Elementary processes governing behavior of turbulent premixed flames

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Abstract

Present knowledge on elementary processes governing the behavior of turbulent premixed flames is summarized. The movements and configurations of local reaction zones or flame fronts in the overall reaction zones of stationary turbulent premixed flames and typical aspects of the turbulence behavior of propagating flames under various conditions and situations are presented. To give basic knowledge on the processes governing behavior of turbulent premixed flames, recent results of experimental studies on flame behavior under several simple sets of conditions, including rotating and accelerating flow fields, are introduced. Finally, effective processes governing the behavior of turbulent premixed flames are discussed. It is pointed out that presently available data are not sufficient to understand the structure of turbulent premixed flames. The transport phenomena within local reaction zones and aerodynamical effects on the local reaction zones seem to be the most important subjects to discuss.

INTRODUCTION

Knowledge of behavior of turbulent premixed flames is necessary for the design of combustors or the assessment of accidental gas explosion hazards. Thus, various studies on this subject have been performed (refs.1–10). In order to understand the behavior of the turbulent premixed flames, dynamic structures of the overall reaction zones should be elucidated, because in a number of models for the prediction of the characteristics of turbulent premixed flames, various dynamic structures of the flame zones have been assumed (refs.1–10). However, in most cases, such assumptions are not based on acceptable evidence.

If an assumption of a wrinkled laminar flame will be adopted, the structure across a flame element should be confirmed to be the same as that of laminar premixed flame. The corrugated flame front must be the results of the interaction with gas flow turbulence, and in such a turbulent flow, turbulence components of scales smaller than the flame front thickness are included. For adopting the wrinkled laminar flame assumption, the effect of small scale turbulence on the structure across the flame front should be confirmed. In most studies on wrinkled laminar flames, only the ratio of the Kolmogoroff scale based on the cold mixture flow approaching to the flame front to the laminar flame thickness has been evaluated (refs.11,12), and if the ratio is larger than unity the flame is believed to be a laminar wrinkled flame. The most reliable means to confirm the appropriateness of the assumption would be comparison of the structure of a local flame front in the reaction zone of the turbulent premixed flame to that of a laminar one. However, such comparison has never been performed.

A criterion for a distributed reaction zone is much difficult to confirm. In recent experimental studies, it has been revealed that even the reaction zone of a turbulent premixed flame established under the conditions to have a distributed reaction zone is composed of fragments of fluctuating corrugated thin flame fronts and the flame front thickness is almost the same with that of a laminar premixed flame (refs.13–15). It seems to me at present that an enormous effort is needed to experimentally confirm the possibility to exist a turbulent premixed flame with distributed reaction zone. Despite of such a situation, a large number of theoretical studies have been performed on the characteristics of turbulent flames in the distributed reaction zone regime (refs.5–7,9,11,12).

The flame front movements caused by the turbulent flow of the unburned mixture and/or the resulting flame front configurations have been assumed in various models of turbulent premixed flames (refs.5–12). Thus, it is clear that knowledge of the flame front movements is extremely important for understanding the characteristics of turbulent premixed flames. In recent studies on this subject, some amount of data have been obtained (refs.13–18). By analyzing the data, the structure of turbulent premixed flames could be elucidated to a further extent.

The concept of flame induced turbulence has been adopted to interpret certain characteristics of turbulent premixed flames. Existence of flame induced turbulence can be confirmed if detailed information on the flame front movement and flow field will be given. In some studies, the acceleration of a flame in a vortex has been attempted to prove (refs.19–21), and in others, flame front turbulence has been shown to grow in an accelerating flow field (refs.22–26). In these studies, several important results have been obtained which partly support previously proposed hypotheses concerning flame induced turbulence, and at the same time a number of novel findings on the flame front behavior caused by the flame–flow interaction.

Thus, understanding of elementary processes governing behavior of turbulent premixed flame is indispensable for future studies on turbulent premixed flames. In this paper, the results of recent studies on dynamic structures of turbulent premixed flames and premixed flame behavior under controlled conditions are summarized. Based on the presently available data, effective processes governing the behavior of turbulent premixed flames are discussed.

BEHAVIOR OF TURBULENT PREMIXED FLAMES

A typical instantaneous flame front configuration recorded by schlieren photography is shown in Fig. 1 (refs.16,27). This turbulent flame was stabilized on a cylindrical turbulent flame burner of 54 mm in diameter, to which a uniform propane–air mixture with the equivalence ratio of 1.1 was supplied. The turbulence was generated by inserting a perforated plate with 250 holes, 2.0 mm in diameter, 60 mm upstream of the burner port. The mean velocity and turbulence intensity of the unburned mixture stream were uniform at the burner port except for the layer within 4 mm of the burner wall, and were 4.4 m/s and 6.3 %, respectively (ref. 27). In this case, the flame front turbulence was caused by the initial gas flow turbulence in the flammable mixture.
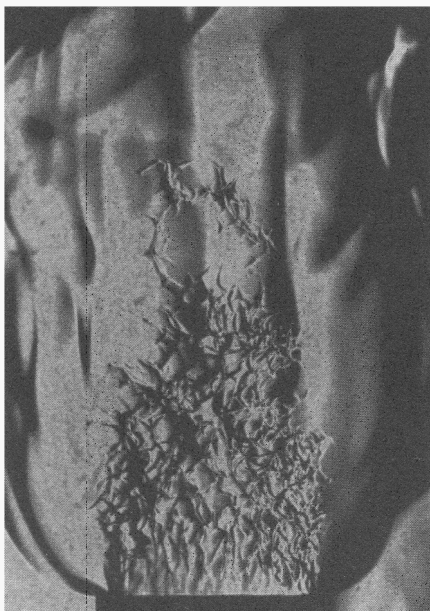

Fig. 1.   Instantaneous schlieren photograph
          of a premixed turbulent burner flame.

U : instantaneous unburned gas velocity
U_n : normal component of U
S_L : laminar burning velocity
V_f : measurable flame velocity

$$V_f \approx U_n + S_L$$

flame front at t_1
flame front at t_2
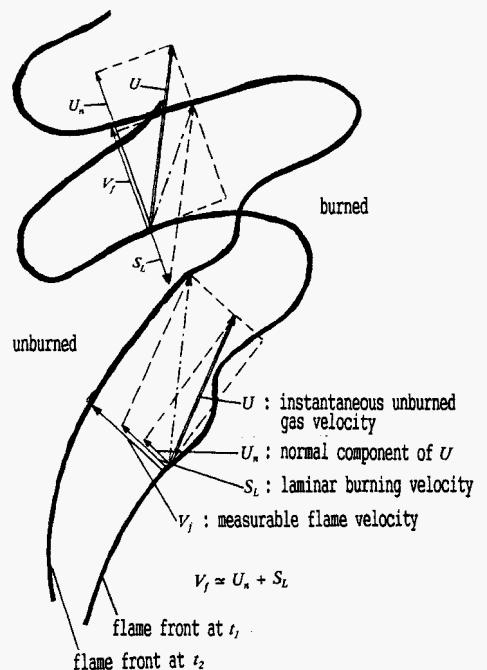
burned

unburned

Fig. 2.   Instantaneous flame front
          configuration and movement

Although the schlieren image on a photograph is of an integral along the optical path, qualitative information on the behavior of the local flame front can be obtained by examining the variation of the schlieren front on a series of schlieren images. It is clear that the direction and velocity of local flame fronts can be easily determined, because the local flame front is observed to move in only gradually changing its configuration (ref.17). To examine these instantaneous movements of local flame fronts in detail, Suzuki et al. (ref.16) used a micro-electrostatic probe composed of two identical platinum wire sensors of 0.1 mm in diameter and 1.5 mm long, where the axes were parallel at a distance of 1.3 mm, and later Suzuki and Hirano (ref.17) used an improved one composed of three sensors, where the axes were 1 mm apart from each other in a triangle array. Local flame front movement is shown to change considerably from one instant to another. The scatter of the velocity vector directions and magnitudes increases as the measuring point moves from the unburned side of the flame zone to the burned side. At the outermost of the flame zone, the flame front moves downward at a certain instant, while at another instant the flame front velocity occasionally attains a value 3 times as large as the average value in the direction close to the average direction. The flame front movements at the top and side of the flame zone are almost the same, although the mean ion current and the turbulent flame zone width are different at these two locations. These flame front behavior must be closely related to the flow field. Suzuki et al. (ref.18) measured simultaneously the instantaneous local flame front movement and the flow velocity of unburned mixture or burned gas near the flame front in a turbulent flame zone by using a micro-electrostatic probe with three sensors and a dual beam LDV system. Although the directions and magnitudes of the vectors representing flame front movements are scattered, the local flame front movement can be expressed as a vector sum of the burning velocity and the flow velocity component of the direction which it faces. The flame front behavior mentioned above is summarized in an illustration shown in Fig. 2.

Figure 3 shows an instantaneous schlieren photograph of a part of high intensity turbulent premixed flame in a strong sheer flow region established on a co-axial burner composed of an inner tube of 26 mm in diameter and
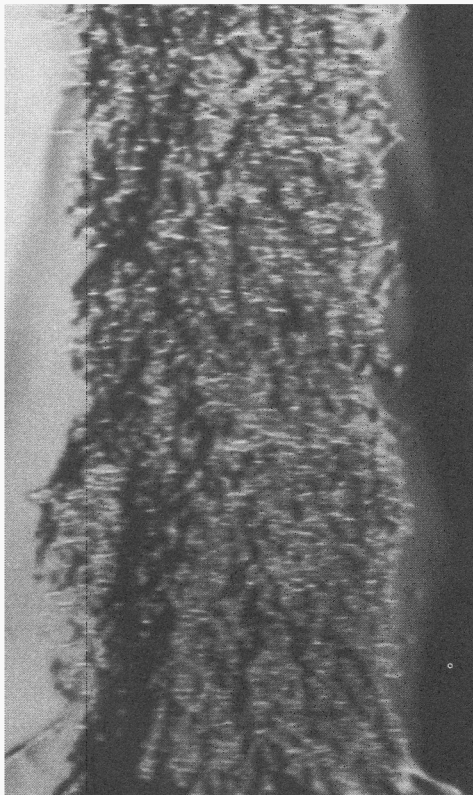

Fig. 3. Schlieren photograph representing configuration of a high intensity turbulent premixed flame stabilized in a sheer flow of a propane-air mixture.
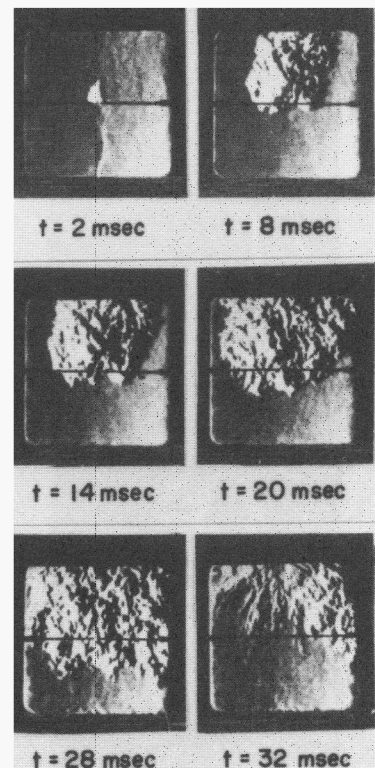

Fig. 4. Series of schlieren photographs representing a flame propagation through a non-uniform methane-air mixture with gas flow turbulence in a small vessel.

an outer circular nozzle of 52 mm in diameter (refs.13,14). The conditions under which this flame is established are for the distributed reaction zone on the Klimov–Williams criterion (ref.7). In this particular case, a propane–air mixture was supplied at a high velocity (20 m/s) to the inner tube and at a low velocity (1.7 m/s) to the outer circular nozzle. Indeed, the local reaction zone configuration with fine curvature is seen to be extremely different from those of low or moderate intensity turbulent flames (see Fig. 1). However, the movement of the local reaction zone can be determined by analyzing an ion current record measured using an micro–electrostatic probe. Furukawa et al. (ref.14) measured the flame shown in Fig. 3 using a micro–electrostatic probe with a platinum wire sensor of 0.1 mm in diameter and 0.5 mm long and concluded that even in the extremely intense turbulence which satisfies the distributed reaction zone condition based on the Klimov–Williams criterion, the local reaction zone thickness is close to that of the laminar flame. This implies necessity to discuss the structure of the distributed reaction zone or to establish a novel criterion for existence of the distributed reaction zone not based on the characteristics of unburned mixture turbulence. This example is the premixed burner flame with the most intensely turbulent flame front which has ever been visualized. However, the behavior of the local flame fronts seems to be controlled by a similar mechanism to that of the first example, i.e., it depends on the gas flow field and the local burning velocity.
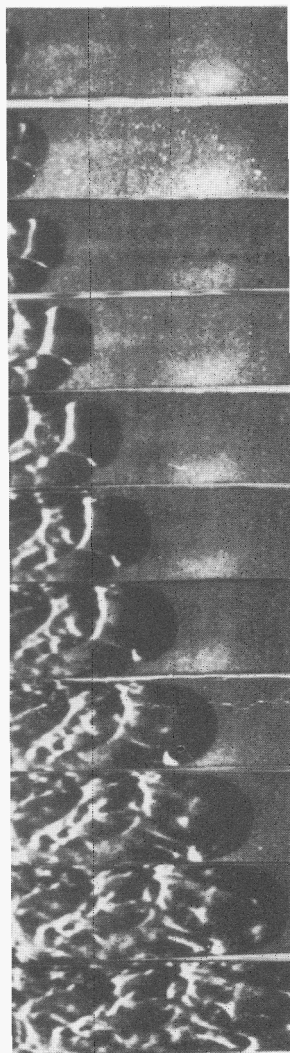

Fig. 5. Series of schlieren photographs representing a flame propagation through a tube. The time interval between adjacent photographs: 0.3 ms.

The flame front behavior of a propagating flame is obviously related to the movement of flammable mixture fragments and/or the non-uniformity of combustible gas concentration ahead of the flame (refs.28,29). The flame propagation velocity, which has been believed to be a measure of the intensity of flame front turbulence, increases with the increase of the gas flow turbulence, and in a number of previous studies of turbulent premixed flames, the dependence of the flame propagation velocity on the intensity of gas flow turbulence has been investigated. Also, based on the characteristics of premixed flames, it can be postulated that non-uniformity of gas concentration makes the flame front turbulent, although only a few studies have been performed on this subject (refs.28,29). Figure 4 shows a series of schlieren photographs representing a turbulent flame propagation through a non-uniform mixture of methane-air with gas flow turbulence in a combustion vessel of 8 cm cube (ref.29). In this experimental study, Dobashi et al. (ref.29) examined the effects of non-uniformity of methane concentration as well as gas flow turbulence on the flame behavior, and indicated that the effects attributable to the non-uniformity of methane concentration can be interpreted considering the resultant non-uniform burning velocity field.

It is well known that a flame propagating through a flammable gas–oxidizer mixture in a tube or duct becomes turbulent when turbulence is generated in the mixture flow induced by the flame propagation. This turbulence is caused by the friction of the mixture flow with the wall, so that the condition for laminar-turbulent transition of a propagating flame is closely related to that of a gas flow (ref.30,31). Figure 5 shows a series of schlieren photographs representing a flame propagation through a tube of 30 x 30 mm cross section and 1290 mm long at an initial pressure of 500 mm Hg. It is seen that in this case the pattern of flame front turbulence observed behind the leading flame front propagates in the same direction with flame propagation. Based on the photographs presented in ref.31 and Fig. 5, it can be easily indicated that the direction of flame turbulence propagation depends on the condition of tube ends and is the same with that of the burned gas flow behind the leading flame front.

Knowledge on the growth of flame front turbulence seems to be helpful to understand the behavior of turbulent premixed flames. The most practical means to make a propagating flame front turbulent is to place obstacles in the way of flame propagation (refs.32,33). When a flame is propagating through a flammable mixture acceleratedly flowing across a block in a channel, a few different types of turbulence can be observed (ref.25). Flame front turbulence appears on the leading flame front normal to the direction of mixture acceleration. Then, the intensity of turbulence increases very rapidly and the flame front structure becomes needle like. This type of flame front turbulence is inferred to be induced by thermodynamic force acting near a curved flame front under acceleration (or pressure gradient). The turbulence of the flame front parallel to the direction of mixture acceleration appears on the flame front close to the top of the block. The area of this type of flame front turbulence spreads gradually, and its intensity seems to increase very slowly. The scale of the flame front turbulence induced by this mechanism is seen to be much larger than that observed at the flame front normal to the direction of acceleration. This type of flame front turbulence is the same as that numerically predicted by Oran et al. (ref.34). Another type of flame front turbulence appears near the walls of the channel. This type of turbulence is inferred to be caused by the mixture flow turbulence near solid walls. The intensity of this common type of flame front turbulence increases slowly and its scale seems to be close to that appearing on the flame front parallel to the top surface of the block. For the case when a premixed flame propagation across a row of obstacles, the dominant mechanism of turbulence growth at the flame front is probably the same as that for the case of a single obstacle. At the same time, however, the flame front turbulence in this case must be enhanced by the gas flow turbulence inherently induced by the interaction between the gas flow and obstacles ahead of the flame.

PREMIXED FLAME BEHAVIOR UNDER CONTROLLED CONDITIONS

As mentioned in the preceeding section, the turbulence at a premixed flame is caused by a set of several mechanisms (refs.8,31). To understand the characteristics of turbulent premixed flames, the effect of each mechanism on the flame front turbulence should be clarified. To this end the most effective way is believed to prepare a simplified phenomena under controlled conditions. In the present section presented are some representative examples of studies on premixed flame behavior under controlled conditions.
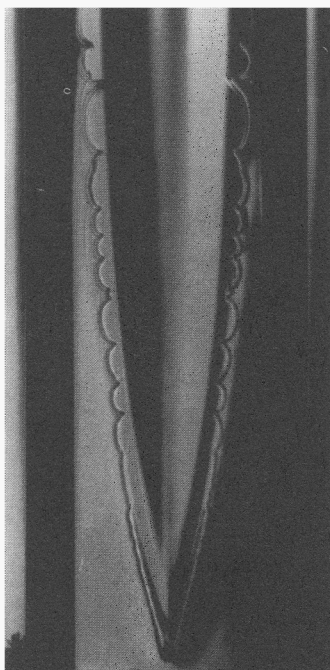
It can be easily understood that the characteristics of turbulent premixed flames depend on initial gas flow turbulence in the flammable mixture. Based on the analogy to the definition of the laminar burning velocity, the turbulent burning velocity has been introduced as the normal component of the mean flammable mixture velocity relative to the turbulent burning zone. The turbulent burning velocity has been considered to be a representative quantity which characterizes a turbulent flame (refs.1–12) and believed to be closely related to the turbulence intensity. A number of studies have been performed to reveal this relation (ref.10). Although the relations obtained in the previous studies are so scattered, a common conclusion is that the turbulent burning velocity increases with the initial turbulence intensity. Indeed, the flame front turbulence depends on the characteristics of initial gas flow turbulence in a flammable mixture approaching a stationary premixed turbulent flame or ahead of a propagating one. At the same time, turbulence must be enhanced by various mechanisms (refs.8,31).

Fig. 6. Instantaneous schlieren photograph of a flame stabilized by a cylinder in uniform laminar flow of a flammable gas.

Figure 6 shows a schlieren photograph of the turbulent premixed flame anchored by a cylinder of 3.8 mm in

diameter installed across a rectangular channel through which a uniform laminar propane–air mixture is flowing (ref.35). The flame front disturbance appearing behind the cylinder propagates downstream with the increase of its amplitude. This result implies that the flame front disturbance grows without the turbulence in the approaching flow. In this study, Yashima et al. (ref.35) also discussed on the mechanisms of turbulence generation near the cylinder. They inferred that the generation of the flame front disturbance was caused mainly by the flame–flow interaction in the narrow region near the cylinder and the coupling of the flame behavior in both sides occurred.

The flame front disturbance is known to be caused and enhanced by preferential diffusion. The effect of the preferential diffusion is observed for the cases when diffusivity difference of the fuel gas from the oxidizer gas is distinct and the concentration of a larger diffusivity species of the fuel or oxidizer is deficient. The aspect of a premixed flame stabilized by a cylinder as shown in Fig. 6 changes significantly with the mixture composition. For a rich propane–air flame examined in ref.35, the disturbance was observed to be irregular and the average frequency increased.

Since a premixed flame is a wave with exothermic chemical reaction, the flame front is a boundary between cold and hot gases. The boundaries of this type are known to be sensitive to the flow field. The above case is an example of the flame–flow interaction. In some of studies on turbulent flames, the vortices in the mixture flow are assumed to enhance flame front turbulence (ref. 12). To confirm the possibility of the turbulence enhancement by vortices, a few studies have been performed of flame propagation in rotating flow fields (refs.19–21). Figure 7 shows a direct photograph of a flame propagating through rotating methane–air mixture flows in a horizontal glass tube of 31 mm in inner diameter and 1000 mm in length (refs.20,21). When a flame propagates through a rotating flow field, the flame velocity becomes much higher than that in a flow field without rotation (refs. 20–21). For a propagating flame in a rotating flow field, a pressure gradient must be established across the leading flame front, which causes a flame velocity much faster than that in a tube without rotation. However, the flame velocity depends on the intensity of rotation, so that the flame does not accelerate without the increase of rotation. This implies that once the flame velocity becomes in an equilibrium with the pressure gradient caused by rotation, the flame does not accelerate any more. This mechanism controlling the flame front behavior still seems important to interpret the flame front behavior in the flame zone of a turbulent flame.
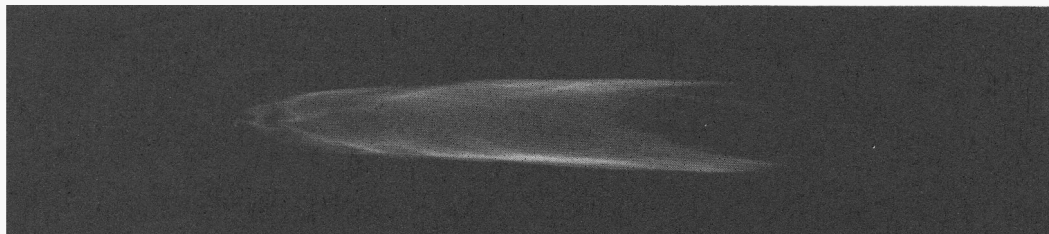

Fig. 7.   Direct photograph of a flame propagating through a rotating methane–air mixture flow in a horizontal glass tube.

Flame front disturbance is extremely sensitive to acceleration or deceleration of the flame(refs.22–26). The effects of compression, rarefaction, and acoustic waves on the flame front disturbance would be interpretable based on the same principle, i.e., these waves cause acceleration or deceleration of the flame front and result in enhancement or suppression of the disturbance. As mentioned in the preceeding section, a typical example of enhancement of flame front disturbance by this mechanism can be found in ref.25. Also, flame front turbulence was observed to be suppressed when a turbulent flame was approaching a blunt body where the gas stream induced by the flame propagation decelerated (ref.36).

The details of the process of enhancement or suppression of flame front turbulence have been studied in a series of studies by Tsuruda et al. (refs.22–26). They examined the behavior of flame front turbulence when a flame propagates through a converging and diverging nozzle filled with a methane air mixture and obtained a quantitative relation representing the effect of acceleration on the induction time t_{fd} of turbulence generation (ref.24). The result is shown in Fig. 8. It is seen that a reciprocal $1/t_{fd}$ of the induction time is linearly increases with the increase of acceleration rate $(dV_f/dt)_d$ at appearance of the flame front turbulence. Despite the interpretation on the effects of preferential diffusion in previous studies (refs.11,37), only slight enhancement of the turbulence development appears at the flame front propagating through a rich propane–air mixture.
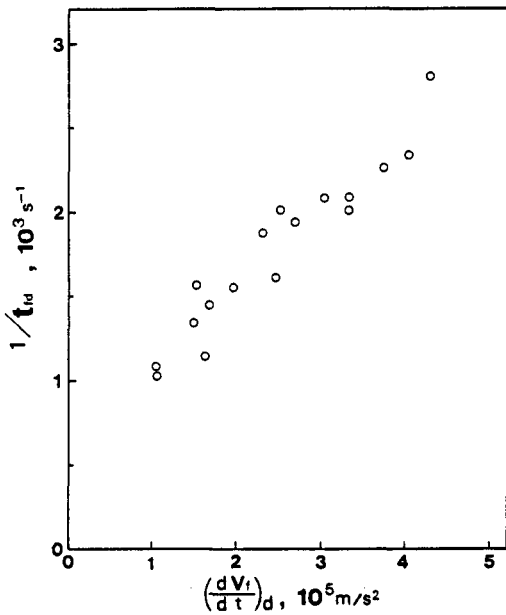
Fig. 8.
Variation of a reciprocal of the induction time with the acceleration rate.

The process of flame front deformation during acceleration was also examined in detail (ref.26). In this case, the rate of acceleration was kept much smaller than those adopted in the study presented in ref.24. Even for a small rate 9.0×10^3 m/s² of flame acceleration, however, the flame front deformation was observed to proceed very rapidly. A local flame front was found to move at a relative velocity of 10 m/s to the other parts of the flame front.

EFFECTIVE PROCESSES GOVERNING FLAME BEHAVIOR

The most important knowledge to understand the characteristics of a turbulent premixed flame must be the transport phenomena within individual local reaction zones in a turbulent flame zone. If the transport phenomena within local flame zones of a turbulent premixed flame can be assumed to be the same as those of a laminar flame, the flame is classified into a wrinkled laminar flame, while if the transport phenomena depend mainly on the mass and heat exchange by turbulence, the flame is classified into a distributed reaction zone flame.

A reacting mixture fragment in the reaction zone of a turbulent flame must move with the movement of surrounding gas. For a usual hydrocarbon–air premixed flame, the time needed from the start of reaction to its finish is $10^{-3} - 10^{-2}$ s. Therefore, the reacting mixture fragment is assumed to be reacting within this time duration. The distance corresponding to this time duration must be the local flame zone thickness which depends on the mixture flow velocity across the local reaction zone where the fragment passes. This flame zone thickness for a laminar wrinkled flame is almost equal to that of a laminar flame, while that of a distributed reaction zone flame must be much larger.

The above discussion on the characteristics of a turbulent premixed flame is based on the thickness of the local reaction zone and the relative gas velocity across it. To elucidate the local reaction configuration needed is the information on movements of reacting mixture fragments. A few studies have been done to examine local reacting mixture fragments in the reaction zone of a turbulent premixed flame (refs.13–18). It is revealed in these studies that the mean velocity of local reaction zones (flame fronts) is almost the same with the mean gas velocity although the mean direction of its movement is slightly different from that of the gas movement (refs.16–18). Based on these results, it can be assumed that only the turbulence component of the gas flow is effective to characterize the flame zone of a turbulent premixed flame.

The turbulence component, the scale of which is larger than the thickness of a local reaction zone, must be effective for the overall movement of the local reaction zone but not effective to enhance the transport phenomena within it. Since the classification of the turbulent premixed flames is considered to be based on the transport phenomena within the local reaction zone, the effect of turbulence component, the scale of which is smaller than its thickness, on the transport phenomena must be examined to determine the characteristics of a turbulent premixed flame. In the studies on turbulent premixed flames, however, their characteristics, especially the structure of the reaction zone, has been discussed on the basis of the overall turbulence intensity in the cold

mixture flow approaching the reaction zone. Thus, it is not astonishing that the local flame zone thickness of a flame satisfying the distributed reaction regime predicted in such a consideration is almost the same as that of a laminar flame (refs.13,14).

Of propagating turbulent premixed flames that I have ever seen visualized flame zones, the flame with the highest-intensity turbulence is that presented in ref.25. In this case, the flame front turbulence of a propagating flame is enhanced by acceleration. The scale of this type of flame front turbulence can be predicted by an instability theory to be a several times as large as the flame front (local reaction zone) thickness. This scale is almost the same as the smallest scale observed in the stationary turbulent premixed flame established in a high-intensity turbulent shear flow (see Fig. 3). Although a turbulent premixed flame is possibly established in a flow of much higher turbulence, the flame front thickness cannot be expected to increase drastically. So far, the flame front, within which the dominant mode of transportation is directly proved to be of gas flow turbulence, has never been realized for usual hydrocarbon-air premixed flames. It seems to me that further detailed studies on the turbulent premixed flame structure are needed to reach reasonable conclusions on this subject.

For a case when the transport phenomena in the local reaction zone of a turbulent premixed flame are not so much different from that of a laminar flame, the characteristics of the flame would depend on flame front movements and relating phenomena such as flame stretch and preferential diffusion. The flame front (local reaction zone) movement in the overall reaction zone of a turbulent premixed flame apparently depend on large-scale turbulence and laminar burning velocity if the coordinates are moved with the mean flow (refs.13-18). At the same time, the flame front movement should be influenced by the flame-flow interaction under acceleration, deceleration, or rotation as pointed out in the preceeding sections. When a local flame front is accelerating or decelerating, the flame front turbulence will be enhanced or suppressed, respectively, and when it comes across a vortex, its velocity will increase.

As mentioned in the preceeding sections, the flame front movement and its relation to surrounding flow field have been examined in detail for stationary turbulent premixed flames (ref.18). However, sufficient evidence has never been found for the existence of such effects in any stationary turbulent premixed flame, although these effects on the flame front movement are confirmed in experimental studies on propagating flames under controlled conditions (refs.19-26,28,29,36,37).

A few facts representing the aerodynamic effects of gas movement on the flame behavior have been pointed out in the studies on propagating turbulent premixed flames (refs.22-30). Those facts are summarized in ref.31. In a practical study on large scale vented gas explosions, Tamanini and Chaffe (ref.38) examined an acoustic effect on the flame propagation by changing the wall material. They indicated that the wall material absorbing acoustic waves is effective to suppress the pressure rise due to flame propagation. This effect can be interpreted by considering enhancement of flame front turbulence during acceleration caused by acoustic waves. It should be noted that such an effect has never been observed in small scale experiments. For the enhancement, a certain duration of time must be needed, so that the acoustic effect can be observed only in large scale experiments.

It can be easily supposed that the configuration of an individual local flame front is changing in the reaction zone of a turbulent premixed flame. A cusp-shaped or stretched flame front, where the effect of preferential diffusion or flame stretch should be considered, must result from this change. The effect of preferential diffusion has been pointed out in the studies on both stationary and propagating turbulent premixed flames. The aspects of flame front turbulence is known to depend on the type of mixture and its composition. When these conditions are in the ranges for appearance of the preferential diffusion effect, the flame front turbulence is observed to be intense and distinct. However, once the flame front turbulence equilibrates with the effect of preferential diffusion, it does not grow further (ref.39). In some cases, the effect of flame stretch has been supposed to be significant. However, there has never been any evidence showing the effect of flame stretch on local flame fronts in the overall reaction zone of turbulent premixed flames except for schlieren images representing the flame front movement.

Throughout above discussion, it has been shown that presently available data are not sufficient to understand the structure of turbulent premixed flames. Further studies are expected to accumulate data useful to elucidate the characteristics of turbulent premixed flames. Especially, novel findings concerning the movement and structure of local reaction zones are anticipated. At the same time, theoretical discussion on the structures of turbulent premixed flames should be done on the basis of novel findings in experimental studies. The transport phenomena within a local reaction zone and aerothermodynamical effects on the local reaction zone movement seem to be the most important subjects to discuss.

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