Turbulence-Flame Interactions in Premixed Lean Hydrogen Flames

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1 Introduction

Conventional wisdom suggests that premixed flames are unable to survive at sufficiently high turbulence levels, e.g. Peters [1] or Poinsot and Veynante [2]. This conclusion is based on experimental studies of highly-stretched methane Bunsen flames (e.g. [3] and the references therein) and of vortex-flame interactions examined experimentally [4] and numerically in two dimensions [5].

However, Aspden *et al.* [6] studied highly turbulent supernova flames numerically. At a Karlovitz number of approximately 230, the flame was sufficiently disrupted by the turbulence that a clear flame sheet was no longer identifiable. Instead, a greatly broadened flame brush was observed, which resembled a homogeneous turbulent mixing zone. The local flame speed was greatly reduced, but the broadening of the flame brush meant that the overall speed was approximately five times faster than the laminar flame speed. Global extinction was not observed.

In this paper, we take a similar approach to [6] to investigate turbulence-flame interactions in premixed lean hydrogen flames at a variety of Karlovitz numbers using high-resolution three-dimensional numerical simulations with detailed chemistry.

2 Numerical Method

The simulations presented here are based on a low Mach number formulation. The fluid is treated as a mixture of perfect gases with a mixture-averaged model of differential species diffusion. Gravity, Soret, Dufour and radiative transport processes are neglected. The thermodynamic relationships and hydrogen kinetics (chemical source terms) are obtained from the the GRIMech 2.11 model [7] with the relevant carbon species removed. The mixture-averaged transport coefficients are evaluated with the EGLIB software package [8]. The discretisation uses a symmetric operator-split coupling of chemistry and diffusion with a density-weighted approximate projection method to evolve the constrained advection. The resulting time-integration proceeds on the advective time scale. Diffusion and chemistry are treated time-implicitly. The scheme is embedded in a parallel adaptive mesh refinement framework based on a hierarchical system of rectangular grid patches. The overall scheme discretely conserves mass and energy, and is second-order accurate in space and time. Details of the low Mach number model can be

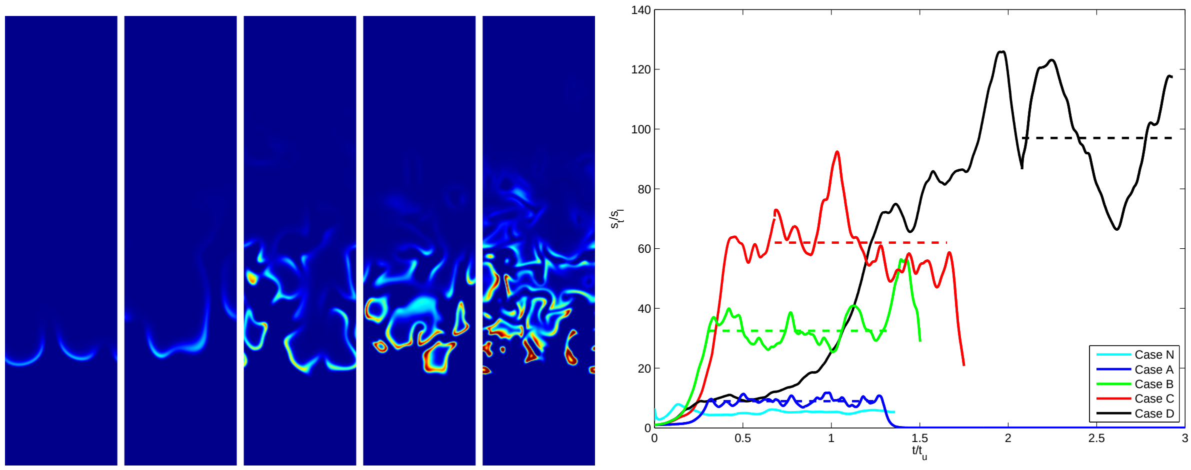

Figure 1: (a) Vertical slices through the five cases depicting consumption rate of H_2; left to right are cases N, A, B, C and D, respectively. As the Karlovitz number increases, note the disruption of the flame sheet, the broadening of the flame brush, the decrease in individual structure size, and the local enhancement of the consumption rate. (b) Turbulent flame speeds normalised by the laminar flame speed, the time is normalised by the turbulent time scale $l/\check{u}$ (in case N the time scale from case A is used). The dashed lines show the time-averaged value and the range used for averaging.

found in [9] and previous applications of this methodology to premixed turbulent flames can be found in [10] and the references therein.

3 Problem configuration

The flow is initialised as a downward propagating flame in a high aspect ratio box (8:1) with periodic lateral boundaries, a free-slip wall at the base, and outflow at the top. A turbulent background is maintained using the same time-dependent zero-mean forcing term used to characterise the scheme [11] and in the supernova study [6]. The initial velocity field is obtained by running an inert calculation using the above forcing term until the turbulence was fully-developed. A flat laminar flame is then superimposed over this velocity field to start the calculation.

Five simulations are presented here, which span a range of Karlovitz numbers. In each case the fuel is lean hydrogen ($\varphi = 0.31$) at a temperature of 298 K, and atmospheric pressure. The laminar flame speed and width is 4.68 cm/s and 0.189 cm, as computed by the PREMIX code [12] with identical transport and chemical kinetics. In all cases the domain width was 0.95 cm (i.e. 5 laminar flame widths). The Karlovitz number was varied by changing the turbulent intensity, which was controlled by the magnitude of the forcing term. The RMS velocity in the five cases was $\check{u} = 0, 0.17, 0.8, 1.54$ and 5 m/s, referred to as cases N, A, B, C and D, respectively. These correspond to Karlovitz numbers of $\mathrm{Ka} = (\check{u}^3 l_L / s_L^3 l)^{1/2} = 0, 10, 100, 266$ and 1562, respectively, where s_L and l_L are the laminar flame speed and thickness, and l is the integral length scale.

In all cases, a base grid of $64 \times 64 \times 512$ was used. One level of refinement (factor 2) was used to focus resolution around the flame. It was found that two levels of refinement were required to resolve the small-scale turbulence in case D due to the higher Karlovitz number.

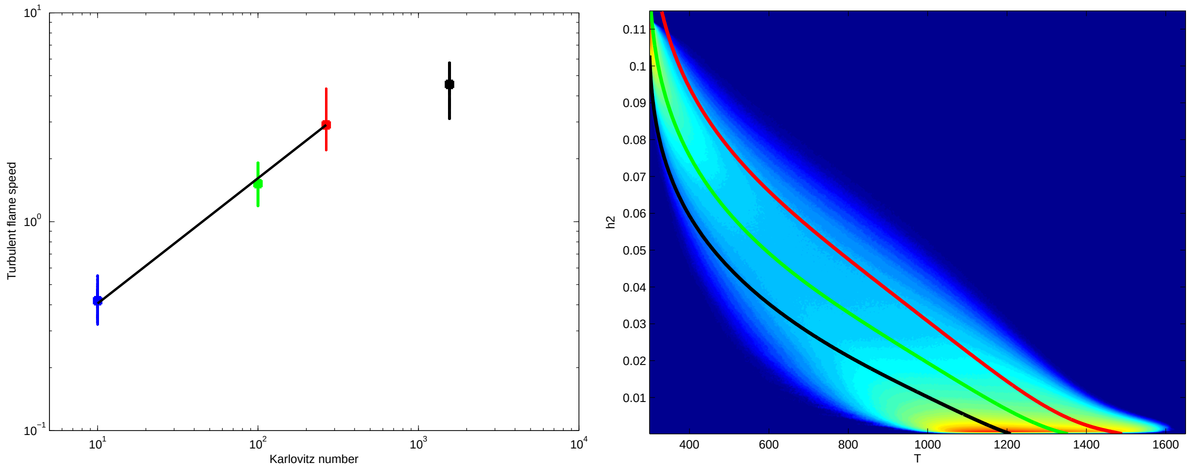

Figure 2: (a) Turbulent flame speeds against Karlovitz number. The marker denotes the mean turbulent flame speed and the bar denoted the speeds attained over the averaging period. The black line denotes a power-law relation with exponent 0.6. (b) Joint probability density function of temperature against fuel mole fraction for case C. The black, green and red lines are the laminar flame paths for $\varphi = 0.31, 0.37$, and 0.43, respectively. The flame appears to burn more richly. Also note that the distribution is decorrelated, unlike the distribution reported in the supernova study of [6] at a similar Karlovitz number.

4 Observations

Figure 1(a) shows a vertical slice through each of the five cases, and depicts a typical snapshot of the consumption rate of H_2. The entire domain width and half the domain height is shown. The images are normalised by the same value (approximately 43 times the laminar value). As expected, since the flames are thermodiffusively unstable, even without a turbulent background (case N) the flame forms cellular structures. As the Karlovitz number is increased, the large-scale structure of the flame becomes disrupted; the flame sheet becomes convoluted and the size of individual structures appears to decrease. The flame burns as a broadened flame brush instead of a more coherent flame sheet. The local consumption rate increases with Karlovitz number; in case D, it is approximately 150 times the laminar value. The broadened flame brush compounded with local enhancement leads to an overall turbulent flame speed that is many times the laminar flame speed, see figure 1(b). The fluctuations arise because of the unsteady nature of hydrogen flames combined with the time-dependence in the forcing term. Once the flame is fully-developed, an time-average turbulent speed can be evaluated, shown by the dashed lines in figure 1(b), which for case D, is approximately 97 times the laminar value. Global extinction is certainly not observed here.

Figure 2(a) shows the turbulent flame speed against Karlovitz number. It appears that there may be a power-law relation between cases A-C, the exponent is approximately 0.6, but this does not fit with case D. There may be some limiting or transitional behaviour, or the domain width may be prohibitively small; further investigation is warranted.

In the supernova study [6], at a Karlovitz number of approximately 230 (i.e. comparable with case C), the turbulence was able to completely dominate the flame, which resembled a turbulent mixing zone. This does not appear to occur here, even at the much higher Karlovitz number. This observation is reinforced by the joint probability density function of temperature against fuel mole fraction for case C, figure 2(b). In [6], the distribution collapsed to a single curve because turbulent mixing was the dominant process. This does not happen for the present flames. It appears that hydrogen diffusion remains an important process, and is not dominated by the turbulence.

5 Conclusions and Future Work

The highly-turbulent premixed lean hydrogen flames presented here suggest that even at high Karlovitz numbers, lean hydrogen flames do not extinguish. In spite of a Karlovitz number much greater than the supernova flame presented in [6], the turbulence was not able to completely disrupt the flame, and hydrogen diffusion remained an important process.

The flames presented here are a subset of a larger study that considers other effects including stoichiometry and domain (integral length) size. Abstract numerical studies can be used to artificially change and identify the importance of different diffusion processes. It will also be interesting to consider other hydrogen mixtures, as well as methane flames under similar conditions.

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