Flame turbulence interactions in lean hydrogen flames at low to moderate Karlovitz number: implications for fractal modeling at atmospheric and high pressure conditions

Thomas Jaravel[1]*, Quentin Douasbin[1], Francis Meziat Ramirez[1], Omar Dounia[1], Olivier Vermorel[1]
*jaravel@cerfacs.fr
1 CERFACS, France

Lean hydrogen/air flames are subject to thermodiffusive (TD) effects, showing both a positive response of local fuel consumption to stretch, and the formation of a wrinkled cellular structure. This alters the flame structure and scales, raising the question of the role of these mechanisms in the turbulent regime and their impact on the flame surface topology. In particular, fractal modeling of the flame surface [1] is found in many subgrid turbulence-chemistry interaction closure, such as the artificially thickened flame model [2].

In this study, described in [3], a setup of flame-turbulence interaction is used to perform Direct Numerical Simulations of premixed hydrogen/air flames, over a wide range of Karlovitz numbers, from laminar conditions to intermediate Karlovitz numbers in the corrugated flamelet regime. The flame surface wrinkling and stretch response contributions to the turbulent flame speed are analyzed. This is completed by a fractal analysis to extract relevant parameters for subgrid modelling (inner cut-off scale and fractal dimension).

The reactivity enhancement through stretch is found to be a significant contributor to the turbulent flame speed. The stretch factor increases with Karlovitz number, showing a positive interaction between turbulence and thermo-diffusive effects, consistently with the empirical correlation from [4]. As for the flame wrinkling, at low Karlovitz number, the wrinkling is dominated by the cellular structure from the thermodiffusive instability. In this regime, the inner cut-off scale is found to be roughly constant and of the order of the freely propagating unstable flame. At higher Karlovitz number, it is demonstrated that turbulent flames subjected to thermodiffusive effects can be matched in terms of fractal parameters to scaling laws obtained for unity Lewis number flames, by accounting for the reactivity enhancement factor in the definition of the flame scales. It suggests that the flame surface topology is mainly dominated by turbulent stretching in this regime. A model for the subgrid turbulent flame speed is proposed based on the fractal parameters scaling laws and the empirical correlation from [4]. It is then evaluated in higher pressure and temperature conditions, to assess the relevance of the proposed model at conditions relevant for gas turbine applications.

References

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