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Analysis of premixed flame propagation between two closely-spaced parallel plates

Daniel Fernández-Galisteo[a,*], Vadim N. Kurdyumov[a], Paul D. Ronney[b]

[a] Department of Energy, CIEMAT. Avda. Complutense 40, Madrid 28040, Spain
[b] Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA, USA

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ABSTRACT

Motivated by experimental observations on premixed-gas flame propagation in Hele-Shaw cells, this work analyzes quasi-isobaric flame propagation between two adiabatic parallel plates using a simple quasi-2D formulation based on averaging the flow properties across the cell gap. Instabilities associated with thermal expansion, buoyancy, viscosity change across the front and differential diffusion of thermal energy and reactants are investigated with one-step chemistry, constant heat capacity and variable transport coefficients through time-dependent computations of the flame front evolution in large domains. These instabilities are found to induce flame wrinkling which increases flame surface area and thus propagation speeds in ways different from those associated with freely propagating flames. The simulations are compared with experiments in Hele-Shaw cells; very good qualitative and (in some cases) quantitative agreement is found.

1. Introduction

The propagation of premixed flames in narrow channels, tubes, gaps or slots is relevant to several areas of the combustion research, for example in internal combustion engines (ICEs) in the narrow gap between the piston and cylinder walls (called the "crevice volume") which is of relevance to the study of hydrocarbon emissions due to partial burning or flame quenching. In fact, even in the main combustion chamber of premixed-charge (*e.g.*, gasoline-fueled) ICEs, at the time of combustion the chamber has a high aspect ratio, typically 1 cm in height and 10 cm in diameter. Additionally, emerging interest for the development of portable power generation devices has led to increased interest in combustion in confined geometries with small gaps (*i.e.*, comparable to the quenching distance) and high aspect ratios [1–6].

Significant progress in the fundamental understanding of freely propagating flames in narrow channels and ducts has been made. Experimental works have demonstrated the feasibility of combustion in microchannels [7] and numerous methods for sustaining micro-combustion have been proposed [8]. Numerical simulations in the framework of the constant-density approximation [9–14] and variable density [15–18] with reduced [19,20] and detailed chemistry [21,22] have systematically separated and studied effects as the channel size, thermal expansion, heat loss, differential diffusion, radical quenching and detailed kinetics on the flame shape and dynamics in channels whose length (in the direction of flame propagation) is much greater than its width in the two transverse dimensions.

A related but distinct configuration is the Hele-Shaw cell [23,24] between two parallel plates separated by a narrow gap, *i.e.*, a domain that is much larger in two dimensions than the third one. Hele-Shaw cells can be employed to study flame propagation in the manner shown in Fig. 1. In this configuration several types of flame instabilities may manifest themselves including

- The *Darrieus–Landau* (DL) instability [25,26] due to the density change across the flame front. DL effects do not depend on the flame structure and have no characteristic length scale. DL effects occur for any propagating front in which the density of the products is lower than that of the reactants, which is the case for essentially all flames. The impact of the DL mechanism is characterized by the ratio ρ_u/ρ_b, where ρ_u and ρ_b are the densities of the fresh and burned gas mixture, respectively.
- The *Rayleigh–Taylor* (RT) instability [27] due to buoyant convection. RT effects do not depend on the flame structure and affect larger scales more than smaller scales. RT is destabilizing for upward-propagating flames, for which the lower-density fluid lies underneath the higher-density fluid, whereas for downward-propagating flames, RT is stabilizing. The impact of the RT mechanism is characterized by the Froude number

* Corresponding author.
E-mail address: d.galisteo@ciemat.es (D. Fernández-Galisteo).

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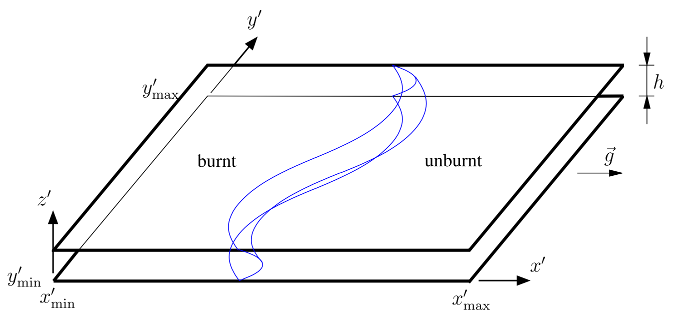

Fig. 1. Sketch of the Hele-Shaw cell with a curved flame propagating from the left to the right between two parallel plates with a cell gap *h*. Shown at the right is the gravity vector, which lies along the *x*-direction. Adapted from [32].

(defined below), which is a measure of the ratio of dynamic to hydrostatic pressure.

- The *Saffman–Taylor* (ST) instability [28] due to the viscosity change across the flame front. ST effects do not depend on the flame structure but require confinement (*e.g.*, in a Hele-Shaw cell) and affect larger scales more than smaller ones. ST is destabilizing when a less-viscous fluid displaces a more-viscous fluid. This is the case for essentially all flames since the viscosity of gases increases with temperature, thus burned products have higher viscosity than the unburned reactants. The impact of ST is characterized by the ratio μ_b/μ_u, where μ_b and μ_u are the dynamic viscosities of the burned and fresh gas mixtures, respectively.
- The *diffusive-thermal* (DT) instability [29] due to unequal values of thermal vs. molecular diffusion coefficients. This is characterized by the Lewis numbers (*Le*) of the reactants, with *Le* of the stoichiometrically deficient reactant having the dominant influence. DT depends on the flame structure and exhibits a maximum growth rate at a wavelength comparable to the thermal thickness of the flame ($\delta_T \equiv \mathcal{D}_{T_u}/S_L$, where S_L is the burning velocity of the planar adiabatic flame and $\mathcal{D}_{T_u}$ is the thermal diffusivity of the fresh gas mixture). DT is destabilizing for *Le* less than a critical value near unity and is stabilizing for larger *Le*.

It is anticipated that these instabilities will wrinkle the flame front and modify its overall propagation rate even though the gas flow may remain laminar. Joulin and Sivashinsky [30] performed a linear stability analysis of flame fronts in Hele-Shaw cells including DL, RT and ST (but not DT). They modeled the flame front as an infinitely thin discontinuity with specified local normal propagation speed and derived a dispersion relation expressing the growth rate of the instability in terms of the density and viscosity differences across the front and the buoyancy effect. They showed that DL and ST are unconditionally destabilizing (due to the density decrease and viscosity increase across the front) and RT is destabilizing/stabilizing for upward/downward propagation. They also showed that heat losses to the walls moderate these instability mechanisms by decreasing the density and viscosity ratios across the front.

The Joulin–Sivashinsky analysis did not include DT effects, which may be significant for Lewis numbers not close to unity. Kang et al. [31,32] extended Joulin and Sivashinsky's work numerically to include DT effects using a 2D compressible reactive Navier–Stokes formulation with the Poiseuille flow assumption. These studies focused primarily on computing the linear growth rates of the aforementioned instabilities and discussing the flame shapes. Their calculations also revealed the influence of both DL and ST effects on the propagation rates. In particular, for $Le = 1$ and ratios of the plate separation h to the thermal flame thickness δ_T of the order $a \equiv h/\delta_T = S_L h/D_{T_u} \approx 15$, where a can be interpreted as a Peclet number, the authors reported an overall flame speed S_T[1] of about 1.4 times that of the adiabatic planar velocity S_L. Excluding ST by neglecting the viscous drag due to Poiseuille flow, S_T/S_L decreased to about 1.25, in agreement with values previously calculated for purely 2D simulations that included DL but not ST effects [33–37].

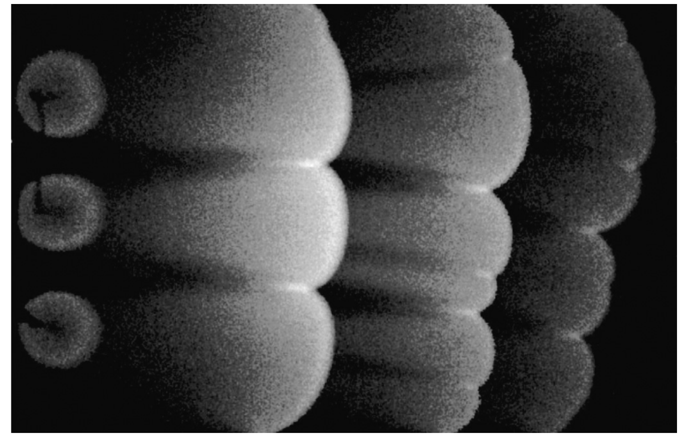

Fig. 2. Sequential, superimposed images of a flame propagating horizontally from left to right in a Hele-Shaw cell in a 25.0% H_2 – 6.25% O_2 – 68.75% N_2 mixture (calculated $S_L = 52$ cm/s, $\rho_u/\rho_b = 4.1$) [39]. Field of view is 597 mm × 394 mm with a cell gap $h = 12.7$ mm, thus $a \approx 171$.

Experimental studies have investigated and identified the contributions of some of these intrinsic instability mechanisms in Hele-Shaw cells [38–40], making use of different mixtures, direction of propagation and distance between the plates. The image in Fig. 2 shows the wrinkled shape of a flame propagating horizontally in a rich H_2–O_2–N_2 mixture (for which the stoichiometrically deficient reactant is O_2 and the effective $Le \approx 1.6$). The flame is ignited by 3 electric sparks near the left side of the cell and propagates from the left (open to the atmosphere) end towards the right (closed) end, so that the flame propagates nearly isobarically into a nominally quiescent gas and thus the observed propagation speed in the laboratory frame of reference is equal to the propagation speed relative to the unburned gas S_T. As discussed later, the large wavelengths of wrinkling are caused by thermal expansion (DL) effects. In contrast, for a lean H_2–O_2–N_2 mixture (for which the stoichiometrically deficient reactant is H_2 and thus the effective $Le \approx 0.34$) (Fig. 3 [39]), DT influences promote the appearance of smaller cellular structures embedded into larger DL-generated wrinkles. It may be noted that without the small-scale DT wrinkling, the larger-scale hydrodynamic structures are cusp-shaped with the sharp peaks pointed toward the burned gas (Fig. 2), whereas when DT instabilities are present, the large-scale structure is more angular or "sawtoothed"; this was a consistent feature of the experiments [39]. For a downward-propagating flame in a lean H_2–O_2–N_2 mixture this angularity is retained but the overall structure is flatter due to the stabilizing RT effects at large scales (Fig. 4). In the experiments, the measured propagation rates are about $S_T/S_L \approx 2.5$ (Fig. 2), $S_T/S_L \approx 15$ (Fig. 3) and $S_T/S_L \to \infty$ (Fig. 4).

The influences of DT and RT on flame propagation in Hele-Shaw cells are readily assessed by changing the effective mixture *Le* and propagation direction, respectively. In contrast, the relative influences of DL and ST are not as easily identified since both occur

[1] The symbol S_T is normally associated with the propagation speed of flames in forced turbulence which is absent in this work, nevertheless, we adopt this notation to signify that the self-induced flame instabilities studied here can also lead to wrinkling which accelerates propagation speeds in a manner analogous to flame wrinkling by forced turbulence.