Introduction

The premixed propagation of lean hydrogen-air flames (φ = 0.3) in Hele-Shaw cells (i.e., two adiabatic parallel plates separated by a small distance h [1–3]) is investigated using numerical simulations with detailed chemistry and transport. We focus on the effect of the distance between plates, h, for a semi-closed system of size 50h × 30h × h, where δy = 1.45 mm is the thickness of the planar adiabatic flame. Hydrodynamic and diffusive-thermal instabilities wrinkle the flame front to form small cellular structures that increase the overall propagation velocity. Symmetric and non-symmetric shapes are observed in the third dimension (i.e., along h).

Formulation

The dynamics of the flame front is determined by solving the variable-density reactive Navier-Stokes equations:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,
\]

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla p + \frac{1}{\rho} \nabla \cdot \mathbf{S} + \nabla \cdot \mathbf{Q} + \mathbf{F},
\]

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,
\]

with the ideal gas equation of state:

\[
\rho R_T T = p.
\]

The species flux and the heat flux have the form

\[
\mathbf{j}_k = \rho D_{km} \nabla Y_k, \quad \dot{\omega}_k = \nu_{km} \nabla h_k - \sum_{l=1}^{\lambda} \nu_{kl} h_k \nabla Y_l + \sum_{l=1}^{\lambda} \nu_{kl} h_k \nabla h_l, \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,
\]

and the diffusivity of the species into the mixture \( D_{km} \) is calculated using mixture-averaged diffusion model. The chemistry is modeled using the Mésocentre de calcul de Poitou-Charentes. Combust. Flame 201 (2019) 91110-91111.

Results

The mixture is ignited at the open-to-atmosphere end \((x = 0 \text{ cm})\) with a series of evenly-spaced hot spots. The reactive front propagates towards the closed end \((x = 17.25 \text{ cm})\). The simulations compare three cases: \(h = 0.1h_f\), \(h = 3h_f\) and \(h = 3h_f\) at \(t = 0.14, 0.31\) and 0.06 seconds from the initial ignition, respectively.

Diffusive-thermal instabilities (associated with the small effective Lewis number of these mixtures, \(Le_{eff} \approx 0.3\)) promote chaotic cell splitting and merging, observed along \(y\) in all the simulations. In Fig. 1, for \(h = 0.1h_f\), the gap is so tight (smaller than the critical wavelength for instability) that only planar flame structures can be seen in the third dimension. For this case, the corresponding three-dimensional problem can be reduced to a two-dimensional set of equations governed by Darcy’s law (i.e., narrow-channel approximation [7]).

For \(h = 3h_f\), the narrow-channel approximation breaks down. We show in Fig. 2 the emergence of non-symmetric shapes in the third dimension, similar to those observed in [8], which increase the total flame surface area. Fig. 3 depicts a symmetric V-shape flame that appears during the early stages of the flame evolution for \(h = 3h_f\).

Work in progress

Long-term flame evolution will be investigated by implementing the formulation in a reference frame moving with the flame. The velocity of this reference frame can be calculated from \(\int \int \int \omega_x \, dx \, dy \, dz / (\rho \int Y_h \, dx \, dy \, dz)\).

References