Studies of Turbulent Flow-Flame Interaction

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The generation and suppression of turbulence by a flame is important in the understanding and modeling of practical combustion systems. Therefore, the nature and magnitude of turbulence in a flame is analyzed. First, a balance equation for turbulent kinetic energy in a flame is discussed. Next, simplified formulas for important terms in the balance equation are derived. Then, interpretation of existing experimental data on premixed and diffusion flames of acetylene, hydrogen, and propane is carried out. For unconfined flames with high heat-release rates, it is found that dilatation and viscous dissipation effects suppress flame turbulence by up to 60 and 40%, respectively. In confined flames, four- to five-fold shear-generated turbulence produces a four-to-five increase in the kinetic energy of approach flow turbulence. The magnitude of the advection term is found to be as much as 30% of this production term. Finally, some new mechanisms of flame-generated turbulence in practical combustion systems are discussed, and implications of the present study to modeling and design of such systems are outlined.

Nomenclature

g = acceleration due to gravity
L = integral scale of turbulence
p = pressure
q = turbulent kinetic energy
Re_λ = turbulent Reynolds number $(=u'_{\rm rms}\lambda/\nu)$
r = radius
S = flame speed
T = temperature
t = time
u,v = velocities
Y = mass fraction
x,y = axial and transverse coordinates, respectively
δ = flame thickness
λ = dissipation scale
η = Kolmogoroff microscale
ν = kinematic viscosity
ϕ = equivalence ratio
ϵ = viscous dissipation
ξ = conserved scalar mixture fraction (Ref. 11)
ρ = density
τ = heat release rate parameter $(\rho_1/\rho_2)-1$
$\tau_{\ell k},\tau_{k\ell}$ = viscous stresses

Superscripts

$(\ )''$ = fluctuation from Favre-mean value
$(\tilde{\ })$ = Favre-averaged value
$(\ )'$ = fluctuation from conventional-mean value
$(\bar{\ })$ = conventional-averaged value

Subscripts

f = flame
i,j = species
k,ℓ = Cartesian components
L = laminar flow
1,2 = unburnt and burnt condition, respectively
p,r = products and reactants, respectively
t = turbulent
x = axial direction
rms = root-mean-square value

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Introduction

THE interaction between turbulent flow and flame is very complex and is not clearly understood. From a practical viewpoint, two main aspects of this interaction are of interest. First, a study of flame propagation through turbulent combustible mixtures would allow the rate of heat release and the combustion efficiency of a given system to be accurately and confidently predicted. Second, a comprehensive investigation of the nature and the extent of flame-generated turbulence in the hot-burning gas region just downstream of the flame front is required. It is this much-neglected second aspect that is analyzed in the paper.

The generation or suppression of turbulence by a flame has important implications in the analysis of practical combustion systems. For example, to predict correctly heat transfer to the combustor walls (and bearing in mind that this determines the film-cooling air requirements) clearly requires knowledge of turbulence level of the hot-burning gases in the combustor; the turbulent mixing processes are responsible, to a great degree, for the production of NO_x and soot in the post-flame region; and the flame-generated turbulence may play a significant role in triggering the combustion instability of combustors and afterburning system.

Background

The term "flame-generated turbulence" was first introduced by Karlovitz.[1] He suggested that the turbulence generated by the flame helps to augment its burning velocity. Westenberg[2] set up an experiment to verify Karlovitz's idea but failed and found only a small degree of flame-generated turbulence. From a physical viewpoint, it is difficult to see how flame-generated turbulence can influence burning velocity because the very process of its generation follows (does *not precede*) the propagation of a flame. Moreover, since a flame always propagates in a direction opposite to the motion of the unburned mixture, any turbulence generated by the flame is convected away and not toward the flame front.

During the 1960s, the phenomenon of flame-generated turbulence remained very much unexplored partly because our understanding of turbulence was in a rudimentary state and, more important, because of the lack of nonintrusive optical diagnostic techniques, e.g., a laser Doppler anemometer (LDA). During the early 1970s, Durst and Klein[3] carried out preliminary LDA measurements of flame turbulence in a premixed Bunsen flame, and Chigier and Dvorak[4] measured turbulence in a swirling flame using LDA. A comprehensive experimental study of the influence of approach turbulence intensity and scale on flame-generated turbulence for a premixed flame was presented by Ballal[5-7] using an LDA technique. The results of these tests showed a strong link between the mechanism of turbulent flame propagation and the flame-generated turbulence.

For diffusion flames, Gunther and Lenze[8] showed that the turbulence velocity, microscale, and exchange coefficients are all larger in a town gas flame than at the same station in an air jet. In contrast, Eickhoff[9] reported a sudden, steep drop in the relative turbulence intensity along the axis of a lifted, town gas flame, in the vicinity of the ignition point. Such interesting observations have provided the impetus for the present work.

Mechanisms of Flame Turbulence

As a turbulent flame propagates through the unburnt mixture 1) it accelerates the hot gases flowing through its reaction zone. If this acceleration creates mean and fluctuating shear between adjacent streamlines, a shear-generated turbulence is produced within the flame; 2) heat release produces expansion of hot gases or velocity divergence. Thus turbulence energy is reduced due to dilatation; 3) the local viscosity of high temperature gases behind the flame front increases almost by an order of magntiude. This reduces the turbulent Reynolds number, increases the viscous dissipation of turbulence energy, and damps small-scale fluctuations; 4) the sign and magnitude of the density gradient $(\partial\rho/\partial y)$ setup within the flame influence the diffusion of turbulence energy; and 5) pressure-related processes could become important especially for a ducted flame. In such a situation, mean axial pressure gradients produce shear-generated turbulence and pressure-velocity correlation terms would represent a positive source of turbulent kinetic energy (TKE) in a flame.

These five mechanisms operate in concert. The magnitude and nature (positive or negative) of their contribution to the *net* flame turbulence depends upon the turbulent flame geometry (flat flame, oblique flame, spherical flame, etc.), enclosed or open flame, and premixed or diffusion systems. Because so many important factors are involved, a question such as "Does a flame generate or damp approach turbulence?" seems inappropriate and does not have a simple yes or no answer. For example, one expects intuitively that in an unconfined plane turbulent flame, turbulent dilatation effects and the viscous dissipation effects would dominate. In practice (such as in afterburners), situations are found where propagation of a flame behind a baffle or a vee gutter in a duct takes place. Here, shear-generated turbulence, damping of small-scale fluctuations due to viscous dissipation, and pressure-related processes will all dominate. In an open turbulent diffusion flame of the type studied by Eickhoff,[9] diffusion of turbulence energy is strong due to the magnitude of the density gradients. To quantify these mechanisms, a good starting point is the balance equation for the TKE in a flame.

Analysis of Flame Turbulence

The TKE balance equation is essentially exact in the low-Mach number flows. For sufficiently high Reynolds number, buoyancy term $(=g_x\overline{\rho u_k''})$ is usually neglected. The Favre-averaged form of this equation is then as follows; see Libby and Williams[10]

$$\underbrace{\frac{\partial}{\partial x_k}(\bar{\rho}\tilde{u}_k\tilde{q})}_{1} = \underbrace{-\overline{\rho u_k''u_\ell''}\frac{\partial\tilde{u}_\ell}{\partial x_k}}_{2} \underbrace{-\frac{1}{2}\frac{\partial}{\partial x_k}(\overline{\rho u_k''u_\ell''^2})}_{3} \underbrace{+\frac{\partial}{\partial x_k}(\overline{u_\ell''\tau_{\ell k}})}_{4} \underbrace{-\overline{\tau_{k\ell}\frac{\partial u_k''}{\partial x_\ell}}}_{5} \underbrace{-\overline{u_k''\frac{\partial p}{\partial x_k}}}_{6} \tag{1}$$

where term 1 is the convection of TKE in the mean flow with velocity $\tilde{u}_k$; term 2 the production of the TKE due to work done against Reynolds stresses; term 3 the turbulent diffusion of TKE; term 4 the molecular diffusion (negligible at high turbulent Reynolds number); term 5 the viscous dissipation of TKE; and term 6 the pressure-velocity correlation term.

In Eq. (1), $\tilde{u}_k$ is the Favre-averaged mean velocity in direction x_k and $\tilde{q}=\frac{1}{2}\overline{\rho u_k''u_k''}/\bar{\rho}$ is the Favre-averaged TKE. It is common practice to lump together terms 3 and 6. This combined term is referred to as the "advection" term.

Term 2 represents the process of shear-generated flame turbulence via 1) the mean velocity gradient $(\partial\tilde{u}_\ell/\partial x_k)$. This mechanism may become the largest single source of flame-generated turbulence in a ducted flame; 2) the work done against the turbulent shear stresses $\overline{u_k''u_\ell''}$. This term will be important at high Reynolds number of the flow such as in practical systems; and 3) the work done against turbulent normal stresses $\overline{\rho u_k''^2}$. Both $\overline{\rho u_k''^2}$ and $(\partial\tilde{u}_\ell/\partial x_k)$ represent turbulent dilatation effects in an open flame where the expansion of hot gases and velocity divergence removes TKE from the flame.

The nature of the contribution (positive or negative) of term 3 to flame turbulence depends upon the sign and magnitude of density gradient setup within the flame. It also depends upon what fraction of the total diffusion is carried out by the action of large energy-containing eddies and the remainder by the gradient-diffusion process attributed to the small dissipative eddies. Added to this complexity and uncertainty, in a flame for example, there may be some turbulent energy production by heat transport along a density gradient. The contribution of this term to flame turbulence therefore will become a subject of some complexity and controversy.

The viscous dissipation (term 5) principally damps the small-scale turbulence. Thus the TKE is shifted to low wavenumber large-scale eddies. Since the directional nature of large-scale turbulence is well known, the flame turbulence tends to become more anisotropic as the viscous dissipation increases.

Finally, the pressure velocity (term 6) correlation may be expanded to give:

$$\underbrace{-\overline{u_k''\frac{\partial p}{\partial x_k}}}_{6} = \underbrace{-\overline{u_k''}\frac{\partial\bar{p}}{\partial x_k}}_{7} \underbrace{-\frac{\partial}{\partial x_k}(\overline{u_k''p})}_{8} \underbrace{+\overline{p\frac{(\partial u_k'')}{\partial x_k}}}_{9} \tag{2}$$

Consider term 7; when it is positive, TKE will increase and vice versa. Axial pressure gradient has appreciable influence on TKE analogous to that of the mean velocity gradient because from the instantaneous equation of motion,

$$\rho v\left(\frac{\partial u}{\partial y}\right) = -\left(\frac{\partial p}{\partial x}\right) \tag{3}$$

As for the effect of transverse pressure gradient $(\partial\bar{p}/\partial y)$, we find that, for example, for a Bunsen diffusion flame, this term is positive and $\overline{\rho'v'}$ is negative. Therefore, suppression of turbulence in a flame takes place.

Term 8 is the conventional pressure-velocity correlation term, which contributes to the diffusion of TKE in the sense of redistributing it among the various components. It is neither a positive nor a negative contribution to the TKE in a flame.

Finally, term 9 represents, in the words of Bilger,[11] "the effects of pressure fluctuations correlated with volume increases" and is acoustic in nature. It is a source of flame-generated turbulence and also of combustion-generated noise with the TKE increase coming from acoustic velocity fluctuations.

Interpretation of Experimental Data

Available experimental data on flame turbulence (Table 1) are very scarce because of the difficulty of measuring complex turbulence correlations in the high-temperature environment of a flame. Therefore, a rigorous comparison between theory and experiments is not possible. In general, turbulent premixed flames have received more attention[3,4,6,7] than have turbulent diffusion flames.[8,9] For practical combustion systems, a simplified analysis provides more valuable insight and design guidelines than does a rigorous analysis involving many unknowns.

Turbulent Dilatation

Let us consider a plane unconfined turbulent flame as shown in Fig. 1. Here, mean flow is normal to the flame so no shear stresses occur. In this flame, buoyancy is neglected and, therefore, mean velocity change $\partial \bar{u}$ is

$$\partial \bar{u} = (\rho_1/\rho_2 - 1)\bar{S}_t \tag{4}$$

This acceleration of mean velocity takes place over an average turbulent flame thickness $\bar{\delta}_t$ and therefore

$$\frac{\partial \bar{u}}{\partial y} = \tau\left(\frac{\bar{S}_t}{\bar{\delta}_t}\right) \tag{5}$$

Neglecting the flame front curvature and fixing the coordinate system in the flame front, we obtain

$$\bar{\rho}_1 \bar{S}_t \partial \bar{q} = -\bar{\rho}_2 \overline{u'^2} \partial \bar{u} \tag{6}$$

Substituting from Eq. (4) and simplifying

$$\partial \bar{q} = -(2/3)\bar{q}\tau/(\tau+1) \tag{7}$$

or

$$\bar{q}_f/\bar{q} = 1 - 0.66(\tau/\tau+1) \tag{8}$$

Equation (8) is plotted in Fig. 2 and shows that turbulence dilatation reduces TKE in a flame by 50-60%, a result of great practical significance. Figure 2 also shows experimental data of Ballal[7] on premixed flames. These experiments were carried out in a ducted-premixed flame using propane, acetylene, and hydrogen fuels burning in air. Contribution of shear-generated turbulence plus approach-flow turbulence was deducted from total measured flame turbulence as described by Ballal.[7] The experimental data show good agreement with the predictions of Eq. (8).

For a turbulent propane diffusion flame, Eickhoff's[9] data are plotted in Fig. 2. Eickhoff[9] mentioned a reduction in turbulence intensity from 22% in an air-jet to 12% in a diffusion flame. The reasonable agreement depicted in Fig. 2 indicates similarity between the characteristics of TKE in premixed flames and those in diffusion flames.

The reduction in TKE in a flame poses another basic question as to whether the low (unburnt flow) Reynolds number laboratory flames are really fully turbulent or are in a state of transition from a turbulent to a laminar flow. The laminarization of flow due to heat release may in fact explain the presence of large orderly flow structures in laboratory diffusion flames.

Shear-Generated Turbulence

Figure 3 shows an oblique-confined turbulent jet-like flame with a small spread angle. For a premixed situation, Ballal[6] has derived a relationship between the mean $(\partial \bar{u}/\partial y)$ and the fluctuating shear gradient $(\partial u_{rms}/\partial L_x)$ in a flame. This is:

$$\left(\frac{\partial u_{rms}}{\partial L_x}\right)_f = 0.23\left(\frac{\partial \bar{u}}{\partial y}\right) \tag{9}$$

Table 1 Experimental data

Flame	Heat release rate parameter, τ	Reference
Premixed		
C_2H_2 + air ($\phi = 1$)	7.9	7
H_2 + air ($\phi = 1$)	7.4	7
C_3H_8 + air ($\phi = 1$)	6.8	3, 5-7
($\phi = 0.65$)	4.5	3, 7
Diffusion		
H_2 + air ($\phi = 1$)	7.4	11, 12
C_3H_8 + air ($\phi = 1$)	6.8	8, 9

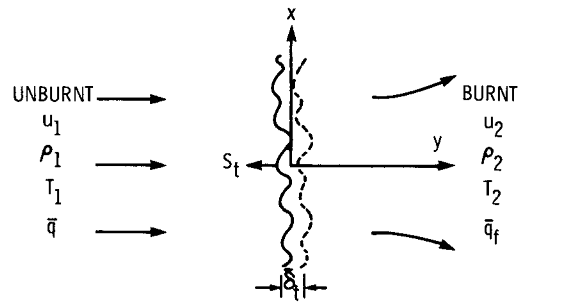

Fig. 1 Schematic diagram of a plane unconfined turbulent flame.

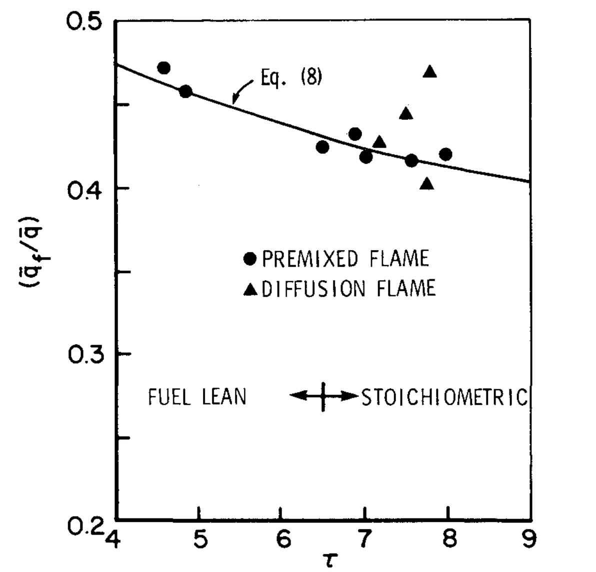

Fig. 2 Effect of dilatation on the turbulent kinetic energy in a flame.

In region 2 of Ballal,[6] $L_x \approx \bar{\delta}_t$ and $\bar{S}_t = 2u_{rms}$. Substituting these results and those of Eq. (5) into Eq. (10) yields

$$(\bar{q}_f/\bar{q}) = 1 + 0.46\tau \tag{10}$$

Equation (10) gives a formula for calculating values of shear-generated flame turbulence and is plotted in Fig. 4. It should be recognized that the measured values of ratio $(\bar{q}_f/\bar{q})$ are plotted. These data are for confined turbulent premixed flames of Ballal[6,7] in region 2. Also shown in this figure are the *corrected* measured values. A good agreement is evident between the measurements and the formula of Eq. (10).

The experimental data for confined hydrogen-air diffusion flames were obtained from Starner and Bilger[12] for identical pressure, velocity, and ambient temperature conditions. However, in one case the fuel jet was ignited and in the other it remained nonignited. Data presented were obtained at points of stoichiometric composition as determined by Starner and Bilger.[12] Again, a good agreement between the corrected data and the formula of Eq. (10) is evident.

Viscous Dissipation

Due to the high-temperature gases in a flame, viscous dissipation is very high and this affects flame turbulence. Principally, the viscous dissipation damps small-scale fluctuations and thereby shifts the TKE spectrum to lower wavenumber range. Figure 5 shows experimental data of Ballal[6] to illustrate this effect. This damping process: 1) reduces the turbulent Reynolds number Re_λ in a flame via a decrease in u_{rms} and an increase in ν; and 2) shifts the flow structure to that of a low-intensity, large-scale turbulence or even a quasilaminar flow. The flame turbulence becomes more anisotropic and resembles that of large-scale motion found in mixing layers or partly mixed diffusion flames.

The TKE is related to viscous dissipation by a simplified form of a very complex set of equations. This simplified version is [13]

$$\bar{q} = 0.76(\epsilon L/\rho)^{0.66} \tag{11}$$

Hence

$$\bar{q}_f/\bar{q} = [\epsilon_f L_f/\epsilon L(\tau+1)]^{0.66} \tag{12}$$

Equation (12) allows the prediction of TKE ratio with heat release parameter τ. This result is plotted in Fig. 6.

The experimental data of Ballal[6,7] on the premixed flames is plotted on the same figure. These measurements were for $y/r = 0.75$, in the vicinity of the jet-flame front. Therefore, they do represent maximum values of dissipation rates and a maximum reduction in TKE. It should be noted that the viscous dissipation $\propto(1/L)$ and, therefore, any changes in flow structure that alter length scales will drastically change results of Fig. 6. Proper account of this effect in calculations should be taken. No experimental data were available for diffusion flames, although the same considerations apply to them.

Advection

The advection process consists of two different effects. First is the turbulent diffusion of TKE in the mean flow with velocity $\overline{u_k''}$. The second is the pressure-velocity correlation term of Eq. (2). The significance and relative magnitude of the $\overline{u_k''q}$ and $\partial\bar{q}/\partial x_k$ have to be thought of in relation to the turbulent eddies in the flow; see Townsend.[13] Since it is not known what fraction of the total diffusion is carried out by the action of the large eddies and what (remainder) fraction by the gradient diffusion process attributed to the smaller eddies, modeling of this term is not possible at the moment. In a flame, there may be some TKE production by heat transport along a density gradient and additional flame-generated turbulence may exist as well.

In view of these difficulties, it is proposed here that, for the present time, the advection term should be calculated by the method of difference to satisfy the balance equation for TKE, i.e., Eq. (1). Therefore,

$$\text{advection} = \text{convection} + \text{production} - \text{dissipation} \tag{13}$$

Figure 7 shows the experimental measured values of the advection/production term at the radius of maximum shear stress ($y/r = 0.5$). Again, the data for ducted premixed flames were those of Ballal,[6,7] and for ducted turbulent diffusion flames those of Starner and Bilger.[12] The magnitude of this term is between 20-40% for confined premixed flames and about 20% for ducted diffusion flames in an accelerating (negative-pressure gradient) flow.

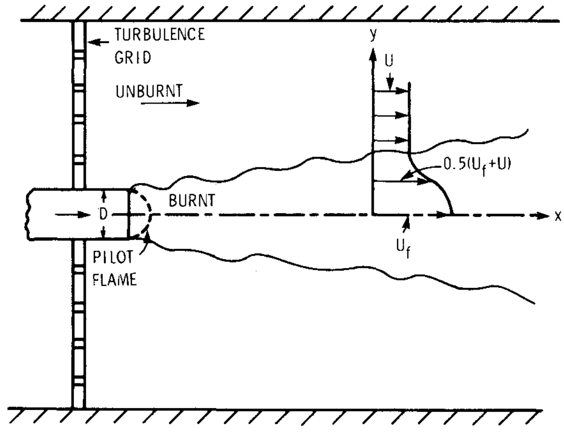

Fig. 3 Schematic diagram of an oblique turbulent ducted jet flame.

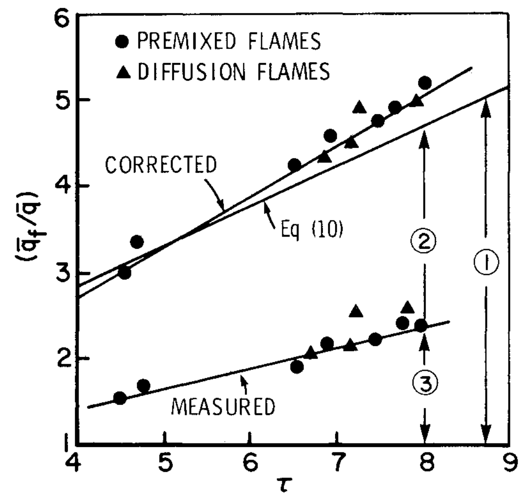

Fig. 4 Effect of shear-generated turbulence on the turbulent kinetic energy in a flame: (1) shear-generated turbulence; (2) reduction in turbulence due to dilatation; (3) measured (net) value of turbulence.

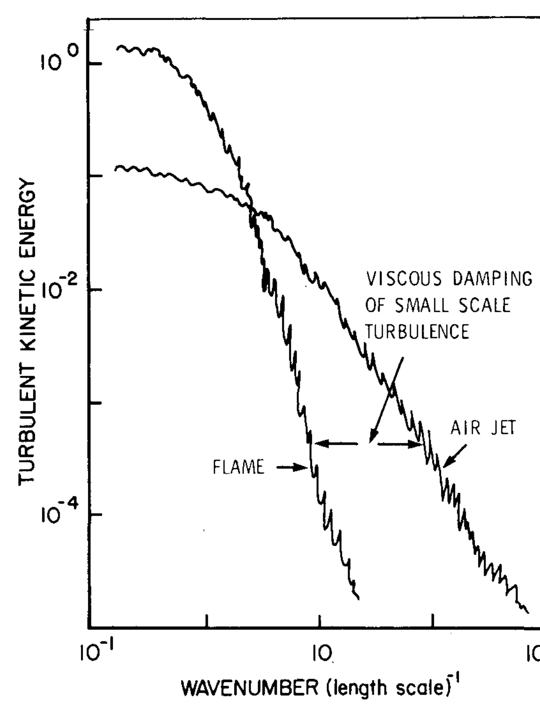

Fig. 5 Comparison of energy spectra of turbulence measured in a flame and in a cold flow to illustrate the effect of viscous dissipation.

Balance of TKE in a Flame

The validity of the simplified analyses and especially of Eqs. (8), (10), (12), and (13) should be ascertained. To do this, total *gain* and total *loss* of turbulence in a flame were calculated for various values of heat release parameter τ using the above equations. These results are presented in Table 2. In this table, it is found that total gain $\approx$ total loss particularly for high-heat release rates of interest in a practical combustion system. This suggests a balance of TKE in a flame, see Ref. 10. Therefore, the validity and importance of the simplified analyses are established.

Additional Mechanisms of Flame-Generated Turbulence in Practical Systems

In practical combustion systems, several new mechanisms in addition to those described earlier may contribute to flame turbulence. These are classified as mechanisms related to: flame front structure and oscillations; fluctuating heat release rates; recirculating or swirling flames; and two-phase combustion.

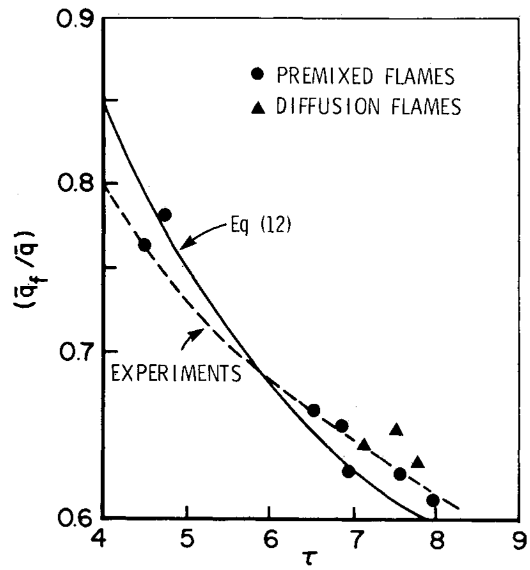

Fig. 6 Effect of viscous dissipation on the turbulent kinetic energy in a flame.

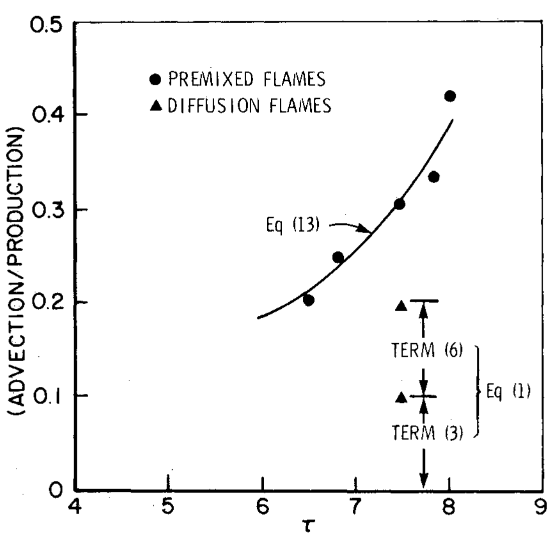

Fig. 7 The ratio of turbulent advection/production plotted as a function of heat release rate parameter in a flame. Relative magnitude of terms 3 and 6 of Eq. (1) are illustrated for a jet diffusion flame.

Flame Front Structure and Oscillations

Practical combustion systems are highly complex, involving contorted turbulent flame fronts and chemical reactions. A study of Ballal[6,7] has identified three different regions of flame propagation and turbulence generation in premixed ducted flames. Only results for region 2 of intermediate turbulence intensity and scale ($L_x \approx \delta_t$, $\bar{S}_t = 2u_{\rm rms}$) were used in formulating Eq. (10). In region 1 of the "wrinkled-pulsating flame front," the flame-generated turbulence can be considerably in excess of that predicted by Eq. (10). This is due to the fluctuating motion of mostly large-scale eddies produced by the unstable pulsations of the wrinkled-laminar combustion wave. Similarly, in region 3, "microexplosions" or "eddy bursts" of small-scale eddies entrained behind the flame front can produce additional flame-generated turbulence. Ballal[6,7] has discussed these aspects in detail and defined flame-generated turbulence as the total turbulence generated by the above-mentioned physical processes that are unique only to a turbulent flame. Equations (14) and (15) provide prediction of this additional flame-generated turbulence in practical systems.

Region 1:

$$(\bar{q}_f/\bar{q}) = 1 + 0.04\,\tau(L/\delta_L) \qquad (14)$$

Region 3:

$$(\bar{q}_f/\bar{q}) = 1 + 0.115\,\tau(\delta_L/\eta) \qquad (15)$$

In Eq. (14), $\bar{S}_t > S_L$ and $(L/\delta_L) \gg 1$. Similarly, in Eq. (15), $(\delta_L/\eta) > 1$.

In a recent experimental study of an open V-shaped premixed turbulent flame, Cheng[14] found a large (four-fold) increase in the unconditional measurements of turbulence intensity and Reynolds stress in the flame brush. This increase was attributed to intermittent measurements in the unburned reactants and burned products separated by the thin fluctuating flame, and the mean velocity difference associated with the acceleration of flow through the flame. In contrast, conditioned values of turbulence intensity in the products were twice as high as those for the reactants. This suggested that physical processes unique to a flame (and not the intermittency contribution) were producing this additional *true* flame-generated turbulence. Cheng[14] offers no explanation for this increase. The author, on the basis of his previous work,[6,7] would like to suggest that unstable pulsations of the wrinkled-laminar combustion wave are the cause of this flame-generated turbulence. This is because from Cheng's experiments $\phi = 0.7$, $\tau = 5$, and $u_r' = 28$ cm/s; from Gaydon and Wolfhard[15] it can be calculated that $S_L = 22$ cm/s and $\delta_L = 0.88$ mm; and from Ballal and Lefebvre[16] it can be estimated that for Cheng's[14] square mesh grid, $L_y = 5$ mm at $x = 100$ mm. From these data, $u_r/S_L < 2$ and $L_y/\delta_L \gg 1$, i.e., Eq. (14) is valid. Therefore, substituting the above values in this equation yields $(\bar{q}_f/\bar{q}) \approx 2.25$; a result in close agreement with the experimental observations of Cheng.[14] This exercise reveals that the equations derived above are not only valid for real flames but their predictions should be compared with carefully conducted experiments in which *true* flame-generated turbulence is distinguished from *total* flame turbulence.

Table 2 Turbulent kinetic energy balance in a flame

Heat release rate parameter, τ	Total gain: Shear	Total gain: Advection	Total loss
8	4.75	2.04	6.84
7	4.25	1.06	5.15
6	3.75	0.712	4.20
5	3.25	0.487	3.00
4	2.80	0.3	2.22

Mixtures producing high heat release also have large laminar burning velocities. The latter have a stabilizing influence on the distortion (or wrinkling) of the flame front and this reduces flame-generated turbulence. Similarly, the effects of flame-front curvature that lead to cellular structures and thermodiffusive flame instability need to be examined.

Fluctuating Heat Release Rates

Most studies on flame-generated turbulence have exposed only the physical mechanisms of turbulence in flame, but chemistry has an important role, too. For example, and particularly in turbulent diffusion flames, turbulent fluxes such as $\widetilde{u''\xi''}$, $\overline{Y_iY_jT'}$, and the scalar dissipation Φ_ξ will contribute in a variety of ways to the fluctuations in heat release rates. These fluctuating heat release rates will produce flame-generated turbulence. This subject is very important and so little work has been done that it merits a separate comprehensive study.

Also worthy of a study is the possible suppression of flame turbulence due to heat loss by radiation from flames in rocket combustors or two-phase combustion (e.g., spray combustion, coal combustion, boron-slurry combustion, etc.).

Recirculating and Swirling Flames

An often-used method of flame stabilization in practical systems is the creation of a recirculation zone behind a bluff body. A large bluff body such as the one used by Roquemore[17] and Roquemore et al.[18] not only sheds toroidal vortices downstream of its face but creates enough flame turbulence to tear apart masses of hot gas downstream of the recirculation zone. These hot-gas parcels, called turbules, are convected downstream with the mean flow. Much fundamental work is required to study vortex structures, oscillations in shear layer, flame turbules, and interaction between the toroidal vortices and the central fuel jet flow. Recently, Roquemore and co-workers[18] have taken a valuable initial step in carefully documenting the flow field behind a bluff body by using a laser-sheet-lighting technique. The next logical step of LDA measurements of flame turbulence should follow this work.

Swirl is commonly used to improve flame stability and fuel-air mixing, and to shorten the flame length. Apart from the work of Chigier and Dvorak,[4] few measurements have been carried out in swirling flames, presumably because of the complexity of their flowfield. The measured flame turbulence in a swirling flow was found by Chigier and Dvorak[4] to be double that in the approach flow. Therefore, more work is urgently required in this area.

Two-Phase Combustion

The combustion of liquid sprays, solid propellants, or coal particles is of considerable interest to combustor designers. A characteristic of this combustible mixture is the heterogeneity of fuel in the oxidizer stream. Thus, local burning or local extinction around droplets or fuel particles can create compositional fluctuations. In some practical systems involving very high heat release rates (e.g., rocket combustors) such compositional fluctuations can be a dominating factor in driving combustion instability and generating flame turbulence. A theoretical analysis of such an effect for a solid propellant rocket has been recently published by Cohen and Strand.[19] It is very clear that further experimental and theoretical work is needed in this area.

Implications to Modeling and Design of Combustion Systems

The present work has important implications in the development of computer models and design strategies for practical combustion systems. For example, the existing models for predicting NO_x and soot in the post-flame region of a gas turbine combustor take no account of the radical change in turbulence structure, and hence mixing, in a flame as compared to approach flow turbulence. In a flame, due to the viscous damping of small-scale fluctuations, the TKE is not randomly distributed but is contained in the directional and orderly motion of the large-scale eddies. This fact has important bearing on modeling code development. Similarly, in free turbulent combusting flows, e.g., jet diffusion flame, both viscosity and mean transverse pressure gradient ($\partial\bar{p}/\partial r$) would almost totally suppress the turbulence "intermittency" in the outer mixing layer. This effect is completely absent in nonreactive turbulent jet and mixing layers.

When a flame is stabilized behind a bluff body, e.g., an afterburner system, large-scale, shear-generated flame turbulence may strongly contribute to exciting acoustic instabilities sometimes known as "buzz." The flame shape becomes distorted by large coherent structures and its mean spreading rate is greatly increased. This enhances wall heat transfer rates. Such effects are directly traceable to flame-generated turbulence and should be included in the modeling and design of propulsion systems.

In both solid and liquid propellant rocket motors, heterogeneity of fuel particles and droplets in the oxidizer stream leads to compositional fluctuations and rapid oscillations in heat release rates. This can trigger combustion instability sufficiently large to destroy the rocket motor itself. It also changes the composition of and radiation from the rocket exhaust plume. Such effects may have important military implications. For these reasons, a comprehensive study of flame turbulence is required.

Conclusions

The generation and suppression of turbulence by a premixed or a diffusion flame are studied. The following conclusions emerge:

1) In the balance equation for turbulent kinetic energy of a flame, turbulent dilatation and viscous dissipation processes suppress flame turbulence, and advection and shear-generated turbulence production mechanisms are principally responsible for flame-generated turbulence.

2) The suppression of flame turbulence due to dilatation (up to 60%) and due to viscous dissipation (up to 40%) may be calculated from formulas derived in Eqs. (8) and (12), respectively.

3) In confined premixed or diffusion flames, shear-generated turbulence, Eq. (10), can produce a four- to five-fold increase in approach turbulent kinetic energy and the magnitude of the advection term, Eq. (13), is found to be about 30% of the production term.

4) Good agreement is found between the predictions of simplified analyses of flame turbulence and the existing experimental data for premixed and diffusion flames of acetylene, hydrogen, and propane. This essentially indicates a similarity between the flame turbulence field in a premixed and in a diffusion-type combustion system.

5) Four additional mechanisms of flame-generated turbulence in practical systems are discussed and a need for future work in this area is highlighted.

6) The implications of the present study on flame turbulence to the modeling and design of practical combustion systems are outlined.

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