ON ENERGY AND DISSIPATION SPECTRA IN TURBULENT NON-PREMIXED JETS WITH LOCAL EXTINCTION

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Abstract

The turbulent kinetic energy (TKE) and its dissipation spectra are analyzed using a DNS database of temporally evolving non-premixed jet flame experiencing high level of local extinction. It is found out that when scaled using Favre averaged turbulent dissipation rate ($\tilde{\varepsilon}$) and the cutoff scale (λ_β) corresponding to the Batchelor scale, both TKE and its dissipation spectra collapse well in different planes across the flame in both low-medium and high wave number dissipative ranges. Further, the spectra are compared with the model spectra, it is found that again using the previous scaling laws the agreement is better than the classical scaling laws for spectra involving Kolmogorov scale, especially in high wave number regions.

Introduction

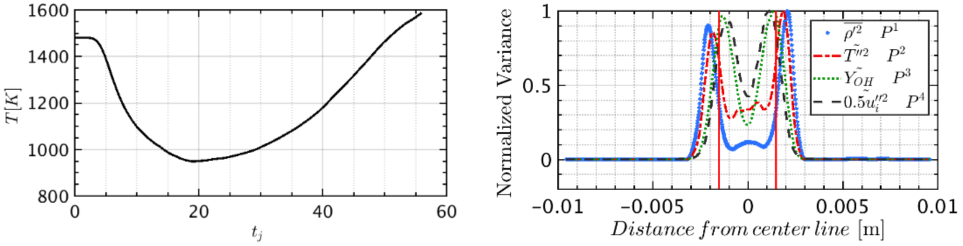
The analysis of velocity and scalar spectra in reactive flows is of great importance both in experiments and numerics. In experiments, one needs to know the true resolution requirements to scalar gradients. Many numerical models also rely on these scaling laws to evaluate constants or to justify assumptions. Knowing that the chemistry mostly occurs in small scales, the kinetic energy and dissipation spectra in high wave number range are of great importance.

In [1] Sandia flames C, D, and E are used to study the scalars spectra of non-premixed jets. A cutoff scale (λ_β) was introduced as the inverse of the wave number at which 2% peak dissipation spectrum occurs. It is found that, when normalized by λ_β, the dissipation spectra of temperature and mixture fraction nearly collapse. However, due to increased noise level in the measured data, there is no evidence of the behavior in high wave number range. In [2] the effect of heat release on the velocity and scalar spectra obtained by DNS of temporally evolving reacting shear layer is studied. Surprisingly, they found that the effect of heat release can be well scaled out by using Favre averaged turbulence quantities in velocity and mixture fraction spectra. In [3] the energy spectra of a premixed flame are studied. They found out that in agreement with [2], in the inertial range, classical scaling laws using Favre averaged quantities are applicable. In the high wavenumber range the laminar flame thickness (δ_L) produces a better collapse while disrupts the collapse in the inertial range. Recently, in [4] in the study of dissipation spectra of a premixed jet, it is found that they collapse when normalized by the corresponding Favre mean dissipation rate and λ_β scale proposed in [1]. However, in contrast to [1] and [2], they saw that normalized dissipation spectra in all the cases deviate noticeably from those predicted by classical scaling laws for constant- density turbulent flows.

The purpose of the present study is to analyze the scaling laws in both inertial range and dissipative range of velocity spectra and to compare them with the model spectra proposed for non-reacting flows, but typically used in reacting flows (usually as a part of LES model development). The focus is on the effect of local extinction on the spectral behavior of velocity, which is missing in the literature. A DNS database of a temporally evolving non-premixed jet (introduced in next section) is used.

Computational setup

The numerical experiment is provided by DNS of temporal evolution of a non-premixed syngas (CO/H_2 as a fuel and air as an oxidizer) jet flame [5]. This flame experiences first extinction up to $20t_j$, with $t_j = 5\ \mu s$ the normalized time, and then reignition (as evident from Figure 1a). The domain is periodic in streamwise (x) and spanwise (z) directions. These are denoted as statistically homogenous directions. The time instant analyzed is $20t_j$, when the flame experiences maximum local extinction. In Figure 1b, the planes selected to carry out the analyses are introduced. Planes P^1 and P^2 are x-z planes with maximum density and temperature fluctuations. P^3 is a plane with maximum Favre averaged OH mass fraction and P^4 is a plane of maximum Favre averaged turbulent kinetic energy (TKE). P^0 is the center plane.



(a) **(b)**

Figure 1. (a) Maximum of Favre averaged temperature; **(b)** Reynolds averaged density fluctuation, Favre averaged temperature fluctuation, mean OH mass fraction and Favre RMS of velocity, normalized by their own maximum values. Vertical lines locate the planes of mean stoichiometric mixture fraction.

Results

The 3-dimensional spectra of velocity are extracted from the database. The term "3-dimensional" here refers to a line spectrum computed by adding the spectra of 3 components of velocity vector. Temporally evolving turbulence have been used before in the literature to analyze spectra [2-4]. The spectra are computed from a fixed temporal snapshot, using the data in each statistically homogenous x-z plane. Recently, in [3] the compressible form of spectrum function is proposed as:

$$E_{u_i}(\kappa) = \frac{1}{2\bar{\rho}}\left(\frac{1}{N_Z}\sum_{j=1}^{N_z} \mathcal{F}_j(\rho u_i'')\mathcal{F}_j^*(u_i'') + \mathcal{F}_j(u_i'')\mathcal{F}_j^*(\rho u_i'')\right) \tag{1}$$

where $\mathcal{F}_j$ and $\mathcal{F}_j^*$ are the Fourier transform and its complex conjugate, respectively. N_Z is the number of data points in z direction and κ is the wave number vector length. Using 1-D spectra for each velocity component, the 3-D spectrum is defined as:

$$E(\kappa) = \frac{1}{2}(E_{u_1} + E_{u_2} + E_{u_3}) \tag{2}$$

The dissipation spectra can be constructed using the relations in non-reacting homogenous isotropic turbulence as [6], but with Favre averaged viscosity:

$$D(\kappa) = 2\tilde{\nu}k^2E(\kappa) \tag{3}$$

Scaling laws

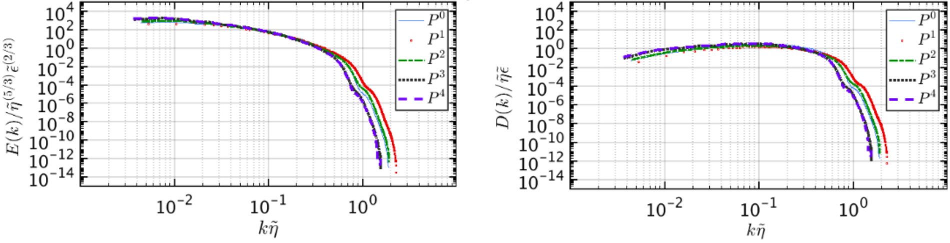
In [2], turbulent kinetic energy spectra are studied using a DNS of a non-premixed flame in a temporally evolving shear layer, a configuration nearly similar to the present study. They found a very good scaling of the spectra when normalized using Favre averaged Kolmogorov length scale ($\tilde{\eta}$) and turbulent dissipation rate ($\tilde{\varepsilon}$). They suggested that spectra in reacting flows follow the conventional Kolmogorov scaling in terms of Favre averaged quantities. The normalized spectrum is defined as:

$$E(\kappa)_{normal} = E(\kappa)/\ (\tilde{\eta}^{5/3}\tilde{\varepsilon}^{2/3}\ ) \tag{4}$$

The normalized velocity dissipation spectrum using $\tilde{\eta}$ and $\tilde{\varepsilon}$ is defined as:

$$D(\kappa)_{normal} = D(\kappa)/\ (\tilde{\eta}\tilde{\varepsilon}) \tag{5}$$

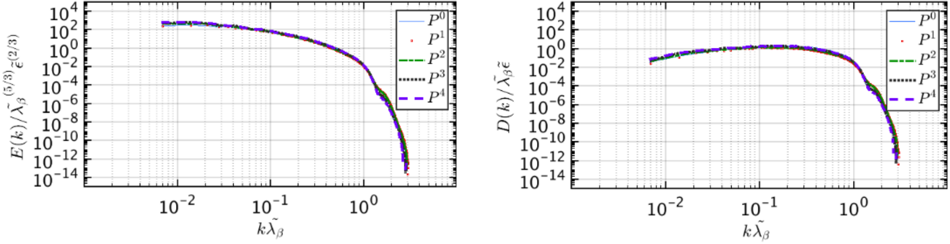
We examine this scaling by plotting the normalized turbulent kinetic energy (TKE) and velocity dissipation spectra in different planes introduced in the previous section at time $20t_j$ where the flame experiences maximum local extinction. As shown and also in agreement with [2] and [3] the TKE spectra (Figure 2a) collapse well in the inertial range. However, in contrast to [2], in high wave number range the collapse is not good. In Figure 2b it is seen that in low wave number range the dissipation spectra is well collapsed, in agreement with [2]. In [2], the effect of heat release rate in non-premixed jets is studied. The one-way coupling is obtained by limiting the utilizing flame-sheet approximation and they eliminate flame structure changes and dynamics. So it seems that the dynamics of the flame, changed locally due to high level of local extinction, has an effect on high wave number range of both TKE and dissipation spectra. However, inertial range remains unaffected and the conventional Kolmogorov scaling laws in Favre averaged form holds.



(a) **(b)**

Figure 2. Normalized energy **(a)** and dissipation **(b)** spectra in log-log axis in different planes, normalized using Favre averaged turbulence quantities $\tilde{\varepsilon}$ and $\tilde{\eta}$.

In [1], a cutoff scale (λ_β) was introduced, and used for normalization, as the inverse of the wave number at which 2% peak dissipation spectrum occurs. The dissipation spectra of scalars (i.e. temperature and mixture fraction) in non-premixed turbulent jets were normalized by λ_β. It is found that the normalized dissipation spectra of temperature and mixture fraction nearly collapse. However, due to increased noise level in the measured data, there is no evidence of that in high wave number range. Further, the TKE and its dissipation spectra are not provided. Here, in Figs 3a and 3b, the TKE and dissipation spectra normalized by λ_β instead η (shown in Figure 2) are reported. Compared to Figure 2, interestingly it is seen that both spectra well collapsed for all considered planes and nearly all wave number range.



(a) **(b)**

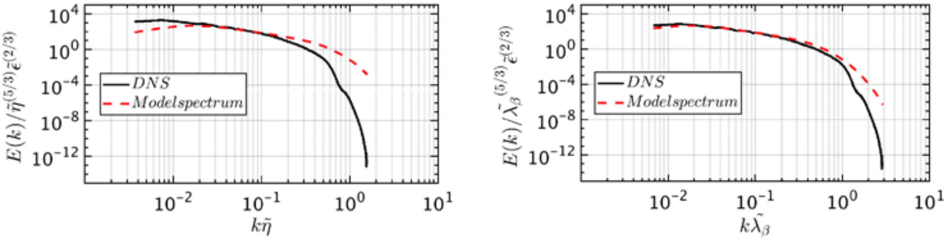
Figure 3. Normalized energy **(a)** and dissipation **(b)** spectra in log-log axis in different planes normalized using the cutoff scale λ_β.

Model spectrum

The model spectrum of Pope [6] is proposed for non-reacting flows as:

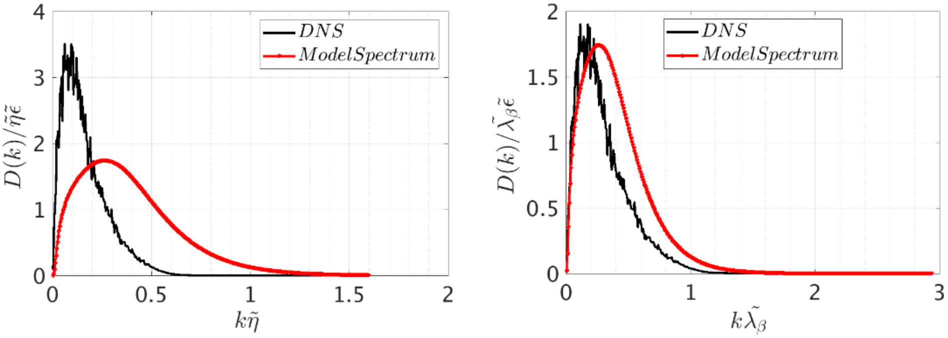
$$E(\kappa)^{Model} = C_k \varepsilon^{\frac{2}{3}} \kappa^{-\frac{5}{3}} f_L(\kappa L) f_\eta(\kappa \eta) \tag{6}$$

where $f_L(\kappa L) = \left((\kappa L)\,/((\kappa L)^2 + c_L)\right)^{5/3+p_0}$ and $f_\eta(\kappa\eta) = \exp(-\beta\left[(\kappa\eta)^4 + c_\eta^4\right]^{\frac{1}{4}} + \beta c_\eta)$, with constants $C_k = 1$, $c_L = 6.78$, $p_0 = 2$, $c_\eta = 0.4$. In [2], for a non-premixed temporal jet without extinction, it is found that when scaled with Favre averaged $\tilde{\eta}$ and $\tilde{\varepsilon}$, spectra of different planes collapse and well follow the model spectrum of Pope [6]. Here we examine this scaling by plotting the energy spectra obtained by DNS and the model, normalized by Favre averaged turbulence quantities in Figure 4a and comparing it with normalization using cutoff scale (λ_β) in Figure 4b. The two spectra are computed in plane P^3. It is seen that using the cutoff scale (λ_β) for normalization, the model spectrum collapses well in inertial range compared to Figure 4a. Further, it is seen that in high wave number region, the agreement of the model spectra in both normalization methods are not good.



(a) **(b)**

Figure 4. Normalized energy spectrum in log-log axis in Plane P^3 compared to model spectrum of Pope [6] with different normalization scales; **(a)** using Favre averaged turbulence quantities $\tilde{\varepsilon}$ and $\tilde{\eta}$; **(b)** using the cutoff scale λ_β.



(a) **(b)**

Figure 5. Normalized dissipation spectrum in linear-linear axis in Plane P^3 compared to model spectrum of Pope [6] with different normalization scales; **(a)** using Favre averaged turbulence quantities $\tilde{\varepsilon}$ and $\tilde{\eta}$; **(b)** using the cutoff scale λ_β.

The effect of normalization is also studied in Figure 5 in linear-linear plots. Similar to energy spectra, normalization with λ_β is preferred. The normalized model dissipation spectrum peaks at $\kappa\tilde{\eta} \approx 0.26$ in Figure 5a. However, in agreement with

[4] the peak of the normalized dissipation spectrum is at lower wave number, around $\kappa\tilde{\eta} \approx 0.1$. Using the cutoff scale λ_β, the peak of dissipation spectrum of DNS shifts closer to the model spectrum ($\kappa\tilde{\eta} \approx 0.19$ instead of $\kappa\tilde{\eta} \approx 0.1$) in Figure 5b.

Conclusion

The velocity spectra of a non-premixed temporal jet flame at the instant of maximum local extinction are studied using a DNS database. The turbulent kinetic energy and velocity dissipation spectra are computed using a compressible formulation in different x-z planes of the computational domain corresponding to maximum of TKE, mean OH mass fraction, temperature, and density fluctuations and the central plane. The cutoff scale (λ_β) is defined as the inverse of wave number at which the dissipation spectrum reaches 2% of its peak at each plane. It is found that when scaled with λ_β, both velocity dissipation and TKE spectra computed in different planes collapse. The collapse in low-medium wave numbers including the inertial range is very good. In high wave number region, the collapse is much better than the case normalized with Favre averaged turbulence quantities. It seems that the large amount of local extinction has an effect on high wave number range of both TKE and dissipation spectra and inertial range remains unaffected and the conventional Kolmogorov scaling laws in Favre averaged form holds. Further, it is found that the agreement with the model spectrum is better if λ_β and $\tilde{\varepsilon}$ are used for scaling.

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