Extinction of Wrinkled Laminar Flame and Existence of Distributed Reaction Zone*

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The existence of two distinctly different combustion regimes are shown by the extinction limit. The effective Karlovitz number Ka_S was proposed to predict extinction. Using measured data, coming from the counterflow laminar flames, the laminar flame thickness and burning velocity were assessed. This flame thickness is much larger than the Zel'dovich characteristic length. Four different calculation methods of extinction Karlovitz number were presented. At the state of extinction of laminar flame, the effective Karlovitz number ranged around unity. On the other hand, in the opposed jet burner, impinging jets produce a strong turbulence with small scale. In this burner, a stable annular turbulent flame is established at the stretch rate of 20 times greater than that of the laminar flame extinction. Although the distributed reaction zone is produced by extremely small scale eddies compared to the laminar flame thickness, there remains unclear how the transition occurs from the wrinkled laminar flame to the distributed reaction zone. In the present paper, a new model that includes the real flame property was suggested.

Key Words: Combustion Phenomena, Premixed Combustion, Ignition, Extinction, Karlovitz Number, Laminar Flamelet, Distributed Reaction Zone

1. Introduction

With the severe environmental problems, the conversion from diffusion to premixed combustion is being undertaken in many practical combustors. However, as compared to the diffusion flame, the premixed flame easily occurs the flame extinction and flash back. It is well known that for the laminar flames, extinction occurs at high stream velocity gradient. However, in the practical combustors, the turbulent flame is used and the effect of the mixture turbulence on the flame extinction is still unclear. Abdel-Gayed et al.⁽¹⁾ and Abdel-Gayed et al.⁽²⁾ proposed that the turbulent strain rate essentially increases the Karlovitz number Ka and enhances the flame extinction. For high Ka , continuous flame sheets are broken-up and are eventually extinguished before the distributed reaction zone is established. On the other hand, there are a few examples, which

proves the existence of the distributed reaction zone under the extremely high turbulent strain rate as in the well-stirred reactor. However, Chen et al.⁽³⁾ and Dulger and Sher⁽⁴⁾ found that the flame zone broadening by Kolmogorov scale turbulence has been observed instead of extinction. In addition, at high Ka , Yoshida⁽⁵⁾ and Yoshida et al.⁽⁶⁾ achieved thick distributed reaction zone. In the practical burners, the transition from laminar flame to wrinkled laminar flame, and from the latter to distributed reaction zone are still open to discussion. In the present study, a new model is proposed as the transition mechanism.

Poinsot et al.⁽⁷⁾ reported the results of completely two-dimensional Direct Numerical Simulations (DNS) of the transient interaction between a vortex pair and a laminar flame. The aim of their work was to determine the extent of the regime of flamelet combustion; they defined this regime from requirement that a line connecting a point in the fresh gas to another point in the burned products crosses at least one active flame front. Using the model based on the Kolmogorov energy cascade, Poinsot et al.⁽⁷⁾ applied their results to turbulent combustion. However, the spread of the turbulence scales is typically so broad to

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extreme end of Kolmogorov scale. The DNS cannot be expected to estimate the extinction by solution of the complete set of equations with full spatial and temporal resolution and it will remain impracticable for the foreseeable future.

In the present paper, data set of extinction was supplemented by using the spherical porous burner. By the Laser Doppler Velocimeter (LDV), the velocity data along the stagnation streamline were obtained at various stretch rates. Actual flame thickness was measured from the velocity distribution according to the method proposed by Fu and Cho⁽⁸⁾, which was much larger than Zel'dovich characteristic length. Gökalp⁽⁹⁾ found that the extinction Karlovitz number changes from 0.01 to around unity depending on the choice of the turbulent and chemical parameters used. He tried 5 kinds of parameter combination. In the present study, we will discuss the extinction mechanism and the existence of the distributed reaction zone. We focused our attention on the flame strain rate, especially on the strain rate induced by the mixture turbulence. The role of the Kolmogorov microscale turbulence will be made clear. The first part of this paper, we will supplement the previous data set and argue the extinction of the wrinkled laminar flames based on the experimental results. In the second part of this paper, we will assess four different calculation methods of extinction Karlovitz number using our previous data and propose the effective Karlovitz number. And finally we will suggest the existence of the distributed reaction zone in connection with the extinction of the laminar flames.

2. Extinction of Wrinkled Laminar Flame

2.1 Experimental apparatus

Figure 1 shows the counterflow burner used to

Fig. 1 Experimental setup

measure the extinction limit of the laminar and turbulent premixed flames. Unburned mixture was ejected from the porous cylinder whose diameter was 30 mm or 16 mm⁽¹⁰⁾ and porous hemisphere of the diameter of 20 mm. Propane-air mixtures of various equivalence ratios were used throughout the present study.

The unburned mixture was ejected from a porous media in the uniform mixture flow with the same equivalence ratio. The unburned gas was supplied from a nozzle with 60 mm × 30 mm cross section for porous cylinder or a nozzle of 45 mm in diameter for porous hemisphere. Stable double flames were stabilized around the cylinder and hemisphere. At the nozzle exit, a turbulence-producing grid could be installed to make the outer flame turbulent. Stagnation flow field was formed near the forward region of the porous cylinder or hemisphere. When the turbulence-producing grid was removed, unburned mixture flow was completely laminar and the thin laminar double flames were stabilized close to the porous cylinder or hemisphere surface. When the turbulence-producing grid was installed at the nozzle, only the outer flame became turbulent. The role of the inner flame was to supply the burned gas to ensure the adiabaticity of the outer flame by eliminating the heat loss from the outer flame to the porous cylinder or hemisphere.

The velocity field was measured by a hot-wire anemometer for cold flow. In several combustion experiments, an LDV was applied. The seeding particles were aluminum dioxide of 1 μm in nominal diameter. Yoshida et al.⁽¹⁰⁾ found that the mean stagnation velocity profiles were quite similar independently of the grid used. The fluctuating velocity was found to be nearly constant even in the vicinity of the stagnation point. The reason why the turbulence did not decay was explained by the fact that the lateral stretch of the vortices produces the additional turbulence by the conservation of angular momentum in the vortices. The Kolmogorov microscale was significantly larger than the laminar flame thickness and the turbulent flames were in the wrinkled laminar flame regime as suggested by Yoshida et al.⁽¹⁰⁾. Although the turbulence producing grid was changed, the mean velocity profiles coincide with potential flow, which means that the turbulence strain rate can be varied independently of the bulk strain rate $2V_0/R$ for cylinder and $3V_0/2R$ for hemisphere, where V_0 is the uniform velocity far from the porous cylinder or hemisphere and R is the radius of the cylinder or hemisphere.

2.2 Extinction of double flames

We defined here the flow ejection velocity from the porous cylinder or hemisphere as v_w . When v_w is

Fig. 2 Critical stretch rate at which laminar double flames are extinguished as a function of the equivalence ratio

small, the inner laminar flame is produced very close to porous cylinder or hemisphere surface, and the heat loss to the porous material surface could not be neglected, and the extinction of the inner flame occurs at relatively small bulk strain rate, which induced the global extinction of the inner and outer flames. However, v_w was large enough, the inner flame was stabilized at a distance from the surface of porous media. Under such conditions, if the bulk strain rate was increased, the outer flame was extinguished randomly at some point on the stagnation line. The bulk strain rate at which local extinction occurs was constant independently of the mixture ejection velocity from the porous media. This type of extinction is different from the former type. A slight increase of the bulk strain rate led to the global extinction of the entire flames. These strain rates have been estimated using cold flow properties. For the porous hemisphere, local extinction was not observed, and the inner and outer flames were extinguished simultaneously.

Figure 2 shows the critical stretch rate at which the laminar double flames were extinguished as a function of the equivalence ratio ϕ . For these measurements, the turbulence-producing grid was removed. Kobayashi et al.⁽¹¹⁾ and Law et al.⁽¹²⁾ used the opposed nozzles to stabilize the twin flame and measured the extinction limits. On the other hand, Yoshida et al.⁽¹⁰⁾ used the porous cylinder and hemisphere. Even though the flow configuration was

Fig. 3 Mean velocity profile along the stagnation stream line measured by LDV and theoretical profile near extinction for M1 turbulence producing grid

different from each other, we can see an extremely good agreement among them, especially in the lean regime where the Lewis number was larger than unity. We can conclude that the extinction by stretch is inherent characteristics of each mixture.

When the turbulence-producing grid was installed, unburned mixture flow from the bottom nozzle became turbulent, and the turbulent flames were apparently extinguished at a smaller bulk strain rate compared to the laminar case, because the turbulent strain was added. As expected, in general, the stronger the turbulence intensity was, the smaller the extinction strain rate became. Figure 3 shows the mean velocity profiles along the stagnation stream line measured by the LDV in the turbulent flame very close to the state of extinction for $\phi=1.0$ and M1 grid (10-mesh wire gauze), where V is the mean velocity, y the distance from the cylinder surface and $(a_T)_c$ the total strain rate at which the extinction of laminar flame occurred. Each profile displays three distinct segments. Starting from the right side, namely nozzle exit, the velocity first decreases along the stagnation streamline due to the divergence of the cold, unreacted flow. The sudden increase in the velocity was caused by the thermal expansion due to the heat release by combustion and, then, it decreases to zero at the stagnation point. Hence, the velocity at the point where the chemical heat release starts is equal to the burning velocity and the middle segment is a good indication of flame thickness. As shown in Fig. 3, the flame thickness was defined as the distance demarcated by the two intercepts of three tangents to the three segments of the velocity profile. The flame thickness was rather insensitive to the strain rate. We

can get the Spalding flame thickness⁽⁸⁾, namely,

$$\delta_L = (S_u - S_b) / (dV/dy)_{max}, \quad (1)$$

where S_b and S_u are the velocity just downstream and upstream of the flame zone. In the present study, the Spalding flame thickness was found to be five times greater than the Zel'dovich characteristic length independently of the equivalence ratio and the strain rate.

Three lines are the theoretical profiles obtained based on the potential flow assumption, the stagnation point being shifted to fit the measured curve. The mean velocity decreases along the theoretical curve just prior to the turbulent flame zone where the measured velocities deviated from the theoretical curve. Therefore, the strain rate should be estimated at this point and the actual bulk strain rate was smaller than the estimated value at the stagnation point of the cold flow. For this case, the actual bulk strain rate is 510 s^{-1} as compared to 625 s^{-1} for cold flow at the stagnation point. Near the state of extinction, the inner and outer flames approached with each other but did not merge and the combustion gas was accelerated laterally between them.

2.3 Total strain rate of wrinkled laminar flame at extinction

Kostiuk et al.⁽¹³⁾ assumed that the total stretch rate a_T is expressed by

$$a_T = a_b + a_t, \quad (2)$$

where a_b is the bulk strain rate of mean flow and a_t is the turbulent strain rate which can be estimated by the inverse of the Kolmogorov time scale. At the state of extinction, the double flames became rather flat, therefore, we neglected the curvature terms.

Yoshida et al.⁽¹⁰⁾ suggested that all the total strain rates at extinction coincide fairly well with each other and also with the critical strain rate for the laminar flame. The contribution of the turbulent strain rate by the Kolmogorov microscale to the total stretch rate was 30% to 40%. The maximum total strain rate was 1900 s^{-1} at $\phi = 1.1$. We suggested that for the extinction of turbulent premixed flame, of importance is the Kolmogorov microscale, rather than the Taylor microscale, Gibson scale or Markstein length scale, because the Kolmogorov microscale is interpreted as the lower cutoff scale of turbulence, which unfortunately cannot be measured directly.

2.4 Prediction of extinction of wrinkled laminar flame

Law et al.⁽¹²⁾ and Sung et al.⁽¹⁴⁾ noted that clearly, only the strain cannot extinguish the wrinkled laminar flame, and incomplete reaction or heat loss is needed. For the back-to-back configuration such as twin flames or the counterflow double flames, the distance between two flames is reduced with the strain

rate. The turbulent flame extinction occurs due to the interaction of flame stretch and chemical reaction. In principle, the turbulent flames can be extinguished by turbulence when the turbulent diffusion rate exceeds the turbulent chemical kinetic rate. To involve both parameters, the Karlovitz number is introduced. The Karlovitz number has been defined as several ways. Abdel-Gayed et al.⁽²⁾ suggested the following expressions, based on the Taylor microscale to estimate the turbulent strain rate and,

$$Ka = (u'/l) / (S_L / \delta_L) \quad (3)$$

where u' is the turbulence intensity, l the Taylor microscale, S_L the laminar burning velocity and δ_L the laminar flame thickness. If $\delta_L = \nu / S_L$ and $l^2 / L = A \nu / u'$ where L is the integral length scale, ν the kinematic viscosity and A is an empirical constant and 40.4 is suggested by Abdel-Gayed et al.⁽²⁾, then

$$Ka_1 = 0.157 (u' / S_L)^2 R_L^{-0.5} \quad (4)$$

where R_L is the Reynolds number based on the integral scale. Correlations of 1650 separate experimental turbulent burning velocity values have been shown by Abdel-Gayed et al.⁽¹⁾. However, the Kolmogorov scale is more essential rather than the Taylor microscale, because the strain rate is highest even though the turbulent energy contained is small. Bray⁽¹⁵⁾ suggested that replacing Ka by $KaLe$ where Le is the Lewis number, when $KaLe > 6.6 \times 10^{-3}$, the dissipation rate can be expressed empirically by $\epsilon = 0.37 u'^3 / L$, and showed that Eq. (4) can be rewritten by the ratio of characteristic time scales.

$$Ka_2 = 0.258 t_L / t_\eta \quad (5)$$

Where $t_\eta = (\nu / \epsilon)^{1/2}$ is the Kolmogorov time scale and $t_L = \delta_L / S_L$ is the chemical time scale. Physical meaning of this equation is that the extinction occurs when the turbulence time scale is shorter than the chemical time scale. The numerical constant 0.258 was adjusted to put together the Eq. (5) to Eq. (4). Therefore, Eq. (5) can be easily recasted to Eq. (4). On the other hand, based on the dimensional analysis, the critical Karlovitz number at which the wrinkled laminar flame is extinguished is expressed by

$$Ka_3 = (\delta_L / \eta)^2 \quad (6)$$

where η is the Kolmogorov microscale. Peters⁽¹⁶⁾ suggested this equation can be transformed to $0.608 (u' / S_L)^2 R_L^{-0.5}$ using the relation $\epsilon = 0.37 u'^3 / L$ which is assumed when Eq. (5) was deduced. The constant factor of this equation is 3.9 times larger than that of Eq. (4).

It should be noted that these Karlovitz numbers include only the strain rate of turbulence and does not include bulk strain rate induced by the mean flow. Figure 4 shows Ka 's at the extinction, using the measured values reported by Yoshida et al.⁽¹⁰⁾. Ka_1 profile should coincide theoretically with Ka_2 profile,

Fig. 4 Extinction Karlovitz numbers as functions of equivalence ratio

because the coefficient of Ka_2 is adjusted to satisfy Ka_1 . However, if we use the actual values measured in the cold flow, Ka_1 curve is slightly larger than the Ka_2 curve consistently. This difference can be attributed to the fact that the unburned mixture was anisotropic and that the Kolmogorov microscale may be overestimated. The Ka_3 profile should be larger than the previous two profiles but is similar to these two profiles between $\phi=0.65$ and 1.2 at about 0.01 and deviates from previous two curves above $\phi=1.2$. This fact also can be attributed to the anisotropy of turbulence and the overestimation of the Kolmogorov microscale. In addition, the actual flame thickness is much larger than the theoretical Zel'dovich characteristic length $\delta_L = \nu/S_L$. On the rich side, the extinction Karlovitz number increases sharply due to the stabilizing effect of the outer diffusion flame.

For the counterflow geometry, Yoshida et al.⁽¹⁰⁾ suggested that the flame may be subjected to the strain of the mean flow. As mentioned before, the extinction of the turbulent flame occurs when the total stretch rate (sum of the bulk strain rate and turbulent strain rate) coincides with the critical stretch rate of the laminar flame at extinction. The turbulent strain rate can be expressed by the inverse of the Kolmogorov time scale. Here, we modified the Bray's expression Eq.(5) to involve the bulk strain rate of the mean flow as follows,

$$Ka_4 = 0.258 t_L / t_r \quad (7)$$

where $t_r = a_r^{-1}$. In Eq.(7), for the limiting case of the strong turbulence, we can assume $a_r = a_t$ and $t_r = t_\eta = a_t^{-1}$ and coincides with Eq.(5). Figure 4 also shows the profile of Ka_4 . Ka_4 is nearly constant within the inflammability limits of propane and is about 0.15 . If the Lewis number is of the order of unity, this value agrees well with critical Karlovitz number at which the break-up of continuous flame sheet occurs in the

Fig. 5 Effective Karlovitz numbers evaluated using the actual flame thickness and laminar burning velocity

vessel where the bulk strain rate is negligible⁽²⁾. In the estimation of chemical time, the problem is how to determine the laminar flame thickness δ_L and the laminar burning velocity S_L . These various expressions of extinction Karlovitz number indicate that the same criterion can be simultaneously interpreted on spatial, temporal and nondimensional grounds. Gökalp⁽⁹⁾ found the extinction Karlovitz number varies from 0.01 to around unity, a variation over 2 orders of magnitude depending on the method of evaluation of δ_L and S_L . In the estimation of chemical time scale, we used the Zel'dovich characteristic length which is expressed by ν/S_L . Recently, scatter of the measured laminar burning velocity S_L diminished extensively by the improvement of the measuring method. Here, we used the laminar burning velocities obtained by Yamaoka and Tsuji⁽¹⁷⁾. As for the thickness of laminar flame δ_L , Jarosinski⁽¹⁸⁾ obtained the magnification factor S of 5.1 as compared to the Zel'dovich characteristic length by solving the energy equation of steady state one-dimensional laminar flame. In our preliminary experiments, we have found that the flame thickness resulting from the mean temperature distribution is about 5 times larger than the Zel'dovich characteristic length. Therefore, we multiplied the Karlovitz number by a factor S of 5 to obtain the effective Karlovitz number KaS and shown in Fig.5. Within the inflammability limits, the effective extinction Karlovitz number is of the order of unity. Therefore, for the premixed counterflow wrinkled laminar flame produced in the forward stagnation region of the porous cylinder or hemisphere, the extinction occurs at the effective Karlovitz number of about unity.

3. Regimes of Turbulent Premixed Flame

3.1 Wrinkled laminar flame

The several diagrams which show the regimes of turbulent premixed flames have been suggested by many authors using independent non-dimensional parameters, Dulger and Sher⁽⁴⁾ noticed that the Damkohler number can be deduced from the Karlovitz number if one can assume the numerical factor in the relation $\eta/L \propto Re^{-0.75}$. The structure of turbulent premixed flame depends strongly on the Damkohler number, which shows the ratio of characteristic turbulence time to characteristic chemical time. The Damkohler number is the inverse of the Kobaszney number⁽¹⁹⁾, which separates the surface combustion regime from the volumetric combustion regime. When the Damkohler number is extremely large, the chemical reaction will complete before the turbulence affects thin laminar flame structure. Therefore, the characteristic feature of the purely laminar flame persists. Because the characteristic turbulent time is large relative to the chemical time, the turbulent strain rate is small and the so-called wrinkled laminar flame is produced. As mentioned before, such a flame will be extinguished when the total strain rate coincides with the critical stretch rate at which the laminar flame extinction occurs⁽¹⁰⁾.

Gökalp⁽⁹⁾ pointed out the importance of the Damkohler number, which is the inverse of the Kobaszney number for the interpretation of Klimov-Williams criterion⁽²⁰⁾. Kobaszney⁽¹⁹⁾ suggested that the surface combustion shifts to volume combustion by the increase of Kobaszney number. However, the flame zone thickness becomes thinner with the increase of Karlovitz number. In the present burner configuration, the thin wrinkled laminar flame could not produce the flame zone broadening. Instead, both flames should extinguish entirely. Therefore, fundamentally two modes should exist in the turbulent premixed flame structure as pointed by Damkohler⁽²¹⁾ fifty years ago. We believe that the wrinkled laminar flame will be extinguished abruptly at the critical strain rate of the purely laminar flame. The wrinkled laminar flame will be locally extinguished when the local stretch of segment of the continuous laminar flame exceeds the critical strain rate. However, re-ignition occurs by the stochastic manner of the turbulence. As a result, the broken laminar flamelets are generated. The number of the broken laminar flamelet increases with the turbulence intensity and the surface density of the flamelets also increases. Therefore, reaction zone is still maintained at the rates much larger than the extinction stretch rate of a wrinkled laminar flame. It can be considered that

another flame structure in which the flamelets are closely packed will exist at strong turbulence with small scale, because flame reiterates extinction and re-ignition in turn and the flame surface density increases. Eventually, if the Kolmogorov scale is much smaller than the flame thickness, the flame zone is broadened and the Karlovitz number is larger than unity. In the practical burners, the combustion will be chaotic. The re-ignition of the wrinkled laminar flamelets occurs depending on the burner configuration. Wrinkled laminar flame is stabilized at some location of the combustors and also at another part distributed reaction zone will be produced. Therefore, the transition will be smooth in the practical combustors. Nevertheless, the extinction limit of the laminar premixed flame obtained in the present study is important as a fundamental property of laminar flame.

On the other hand, we can expect that the different structure of the premixed flame can exist when the characteristic turbulent time scale is extremely short as in the stirred reactor. Small-scale turbulence intrudes into the purely laminar flamelets closely packed and destroys the laminar flamelet structure, and the transport phenomena in the reaction zone is enhanced by the small-scale turbulence. To destroy the laminar flamelet structure and to make the reaction volume uniform, Williams⁽²⁰⁾ suggested that Kolmogorov microscale η should be smaller than the laminar flame thickness δ_L . Therefore, $\eta = \delta_L$ is the extreme condition which separates the wrinkled laminar flamelets from the distributed reaction zone, and is referred to as the Klimov-Williams criterion. However, we do not have any knowledge about the structure of such flame and there exists scarce experiments which prove the existence of the distributed reaction zone. Abdel-Gayed et al.⁽²⁾ constructed the combustion diagram in which the distributed reaction zone is located in the flame quenching regime. The quenching regime is separated from the flamelet regime by the transition regime in which break-up of continuous flame sheets and the re-ignition of quenched region occurs and fragmented reaction zones are generated.

Abdel-Gayed et al.⁽²⁾ suggested that the Karlovitz number modified by the Lewis number would be an appropriate criteria for predicting the state of complete extinction of flames in practical engines. However, recently, several researches have reported about the flame zone broadening of the turbulent premixed flames by the small scale eddies, instead of quenching. As mentioned before, wrinkled laminar flame actually extinguishes partly at effective Karlovitz number $KaS=1$, if the wrinkled laminar flame is thin. If the

Fig. 6 Opposed jet burner to produce the distributing reaction zone

turbulent time scale becomes smaller as compared to the chemical time scale, small scale eddies may cause the reaction zone broadening in the range of $KaS > 1$.

3.2 Distributed reaction zone

Data set used here is from the experiment of the opposed jet premixed flame. Figure 6 shows the opposed jet burner that was designed to produce the distributed reaction zone. The elements are the two oppositely placed tubes of which inside diameter is 10 mm and 500 mm long. Impingement of two opposed turbulent mixture jets generates a strong turbulence with small scale. An inner rod of outer diameter of 3 mm was installed along the center of the two tubes. Resulting annular jets provide the stable impinging jet flow field. Impinging mixture jets change the direction radially and a stable annular turbulent flame is produced in the radial turbulent mixture flow. Propane was used as fuel. The turbulent flame was stable over a wide range of the mixture jet velocity V_j up to 40 m/s. In the impinging flow field, the turbulence intensity is high and the scale of turbulence is extremely small. Even for $V_j = 9.1$ m/s, maximum fluctuating velocity u'_0 is about 3 m/s and for $V_j = 30.4$ m/s, u'_0 is 7 m/s. These values are by one order of magnitude greater than those produced by the turbulence-producing grids.

The detailed velocity measurements were made by hotwire anemometer. The typical value of strain rate of the stable opposed jet burner flame estimated by Eq. (2) is $3 \times 10^4 \text{ s}^{-1}$ for $V_j = 30.4$ m/s as compared to 1900 1/s which is the maximum extinction limit of propane-air mixture. As mentioned before, the wrinkled laminar flamelets should be extinguished locally at such a high strain rate as $3 \times 10^4 \text{ s}^{-1}$. The Karlovitz number estimated by Eq. (3) for the opposed jet burner is 0.20 by using the Zel'dovich flame thickness. In Fig. 4, we can see that Ka_1 is about 0.01. Therefore, if these flames are the wrinkled laminar flames or

laminar flamelets, the reaction zone itself cannot exist locally. It is a fact that we can stabilize an opposed jet flame in the regime where the wrinkled laminar flame should be extinguished. Therefore, there cannot exist the flame surface and reaction should occur volumetrically. The continuous wrinkled laminar flame is torn to flamelets by the stretch rate larger than the critical stretch rate of laminar flame. Because the turbulence is chaotic, the number of flamelets distorted by turbulence increases with the turbulent intensity, and flame surface density increased. Eventually the Kolmogorov scale is smaller than the flame thickness and flame zone is broadened and the Karlovitz number is larger than unity.

The transition from the wrinkled laminar flame to the distributed reaction zone is interesting. Flame zone broadening due to the intrusion of the small scale eddies is confirmed by the Laser-Induced Predissociation Fluorescence (LIPF) by Chen et al.⁽³⁾ with a turbulent Bunsen flame. The stretch rate at which the extinction occurs exceeds over three times larger than the laminar flame extinction limits of propane. In addition, the definition of the stretch rate was rather crude. More generic definition will provide much larger value such as effective Karlovitz number KaS . Anyway, it can be concluded that even if the stretch rate exceeds the critical stretch rate at which laminar flame should be extinguished, the broadened reaction zone can exist. Dulger and Sher⁽⁴⁾ discussed the flame broadening by the turbulence scale smaller than the laminar flame thickness and the effect of the non-unity Lewis number. Shy et al.⁽²²⁾ employed an aqueous autocatalytic reaction in a Taylor-Couette flow system. This system provided factor of 330 change in Karlovitz number. The distributed reaction regime was easily achieved with transition at $Ka \propto O(1)$. No global extinction was observed even at values of Ka more than 2500 times greater than those at which gaseous flame is extinguished.

Karlovitz number can be thought of as the ratio of the mean rate of hydrodynamic strain in a turbulent flow field to mean chemical reaction rate. Ronney and Yakhot⁽²³⁾ recognized the importance of the small scale turbulence and suggested that, at large Karlovitz number, flame front broadening occurs by the small eddies. At sufficiently high Ka , it is expected that all scales of turbulence would lie inside the broadened high Ka , it is expected that all scales of turbulence would lie inside the broadened flame front, this regime of turbulent combustion is referred to as distributed combustion and is thought to have properties quite different from flamelet combustion. They assumed the flame front broadening by small scales. However, this broadened flame front is assumed to be

subjected to wrinkling by the scales of turbulence larger than flame front in exactly the same way as thin laminar flamelets. They applied essentially the partly distributed combustion. Indeed, the transition mechanism from the wrinkled laminar flamelet to the distributed reaction zone is still controversial and further investigations are needed.

4. Conclusion

(1) If the Kolmogorov microscale is larger than the laminar flame thickness, extinction of the wrinkled laminar flame occurs, when the sum of the bulk strain rate and the turbulence strain rate estimated by the Kolmogorov time scale. This total stretch rate coincides with the critical velocity gradient of the laminar flame. At the state of extinction, the effective Karlovitz number Ka_S is about unity.

(2) The wrinkled laminar flames is extinguished at a constant Karlovitz number within the inflammability limits. There are some expressions for the definition of the Karlovitz number even though the definition is the same. The calculated Karlovitz number at the state of extinction is different depending on the choice of the chemical and turbulent parameters. This is due to the fact that the mixture turbulence is anisotropic and that there exist ambiguities in the expression of flame thickness and laminar burning velocity.

(3) If the Kolmogorov microscale is smaller than the laminar flame thickness, small scale eddies broaden the flame zone and the distributed reaction zone is stabilized even though the effective Karlovitz number Ka_S is greater than unity.

(4) Stable distributed reaction zone can be achieved by the impinging jets, even though the stretch rate is about 20 times and the Karlovitz number is 200 times larger than those at which the wrinkled laminar flames is extinguished

(5) The laminar flamelets are generated from the wrinkled laminar flame by the local extinction of the wrinkled laminar flame. With increasing the turbulence intensity, the surface density increases which leads to the distributed reaction zone.

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