Non-premixed Flame-Turbulence Interaction in Compressible Turbulent Flow

D. Livescu¹ and C.K. Madnia²

¹University of California,
Los Alamos National Laboratory,
T-3/MS B216, Los Alamos, NM 87545, USA.
²Department of Mechanical and Aerospace Engineering,
State University of New York at Buffalo,
Buffalo, NY 14260, USA.

Contact address: madnia@buffalo.edu

1 Introduction

Nonpremixed turbulent reacting flows are intrinsically difficult to model due to the strong coupling between turbulent motions and reaction. The large amount of heat released by a typical hydrocarbon flame leads to significant modifications of the thermodynamic variables and the molecular transport coefficients and thus alters the fluid dynamics [1],[4]. Additionally, in nonpremixed combustion, the flame has a complex spatial structure. Localized expansions and contractions occur, enhancing the dilatational motions. Therefore, the compressibility of the flow and the heat release are intimately related. However, fundamental studies of the role of compressibility on the scalar mixing and reaction are scarce. In this paper we present results concerning the fundamental aspects of the interaction between non-premixed flame and compressible turbulence.

2 Results

In order to assess the influence of compressibility on the coupling between turbulence and reaction, direct numerical simulations (DNS) of decaying isotropic and homogeneous sheared turbulence are performed for different initial values of the turbulent Mach number, $M_{t0}$, under reacting and nonreacting conditions. The continuity, momentum, energy and species mass fractions transport equations
Reacting compressible turbulence

are solved using the spectral collocation method. The chemical reaction is modeled as one-step, exothermic, and Arrhenius type. The scalar fields are initialized with a double-delta PDF (“random blobs”). The range of non-dimensional mean shear rates considered for homogeneous shear flow cases extends from 4.8 to 22. In this paper the results for $S^* = 7.24$, which are in the range dominated by nonlinear effects, are presented. The reaction parameters mimic the low to moderate Reynolds number combustion of a typical hydrocarbon in air. Details about the numerical method as well as the influence of the reaction parameters on the flame-turbulence interaction can be found in Livescu, Jaber & Madnia [3]. The range of Mach numbers considered in the present study extends from a nearly incompressible case with $M_{t0} = 0.1$ to $M_{t0} = 0.6$ which is at the upper limit for the numerical method considered. The decaying isotropic turbulence simulations have the value of the Taylor Reynolds number $Re_{\lambda}= 55$ at the time when the scalar field is initialized. For the turbulent shear flow simulations the range of $Re_{\lambda}$ extends from 21 to 50. In this paper the results corresponding to $Re_{\lambda} = 21$ are considered. The results obtained for higher $Re_{\lambda}$ cases are consistent with those presented in this paper.

Figure 1(a) shows that for turbulent shear flow cases the peak of the mean reaction rate decreases its magnitude and occurs at earlier times as the value of $M_{t0}$ is increased. Similar results are obtained for the isotropic turbulence cases, although the $M_{t0}$ influence on the evolution of the reaction rate is weaker than in shear flow. In order to better understand this behavior, the reaction rate, $w = D\rho^2Y_A Y_B \exp(-Ze/T)$, is decomposed into its components, the mixing term, $G = \rho^2 Y_A Y_B$, and the temperature dependent term, $F = \exp(-Ze/T)$. For turbulent shear flow, the results presented in figure 1(b) indicate that the Mach number has a different influence on the evolutions of $F$ and $G$. As $M_{t0}$ increases $F$ increases, indicating elevated temperatures. The increase in the temperature at higher $M_{t0}$ can be associated with an enhanced viscous dissipation in the mean temperature transport equation. Moreover, this effect is more important for turbulent shear flow where the viscous dissipation levels are higher. For both flows considered, higher temperatures expedite the ignition and the mean reaction rate peaks at an earlier time. However, at earlier times the reactants are less mixed so that the mixing term $G$ has lower values. The combined effects of $F$ and $G$ terms result in a decrease in the magnitude of the peak of the mean reaction rate.

The results presented above are consistent with those of Livescu & Madnia [2] which show that the scalar mixing is more sensitive to changes in Mach number in homogeneous turbulent shear flow than in isotropic turbulence. For turbulent shear flow, due to the presence of a mean velocity gradient the scalar field develops a preferential spatial orientation. Figure 2(a) shows that the angle between the direction $x_1$ of the mean velocity, and the scalar gradient projection on the plane formed by the direction $x_2$ of the shear and $x_1$, has a most probable distribution approaching values close to $\pm 90^\circ$ after some development time. This indicates that the scalar blobs are distorted into parallel layers oriented at a small
angle with respect to the plane perpendicular to the direction of the shear.

![Graphs showing the effect of Mach number on reaction rate and components](image)

Figure 1: Mach number influence on the evolution of (a) mean reaction rate and (b) reaction rate components in turbulent shear flow.

Due to the spatial structure of the scalar field, the relative orientation between the scalar gradients and different quantities pertaining to the velocity field are different in turbulent shear flow than in isotropic turbulence. In particular, Livescu & Madnia [2] show that a passive scalar gradient is no longer aligned with the most compressive eigenvector of the solenoidal strain rate tensor as in isotropic turbulence and the relative angle changes with Mach number. As a result, the production term in the scalar dissipation equation decreases as $M_{t0}$ is increased and the mixing becomes worse. Similar results are obtained for a reacting scalar. However, in this case the heat of reaction affects the turbulence. Since the reaction takes place mostly at the interface between the scalar layers, the localized expansions and contractions due to the heat of reaction also develop a preferential spatial orientation.

For a nonreacting homogeneous shear flow it is known that the explicit dilatational effects occur predominantly in the direction of the shear [3]. In the reacting case, due to the anisotropy in the heat release, these effects are further amplified. In particular, figure 2(b) shows that the dilatational kinetic energy in the direction of the mean shear is increased by the reaction. Moreover, this increase is more significant at higher values of $M_{t0}$.

3 Concluding Remarks

The Mach number effect on the two-way interaction between turbulence and non-premixed flame is studied in isotropic turbulence and homogeneous turbulent shear flow using data generated by DNS. The results show that the reaction rate and its components is less affected by changes in $M_{t0}$ in isotropic turbulence
than in turbulent shear flow. For the latter case, the scalar field, and thus the reaction, develops a preferential spatial orientation. As a result, the relative orientation between the scalar gradients and different quantities pertaining to the velocity field is different than in isotropic turbulence. This affects the mixing process and leads to an increased sensitivity to the initial value of the turbulent Mach number. Moreover, the anisotropy in the explicit dilatational effects is significantly amplified by the reaction.

References

[1] F. A. Jaberi, D. Livescu, and C. K. Madnia. Characteristics of chemically reacting compressible homogeneous turbulence. *Physics of Fluids* 12:1189–1209, 2000.

[2] D. Livescu, and C. K. Madnia. Compressibility effects on the scalar mixing in reacting homogeneous turbulence. In *Turbulent Mixing and Combustion*, Editors: A. Pollard and S. Candel, Kluwer Academic Press, in press.

[3] D. Livescu, F. A. Jaberi, and C. K. Madnia. The effects of heat release on the energy exchange in reacting turbulent shear flow. *J. Fluid Mech.*, 450:35–66, 2002.

[4] L. Vervisch, and T. Poinsot. Direct numerical simulation of non-premixed turbulent flames. *Annu. Rev. Fluid Mech.* 30:655-691, 1998.