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Assessment of local and non–local turbulent flow components on turbulence–flame interaction

Aimad Er-raiy¹, Radouan Boukharfane², Linda Alzaben¹ and Matteo Parsani¹

¹King Abdullah University of Science and Technology (KAUST), ECRC
Thuwal 23955, Saudi Arabia
²Mohammed VI Polytechnic University (UM6P), MSDA
Ben Guerir 43150, Morocco
E-mail: aimad.erraiy@kaust.edu.sa

Abstract. In the framework of turbulence-flame interaction, the flame is characterized by the gradient of a reactive scalar such as the progress variable, whereas the turbulence is represented by the vorticity and the strain rate. Quantitative assessment of this interaction is performed through the study of the coupled transport between these quantities that are subject to the effects of heat release and chemical reactions. The present analysis aims at improving the understanding of the small scale turbulence–flame interaction properties, through the introduction of an additive decomposition of the strain rate and vorticity fields into their local and non-local components. The respective role of the local and non-local effects is studied for a broad range of Karlovitz numbers, by virtue of direct numerical simulations (DNS) of turbulent, premixed, lean, and statistically planar flames of methane-air. In the conditions of the present study, the alignment between flame front normals and the strain rate is found to be dominated by the local contribution from the strain rate tensor.

1. Introduction

Turbulence-flame interactions are often quantitatively investigated by means of characterizing the two-way coupling between the turbulent flow field and the gradient of the progress variable $c$ that evolves according to

$$\frac{D(\nabla c)}{Dt} = \nabla \left( \frac{Dc}{Dt} \right) + \|\nabla c\| \left( \mathbf{S}_A \cdot \mathbf{n} + \frac{1}{2} \mathbf{n} \times \mathbf{\omega}_A \right)$$

(1)

where $\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla$ is the material derivative operator, $\|\nabla c\|$ is the norm of the scalar gradient, $\mathbf{S}_A$ is the strain rate (symmetric part of the velocity gradient $\mathbf{A} \equiv \nabla \mathbf{u}$), $\mathbf{\omega}_A = \nabla \times \mathbf{u}$ is the vorticity vector and $\mathbf{n} \equiv -\nabla c/\|\nabla c\|$ refers to the normal vector to the flame front. In this regard, both the strain-rate and the vorticity terms in the equation (1) play a role in the dynamics of the flame wrinkling and orientation, whereas only the strain-rate term affects the local thickness. In light of the above, the turbulence-flame interactions are reflected by the alignments of flame normals with the normalized vorticity vector $\hat{\mathbf{\omega}}_A = \mathbf{\omega}_A/\|\mathbf{\omega}_A\|$ and with the principal directions $\mathbf{e}_i^A$ of the strain-rate tensor $\mathbf{S}_A$. The alignments examined with the absolute value of the cosine of the angle between two vectors, so that the value 1 indicates a perfect alignment, while the

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value 0 refers to a perfect misalignment (perpendicularity). Given the symmetry of the strain-rate tensor, the eigenvalues $\mathbf{e}_A^i$ correspond to the three real eigenvalues, $\lambda_i$, of $\mathbf{S}_A$ ordered as $\lambda_1 > \lambda_2 > \lambda_3$, where $\mathbf{e}_A^1$, $\mathbf{e}_A^2$, and $\mathbf{e}_A^3$ can be referred to as the extensive, intermediate, and compressive directions. One of the key findings of this family of analysis, conducted either on the passive and reactive scalars with passive chemical reactions or flame characterized with a high turbulence intensities, is the preferential alignment of the scalar gradient with the most compressive direction $\mathbf{e}_A^3$ [1, 2, 3]. However, this behaviour is altered in weak to moderate turbulence, where the flame–induced thermal expansion affects the turbulence–scalar interaction and the normals are aligned with the most extensive direction $\mathbf{e}_A^1$ [2, 4]. More recently, by performing a complex Schur decomposition of the velocity gradient tensor Keylock [5], dissociated the normal/local dynamics of the velocity gradient from the other dynamics of the velocity gradient in the context of non–reacting homogeneous isotropic turbulence (HIT). Thanks to this additional decomposition, supplementary elements of explanation of the behaviour of strain and vorticity alignments are provided. The present work is based on a similar methodology to [5], with the aim of quantifying the respective role of the local and non-local effects in the context of turbulence–flame interaction.

2. Local/non–local decomposition
The velocity gradient tensor $\mathbf{A}$ can be split using the complex Schur decomposition into a sum of an eigenvalue part, $\mathbf{A}_\lambda$, and a non–normal matrix, $\mathbf{A}_N$, such that

$$\mathbf{P}^* \mathbf{A} \mathbf{P} = \mathbf{T} = \mathbf{D}_\lambda + \mathbf{N}, \quad \mathbf{A}_\lambda = \mathbf{P} \mathbf{D}_\lambda \mathbf{P}^*, \quad \text{and} \quad \mathbf{A}_N = \mathbf{P} \mathbf{N} \mathbf{P}^*, \quad (2)$$

where $(\cdot)^*$ is the Hermitian operator, $\mathbf{P} \in \mathbb{C}^{(3 \times 3)}$ is a unitary matrix, i.e., $\mathbf{P}^* \mathbf{P} = \mathbf{I}$, and $\mathbf{T} \in \mathbb{C}^{(3 \times 3)}$ is an upper-triangular matrix. The matrix $\mathbf{D}_\lambda$ is the diagonal matrix of the eigenvalues of $\mathbf{A}$ and $\mathbf{N}$ is a strictly upper-triangular matrix. In view of this decomposition, the strain rate tensor can be decomposed into a local and a non-local components, i.e., $\mathbf{S}_A = \mathbf{S}_L + \mathbf{S}_N$ such that

$$\mathbf{S}_M = (\mathbf{A}_M + \mathbf{A}_M^*)/2, \quad \text{where} \quad M = L, N \quad (3)$$

3. DNS database and problem setup
The DNS database consists of two simulations of an inlet–outlet configuration of statistically-planar turbulent premixed lean methane flames evolving in a box with periodic lateral boundary conditions. The computational domain size is $16\delta_L \times 8\delta_L \times 8\delta_L$, where $\delta_L$ is the laminar flame thermal thickness, discretized over a mesh of $2N \times N \times N$. Under the thermodynamic conditions retained for this study, consisting of an atmospheric pressure, a fresh gases temperature of 298 K and an equivalence ratio of 0.7, the laminar flame speed and thickness are about $S_L \approx 18$ cm/s and $\delta_L \approx 660 \mu$m, respectively. The kinetics of the methane–air combustion are described using the 16 species and 35 reactions mechanism of Smooke & Giovangigli [6]. The simulation is initialized by superimposing a one-dimensional unstrained laminar flame solution onto a turbulent velocity field obtained from a preliminary inert HIT simulation on a periodic box of size $(8\delta_L)^3$. The latter corresponds to the establishment of turbulence starting from synthetic turbulent fluctuations prescribed by an energy spectrum. In this auxiliary HIT computation, the turbulence was maintained and driven to establish quasi-stationary state by introducing a zero-mean time-dependent linear forcing term into the momentum equation. In addition to its use as an initial velocity field in the reactive simulation, the obtained HIT solution is used to feed the inflow turbulent velocity fluctuations. These fluctuations are injected using an active control method based on the strategy introduced in [7] to maintain the flame mean location in the centre of the computational domain. The same forcing procedure was used in the fresh gases to maintain turbulence properties at the desired values.
The parameter of interest in the current DNS database is the Karlovitz number defined as 

\[ Ka = \left( \frac{u'}{S_L} \right)^3 \left/ \left( \frac{\delta_L}{l_t} \right) \right. \]

where \( u' \) and \( l_t \) refer to the turbulent intensity and integral length scale, respectively. The first case \( C_1 \), corresponds to a low Karlovitz number \( Ka \approx 3 \), whereas the second, \( C_2 \), is characterized by \( Ka \approx 1400 \). An illustration of the two cases is given by fig. 1, which reports the instantaneous isosurfaces of the progress variable based on temperature. The grid resolution was adjusted to satisfy the requirements of solving turbulent and chemical length scales, such that \( N \) is set to 128 and 512 for \( C_1 \) and \( C_2 \) cases, respectively.

![Figures showing instantaneous isosurfaces for two cases](image)

Figure 1: Instantaneous isosurfaces of the progress variable based on the mixture temperature, for (a) \( C_1 \), (b) \( C_2 \). The left (right) column displays the fresh (burnt) gases side.

4. Results and discussion
Following the order of magnitude analysis, the evolution of the local flame width, \( \| \nabla c \|^{-1} \), is driven by the production term \( TSI = \| \nabla c \| \mathbf{n} \mathbf{S} \mathbf{A} \mathbf{n} \). Positive values of the latter reflect a broadening of the flame under the action of strain, whereas negative values correspond to a decreasing of \( \| \nabla c \|^{-1} \). The conditional average of the TSI term, as well as its local/non–local decomposition, as a function of the progress variable is scrutinized in fig. 2. It is apparent, consistently with previous studies, that for the low Karlovitz case, i.e, \( C_1 \), this term is positive for all progress variable values, similarly to a laminar flame, whereas it becomes negative for the high Karlovitz case, where the action of strain results in flame brush thinning. Figure 2 indicates, independently of the combustion regime, that the contribution of the local effects in turbulent straining of the flame front dominates in the overall strain action. Furthermore, the contribution of non-local strain is negligible in the \( C_1 \) case, and tends to exhibit the same behavior as in a laminar flame, in which \( \mathbf{A}_N = \mathbf{0} \), whereas it is less negligible in the \( C_2 \) case. The sign and the magnitude of the TSI term are, in particular, determined by the alignments between flame normals, \( \mathbf{n} \), and strain eigenvectors \( \mathbf{e}_i^A \). Therefore, in the light of the above, it is expected that the alignments \( |\mathbf{n} \cdot \mathbf{e}_1^A| \) are also dominated by the angles between the eigenvectors of the local component of the strain tensor, \( \mathbf{e}_1^L \), rather than those associated with the non–local effects, \( \mathbf{e}_1^N \). This is illustrated in fig. 3, which reports the distributions of the absolute cosine of the angle between the normals and the principal directions of \( \mathbf{A}, \mathbf{L} \) and \( \mathbf{N} \) in the reacting zone characterized by \( 0.4 < c < 0.8 \). The \( C_1 \) case exhibits a behavior similar to the laminar flame, which consists of an alignment of the normals with the most extensive direction, i.e., \( \mathbf{e}_1^A \) associated with the largest eigenvalue, giving rise to positive values of TSI term, whereas the \( C_2 \) case shows the same trends as a non-reactive scalar, which is a predominance of the alignment with the most compressive direction \( \mathbf{e}_3^A \). In both cases, it can be seen that the orientation of the
Figure 2: Progress variable conditional average of $\|\nabla c\| n S n$ normalized by $(\delta L S L)^{-1}$.

flame, with respect to $e A^i$, is mainly driven by the local contribution, whereas the flame normals do not show any preferential alignments with the non-local contributions.

Figure 3: PDF of the absolute value of the cosine angle between the flame normals and the principal directions of the strain rate tensor for $0.4 < c < 0.8$.

5. Conclusion
The relative importance of local and non–local contributions into the turbulence-flame interaction is investigated through a DNS of low and high Karlovitz turbulent statistically-planar premixed lean methane flames. As far as the magnitude of the TSI term and the orientation of the flame normals with principal strain directions are considered, it is shown that, independently from the regime under investigation, the local strain contribution is dominant, making it possible to approximate the action of turbulence within the one of the eigenvalue part of the velocity gradient tensor.

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