Direct Numerical Simulation of turbulent partially premixed flames

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Extended Abstract

Partially premixed flames occur in many practical systems, like direct injection piston engines or gas turbines combustors. In these systems, the fuel and the oxidizer are injected separately and partially mix before they ignite. The resulting flame propagates into a non-homogeneous mixture, in which lean and rich pockets are randomly distributed. This has the potential to significantly alter the flame structure and behavior, and has been the subject of many studies, that show contradictory results concerning combustion efficiency. While the experiments of Zhou et al [1] conclude on a higher overall burning rate in non-homogeneous mixtures, many studies based on numerical simulations found no effect or an opposite effect [2,3,4].
Direct Numerical Simulation (DNS) is a powerfull tool to help the understanding of the mechanisms that control partially premixed flames and their efficiency, as compared to the classical perfectly premixed case. It also allows a parametric study to evaluate the sensitivity of such flames to the spatial distribution of the inhomogeneities and their repartition around the mean equivalence ratio. Finally results of DNS may be used to evaluate the performance of classical turbulent combustion models and assess the validity of the new models that partially premixed combustion require.
We present here DNS of two different situations of partially premixed flames: (1) temporal DNS of premixed flames propagating into a non-homogeneous mixture using complex chemistry (fig. 0.1, left) (2) spatial DNS of partially premixed flames stabilised by hot gases (fig. 0.1, right). These two configurations are generic of the different situations of partially premixed combustion that can be found in practical systems. The first case corresponds for example to what happens in direct injection piston engines, in which the liquid injected fuel first evaporates before burning, leading to a mixture with a distribution of rich and lean pockets. The second case is more relevant to gas turbine combustors, in which the reactants are injected separately and burn after sufficient mixing and preheating, leading to a flame stabilising in a region of variable equivalence ratio.

Temporal DNS of a partially premixed flame

Partially premixed propane-air flames have been computed, using a detailed reaction mechanism based on 30 species and 76 reactions (including thermal NO chemistry), multicomponent molecular transport of species and full resolution of both the turbulent and the chemical scales. The conservation equations for mass, momentum, chemical species mass fractions and total energy are solved using the NTMIX-CHEMKIN code described in [5]. An *initially laminar lean flame* ($\phi = .6$) was established and propagated into homogeneous

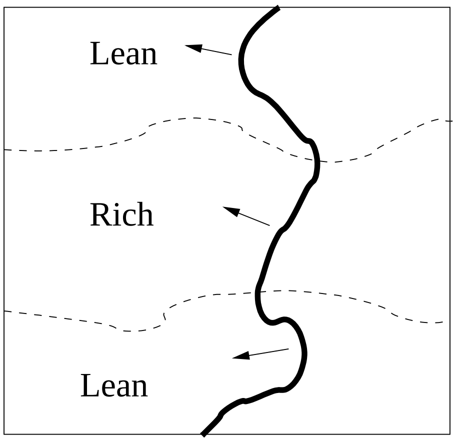

Figure 0.1: Configuration for the temporal DNS of partially premixed flames

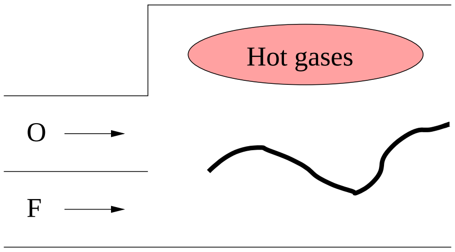

Figure 0.2: Configuration for the spatial DNS of partially premixed flames

and non-homogeneous turbulent mixtures having the *same global lean stoichiometry*.
The effect of stratification on combustion efficiency is the result of four different mechanisms that may have opposite effects: (i) increase of flame wrinkling due to variable flame speeds, (ii) variable local heat release along the flame front, (iii) different response to turbulence straining and curvature and (iv) interaction between richer and leaner flames. Depending on the initial distribution of the equivalence ratio in the fresh gas mixture, all these mechanisms may lead to an increase or decrease of the total heat release of the flame. Another parameter is the characteristic size of the rich and lean pockets: for very large size pockets (compared to the flame thickness), there will be little effect as the variability of the equivalence ratio will be low and for very small size pockets, the effect will also be small as the variability of the equivalence ratio will be smoothed by turbulence before reaching the flame. An important effect will be seen only for intermediate size pockets, with a possible optimum size in terms of combustion efficiency.
A series of simulations with different distributions of equivalence ratio and different pocket sizes have been run, showing a maximum gain in burning rate up to 50Classical flamelet and CMC models have been evaluated, both showing some difficulties to take into account all stratification effects.

Spatial DNS of a flame stabilised by hot gas

In gas turbine combustors, the flame is stabilised by a hot gas recirculation zone that forms close to the injectors. The effect of turbulence on the flame stabilisation has been studied by injecting a turbulent flow field through the inlet. This procedure allows to maintain the turbulence level in the computational domain and to perform a spatially evolving, stationary, simulation. Because our code solves the fully compressible conservation equations, some special care was needed when imposing the unsteady inlet boundary condition that mimics turbulence injection and we will describe the method we used.
The simulations showed an important impact of turbulence on the stabilisation mechanisms. In the laminar case, the flame stabilises with a "triple flame" structure. The distance from the injectors corresponds to the ignition time that can be calculated by a simple 1D asymptotic analysis. The main effect of turbulence is to decrease the ignition distance, thanks to a more efficient mixing between the reactant and the hot gas fluxes. A complex structure appears in the stabilisation region, with in particular the formation of multiple "triple points". Implications for the modelling of flame stabilisation have been studied.

References

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