio is about 3.8. The opening time of gas sampling valve is too long (0.5~0.8 m sec) for the purpose of sampling the local gas in the combustion region. However, the results suggest the enlargement of combustion region due to the turbulence, as shown from the results of analyses of the high speed motion pictures and the ion-currents.

4. Flame propagation

The effects of turbulence on the flame speed, w_f , were investigated. The flame speed was determined from the high speed motion pictures. The position of laminar flame was decided by the front of luminous zone in the photographs, and the position of turbulent flame front was

decided by the envelope curve of turbulent luminous zone.

Figure 12 shows the effect of the turbulence intensity, ΔU , on the extent of flame development, ρ_f , and the extent of pressure rise, $(p-p_1)/(p_{\max}-p_1)$, in the stoichiometric mixture. Here, $\rho_f = r_f/r_{f0}$; r_{f0} is radius of combustion chamber ($r_{f0} = 40$ mm), r_f is radius of flame, p is pressure, p_1 is initial pressure and $p_{\max}$ is maximum

pressure. It is clear that the combustion completes in shorter time, with an increasing ΔU .

Figure 13 shows the change of flame speed versus the flame development in the stoichiometric mixture. In the initial stage of flame development, the laminar flame develops at almost constant speed, while the turbulent flame speed increases as the flame development proceeds.

(a) $\phi=1.00$, $\Delta U=0$

(c) $\phi=1.39$, $\Delta U=0$

(b) $\phi=1.00$, $\Delta U=1.0$ m/sec

(d) $\phi=1.39$, $\Delta U=1.0$ m/sec

Fig. 11 Change of gas composition across combustion region

Fig. 12 Flame development and pressure rise

Fig. 13 Change of flame speed versus flame development

The flame speed is affected significantly by the intensity of turbulence. The maximum flame speed increases from 3.5 m/sec ($\Delta U = 0$ m/sec) to 13.8 m/sec ($\Delta U = 1.37$ m/sec). In the initial stage of flame propagation in weak turbulence, however, the turbulent flame speed is slower than the laminar flame speed. In such cases, it may be considered that the flame propagation is prevented by the turbulence.

Figure 14 shows the effects of ϕ and ΔU on w_f at ρ_f being 0.4. In the weak turbulence ($\Delta U \leq 0.10$ m/sec), the maximum flame speed appears when $\phi = 1.0$, while in the strong turbulence ($\Delta U \geq 1.00$ m/sec), the flame speed is independent of mixture ratio in a wide range of ϕ , 0.88~1.27, and the turbulence intensity is a dominant factor to determine the flame speed. This phenomenon appears not only on the flame speed at ρ_f being 0.4, but also on the average speed of the flame

Fig. 14 Effects of mixture ratio and turbulence intensity on flame speed

Fig. 15 Effects of mixture ratio and turbulence intensity on $t_{0.9} - t_{0.2}$

in the range of ρ_f , 0.2~0.9. Figure 15 shows the flame propagating time from the flame development at ρ_f being 0.2 to that at ρ_f being 0.9. In the strong turbulence, the values of $t_{0.9} - t_{0.2}$ are independent of ϕ in a wide range of ϕ , 0.88~1.27. In the combustion chamber of an actual gasoline engine, it was found that the fuel-air ratio hardly affected the flame speed after a full development of flame⁽¹¹⁾⁽¹²⁾.

The effects of the fuel-air equivalence ratio, ϕ , and the intensity of turbulence, ΔU , on the extent of flame speed increase, w_f/w_{f0} , are shown in Fig. 16, where w_{f0} is the laminar flame speed. In the range of ϕ , 0.88~1.27, w_f/w_{f0} increases in the mixture ratio of low heating value. In the lean or rich mixture beyond the above range, w_f/w_{f0} tends to decrease, and this tendency is remarkable in the strong turbulence. This phenomenon may be explained as follows: In the mixture of high heating value, the flame speed is increased by the enlargement of combustion region due to the turbulence, while on the other hand, in the strong turbulent mixture of low heating value, the flame temperature decreases by the increase of the heat transferred to the unburned mixture, thus the flame speed decreases.

The turbulence was produced by three kinds

Fig. 16 Effects of mixture ratio and turbulence intensity on w_f/w_{f0}

Fig. 17 Effect of scale of turbulence on flame speed

of perforated plates in which $D_p=3, 5$ and 7 mm; and the effect of ΔU on w_f at the point of $\rho_f=0.4$ was investigated. The test result is shown in Fig. 17. The scale turbulence may be varied by different values of D_p , but in this experimental condition at least, the flame speed is hardly affected by the scale of turbulence, but affected remarkably by the intensity of turbulence.

The effect of the turbulence intensity, ΔU , on the ignition lag, t_v , was investigated, and the result was shown in Fig. 18. The ignition lag, t_v , in the spark ignition was determined by detecting the ion-current through the spark electrodes, which was caused by the ions produced by the combustion immediately after the ignition spark. In general, the ignition lag, t_v , tends to decrease with the increase of ΔU , although t_v tends to increase with the increase of ΔU in the range of weak turbulence. The time required for the propagation of flame to the point of $\rho_f=0.2$ after the beginning of spark discharge, $t_{0.2}$, was determined from high speed motion pictures of flame, and the result was shown in Fig. 19. The ΔU -dependence of $t_{0.2}$ is similar to that of t_v . Figures 20 and 21 show the effects of ΔU and ϕ on $t_{0.2}$ and $t_{0.2}-t_v$. The value of $t_{0.2}$ is affected remarkably by ϕ in all values of ΔU . On the other hand, in the strong turbulence, the value of $t_{0.2}-t_v$ is hardly affected by ϕ in the range of $\phi, 0.88-1.27$.

From the results shown in Figs. 14, 15, 20

Fig. 18 Effect of turbulence intensity on ignition lag

Fig. 19 Effect of turbulence intensity on $t_{0.2}$

and 21, the effects of the propane-air mixture ratio and the turbulence intensity on the turbulent flame propagation are considered as follows: In the short time interval corresponding to the ignition lag, the flame propagation is affected by both factors of ϕ and ΔU . With developing of the flame, the effect of ϕ on the flame speed decreases and the effect of ΔU increases. In a further developed flame, ΔU becomes a dominant factor for determining the turbulent flame speed.

5. Conclusions

The uniform turbulence was produced in the combustion chamber of constant volume, and the effects of turbulence on the flame development were investigated. The main results are as follows:

(1) By increasing the intensity of turbulence, the enlargement of combustion region was confirmed by the flame photographs, the ion-currents and the changes of gas composition in the combustion region.

(2) In the quiescent mixture, the laminar flame with thin luminous zone develops in

Fig. 20 Effect of mixture ratio on $t_{0.2}$

Fig. 21 Effect of mixture ratio on $t_{0.2}-t_v$

circular form from the ignition point up to the peripheral wall of combustion chamber. The turbulent flame has a complicated irregular front and propagates at high speed. In the condition of weak turbulence, the flame immediately after the ignition has a front being similar to that of a laminar flame, but the flame front is distorted as the flame develops.

(3) The wave form of ion-current in turbulent combustion region is very complicated and suggests the statistical characteristics of turbulent combustion. A clue to elucidating the mechanism of turbulent flame may be found in analyzing the ion-currents. A lot of small burning parts are included irregularly in the turbulent combustion region enlarged by the turbulence. The chemical reaction in the small burning part is similar to one in the reaction zone of the laminar flame. It may be considered that the chemical reaction rate in the "elementary zone of combustion" is not much affected by the intensity of turbulence, while the apparent burning velocity seriously increases due to the enlargement of combustion region by the turbulence.

(4) The effects of the fuel-air mixture ratio and turbulence intensity on the turbulent flame propagation are considered as follows: In the short time interval corresponding to the

ignition lag, the flame propagation is affected by both factors of ϕ and ΔU . With a developing of the flame, the effect of ϕ on the flame speed decreases and the effect of ΔU increases. In a further developed flame, ΔU becomes a dominant factor for determining the turbulent flame speed.

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Errata (Vol. 14, No. 72, June, 1971)

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