Generation of Flame Front Turbulence

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Introduction

A number of investigators, who are interested in the basic characteristics of premixed flames and/or the combustion phenomena during accidental gas explosions or in spark ignition engines, have studied the mechanisms by which a premixed flame becomes turbulent. The results of those studies, which have been summarized in several reviews [1-4] and books [5, 6] in the past, indicate that the turbulence at the premixed flame front is attributable to one or a set of the following causes:

1. Initial gas flow turbulence in the flammable mixture through which the flame propagates [3, 4, 7].
2. Non-uniform concentration (temperature, pressure, etc.) distribution in the flammable mixture [3].
3. Gas flow turbulence in the flammable mixture generated at the shear-flow region between the wall or obstacle and the gas flow induced by flame propagation [3, 4, 8].
4. Gas flow turbulence generated near the flame due to acceleration (or deceleration) parallel to it [3, 8].
5. Interaction of the flame front with an acoustic wave, or acceleration (or deceleration) of the gas flow normal to it [3,4,8-10].
6. Interaction of the flame front with the gas flow induced by the flame deformation (the later stage of 5) [3,4,8-10].
7. Diffusivity difference of the fuel gas from the oxidizer gas and/or the difference of mass and thermal diffusivities of the reactant (fuel or oxidizer gas) [11,12].

Some of these causes are well known to make the flame front turbulent but not yet confirmed to be effective to enhance the turbulence, while others are known to enhance the turbulence. However, the possibility of enhancement of flame front turbulence in the turbulent premixed flames caused by each mechanism is still ambiguous, although flame induced turbulence has been assumed in a number of theoretical studies on turbulent premixed flames.

In this article, present understanding is summarized on the mechanisms of the turbulence growth at the premixed flame front elucidated through recent studies.

Flame Front Turbulence Caused by Gas Flow Turbulence and/or Non-Uniform Concentration

Flame front behavior is closely related to the intensity of gas-flow turbulence and the non-uniformity of combustible gas concentration ahead of the flame [7]. Based on the characteristics of premixed flames, it can be postulated that non-uniformity of gas concentration makes the flame front turbulent, too [3]. However, the effect of the non-uniformity of gas concentration on the characteristics of premixed flames is somewhat different from that of the intensity of gas-flow turbulence.

The intensity of gas-flow turbulence in the component perpendicular to the turbulent flame zone should be enhanced due to the expansion of gas due to combustion [7]. On the other hand, the non-uniformity of fuel or oxidizer concentration may not be enhanced across the turbulent flame zone.

There are two possibilities of turbulence enhancement at the turbulent premixed flames established in a turbulent gas stream. One is the flame front turbulence enhancement caused by the turbulence intensity increase in the burned gas flow, and the other is that caused by local acceleration of the gas in the flame zone (Causes 4-6). The former may not much influence upstream flow field because the characteristic length of turbulence transfer could be the thickness of the turbulent flame zone. Also, the latter may not be appreciable because the growth of the turbulence at the flame front needs a certain period much longer than the characteristic time of the turbulence.

No one may indicate the possibility of turbulence enhancement at the turbulent premixed flames caused by non-uniformity of fuel or oxidizer concentration except for the turbulence induced by the diffusive-thermal mechanism (Cause 7). However, even the diffusive-thermal mechanism may not enhance the turbulence as discussed later.

Growth of Flame-Front Turbulence during Flame Propagation through a Tube or across an Obstacle

The flame-front turbulence generated at the shear-flow region between the wall and the gas flow induced by flame propagation is the most familiar one. It appears when a flame propagates through the flammable mixture in a tube or duct, and detailed accounts on this type of flame-front turbulence can be found in a number of previous papers on this subject [3, 8]. In this case the turbulence generation in the unburned mixture is essential. The mechanism of the turbulence enhancement if any must be the same with that in the turbulent premixed flame zone. The acceleration of the propagating flame may be caused not by the turbulence increase in the flame zone but by that in the unburned mixture.

It is of practical importance to know the dominant mechanisms of flame-front turbulence growth in commonly used systems and to control flame-front turbulence. The most practical means to make a propagating-flame turbulent is to place obstacles in the way of flame propagation.

A comprehensible experimental result was presented in Ref [8] as a series of photographs. When a flame is propagating through a methane-air mixture acceleratedly flowing across a block, 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 may be induced by the aerothermo-dynamical force acting near a curved flame front under acceleration or pressure gradient (Causes 5 and 6).

Later, turbulence of the flame front parallel to the direction of mixture acceleration appears on the flame front close to the top surface 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 induced by the mechanisms 5 and 6.

Another type of flame front turbulence appears near the top wall and window of the combustion chamber. This flame-front turbulence is caused by the mixture-flow turbulence near solid wall (Cause 3). The intensity of this common type of the 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 a case when a premixed flame propagates 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, and the aerodynamic force develops the turbulence. In this case, however, the flame front turbulence must be enhanced at the same time by the gas-flow turbulence inherently induced by the interaction between the gas flow and obstacles ahead of the flame.

Behavior of Flame Front Turbulence in an Accelerating or Decelerating Mixture Flow

The flame-front turbulence grows very rapidly in an accelerating mixture flow as mentioned in the previous section. Although this type of turbulence generation has been predicted since 1950's, the first clear proof of it was made in the late 1980's [8-10]. At a short period after a pressure wave passes across a laminar propagating premixed flame, small-scale disturbance suddenly appears at the flame front. The scale is almost equal to that predicted using the well-known theory.

The disturbance caused by this mechanism grows in an accelerating flow field, and the velocity of the induced gas flow becomes beyond the velocity of the propagating flame. This gas flow necessarily causes turbulence near the flame front.

In the decelerating mixture flow the disturbance on the flame front must decrease and the flame front should become smooth. This process was shown in an experimental study of flame behavior near an obstacle [11].

It should be noted that it needs certain duration of time for growth and reduction of the flame front disturbance. This can be explained by assuming that the dominant process is of momentum, heat, and mass transfer. For momentum, heat, and mass transfer in a layer, which is the flame front thickness in this case, a characteristic time is necessary.

Flame Front Disturbance Caused by the Diffusive-Thermal Mechanism

In some 1950's papers [12], a number of clear photographs representing the flame-front disturbance caused by the diffusive-thermal mechanism were presented. Since then, various experimental and theoretical studies have been performed to interpret the phenomena or to predict the characteristics of the flame-front turbulence caused by this mechnism. The flame front disturbance of this type does not grow because of its intrinsic characteristics. Once the disturbance comes in balance with the effect of diffusive-thermal force, its amplitude stops to increase. Thus, the disturbance caused by this mechanism cannot be expected effective for further increasing disturbance.

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