Flame Propagation in Narrow Channels at Varying Lewis Number

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1 Abstract

The propagation of quasi-2D premixed-gas flames in H_2-O_2-inert mixtures having various Lewis numbers from fuel-lean to fuel-rich conditions were studied using a Hele-Shaw cell. Various instabilities were observed including those attributed to thermal expansion of the burned gas (Darrieus-Landau, DL), buoyancy (Rayleigh-Taylor, RT), viscosity contrast across the flame (Saffman-Taylor, ST), and diffusive-thermal (DT) effects. By varying the concentrations of hydrogen, oxygen, and nitrogen, a range of equivalence ratios and Lewis numbers were obtained at fixed adiabatic flame temperature. The direction of propagation relative to the gravity vector was also varied. It was found that the flame front shapes and propagation rates were strongly affected by all 4 of the aforementioned instability mechanisms but in many cases the contributions of each mechanism were identifiable and nearly independent of each other.

2 Introduction

Despite challenges associated with its storage, hydrogen remains an appealing fuel due to increased concern with the environmental impacts of hydrocarbon fuels. While the advantages of H_2 as a fuel (e.g. combustion at flame temperatures lower than those possible with hydrocarbons) could be exploited to reduce NOx and other emissions, what is most significant is that it does not contain any carbon, and thus does not contribute any carbon dioxide to the atmosphere. Despite the long history of investigation into H_2 combustion, the propagation rates and extinction conditions of flames in H_2-O_2-N_2 mixtures are still not well understood. Lean combustion is especially challenging because of the low molecular weight of hydrogen and thus the low effective Lewis numbers (Le) of flames in lean H_2-O_2-N_2 mixtures resulting in a substantial influence of DT which may also couple with other instabilities. The Lewis number of lean H_2-O_2-N_2 mixtures is about 0.3 whereas for rich mixtures, where O_2 rather than fuel is the stoichiometrically limiting reactant, Le $\approx$ 1.3. Consequently, the objective of this is work is to examine the interactions of DL, RT, ST, DT and potentially other instabilities on the behavior of flames in H_2-O_2-N_2 mixtures of varying equivalence ratio and thus varying effective Le mixtures in a very simple, well-defined geometry. We chose to employ a Hele-Shaw cell in the gap between two parallel flat plates because of this simplicity. Moreover, the apparatus enables assessment of DL instabilities [1, 2] in a quasi-2D geometry as well as the combined influences studied by Joulin and Sivashinsky [3] include the buoyancy and viscosity effects [4].

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3 Experimental methods

The experiment was composed of a planar combustion chamber, known as a Hele-Shaw cell, a spark generator, a partial pressure mixing system, a Vision Research Miro eX2 high speed camera, a vacuum pump, and a computer controlling the system through LabVIEW VI. The overall diagram of this experimental setup is illustrated in Figure 1 (left). The Hele-Shaw cell is made of two acrylic plates separated by a hollow aluminum frame 0.5 inches thick to create a combustion chamber 59.5 cm long, 39.5 cm wide and 0.5 inches thick. The chamber has three spark electrodes installed at one end so that after ignition, three circular flames quickly merge into a single roughly planar flame. At the ignition end of the cell an exhaust manifold is connected to the atmosphere through a ball valve. The chamber and a separate mixing chamber were first evacuated. The mixing chamber was then filled using the partial pressure method. The Hele-Shaw cell was then filled with the mixed gas to a pressure slightly above one atmosphere. Just before ignition the ball valve was opened so that combustion takes place at nearly constant pressure (as confirmed by time-resolved chamber pressure measurements.) The camera was commanded to begin recording, and the gas was ignited. Videos of the flame propagating through the cell were collected using the Vision Research Phantom Camera Control software. After processing the video files to increase flame visibility, the burning rate was determined by counting the number of pixels over which the flame had passed as a measure of the burned fraction vs. time. A typical position vs. time plot is shown in Fig. 1 (right). It can be seen that after the initial transient period, a nearly constant slope (thus steady propagation speed) is observed until the flame approaches the opposite end of the Hele-Shaw cell.

4 Results

Typical images of flames are shown in Figures 2a – d. Figure 2a shows a case for a lean mixture having low effective Le (since the fuel, H_2, is the scarce reactant) where both small-scale DT instabilities and larger-scale DL instabilities can be observed. Fig. 2b shows a case in a mixture very close to the extinction limits where due to substantial heat loss in the burned gases, large-scale wrinkling due to DL and ST effects are suppressed but the smaller-scale DT cells are retained. Figure 2c shows a low-Le case for downward propagation where RT effect are stabilizing and the large-scale structures are suppressed, resulting in a flame that is nearly flat on the large scale but still highly wrinkled at smaller scales. Figure 2d shows a rich mixture having high Le. It can be seen that the low-Le DT instabilities are no longer present, but the larger-scale DL and ST instabilities are still present. It is interesting to note that the combined effects of DT and DL/ST result in flames that are very angular at low Le (Fig. 2a) whereas for higher Le, the flames are cusped (Fig. 2d).

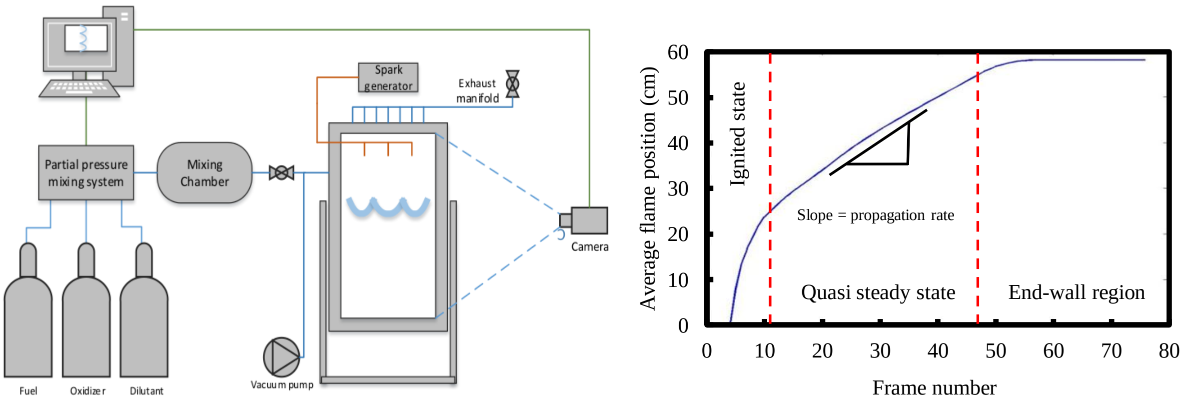

Figure 1. Left: Experimental apparatus; right: typical plot of flame position vs frame number for H_2,O_2,N_2, equivalence ratio = 2.0, adiabatic flame temperature = 1300 K.

It was hypothesized that since steady, spherical “flame balls” can exist in large chambers [5], a 2D analog (“flame circles”) could be possible in the quasi-cylindrical geometry in the Hele-Shaw cell. As in the case of flame balls, such structures would not be possible under the influence of buoyancy, however unlike flame balls, for which buoyancy must be eliminated using microgravity experiments, in the case of flame circles, it may be possible to observe them in a Hele-Shaw cell oriented horizontally. While flame circles cannot be perfectly steady because Laplace’s equation does not have a steady solution in cylindrical geometry in an unconfined geometry because the boundary condition as $r \rightarrow \infty$ cannot be satisfied (unlike the spherical case) the singularity as $r \rightarrow \infty$ is very weak (logarithmic) and thus one might expect such structures to persist on long time scales. In fact, no such behavior was observed; we can state that low-Le flames in Hele-Shaw cells behave more like propagating flames with DT instabilities rather than flame circles with weak effects of propagation (thus convection.)

The effect of mixture strength (characterized by calculated adiabatic flame temperature) and effective Lewis number (characterized by equivalence ratio, varying from Le ≈ 0.3 for lean mixtures to Le ≈ 1.3 for rich mixtures) is shown in Fig. 3. It can be see that as equivalence ratio increases, in general the propagation speed decreases due to the increased effective Le, however, for the stronger mixtures at high equivalence ratio, there is a slight increase in propagation rate. Moreover, for the weaker mixtures (lower adiabatic flame temperature) there is very little effect of equivalence ratio on propagation speed for the range of conditions where propagation is possible (though the weaker mixtures will not burn at all at higher equivalence ratios.) It is also interesting to note that there is almost no effect of orientation relative to the gravity vector on the propagation rate for low-Le

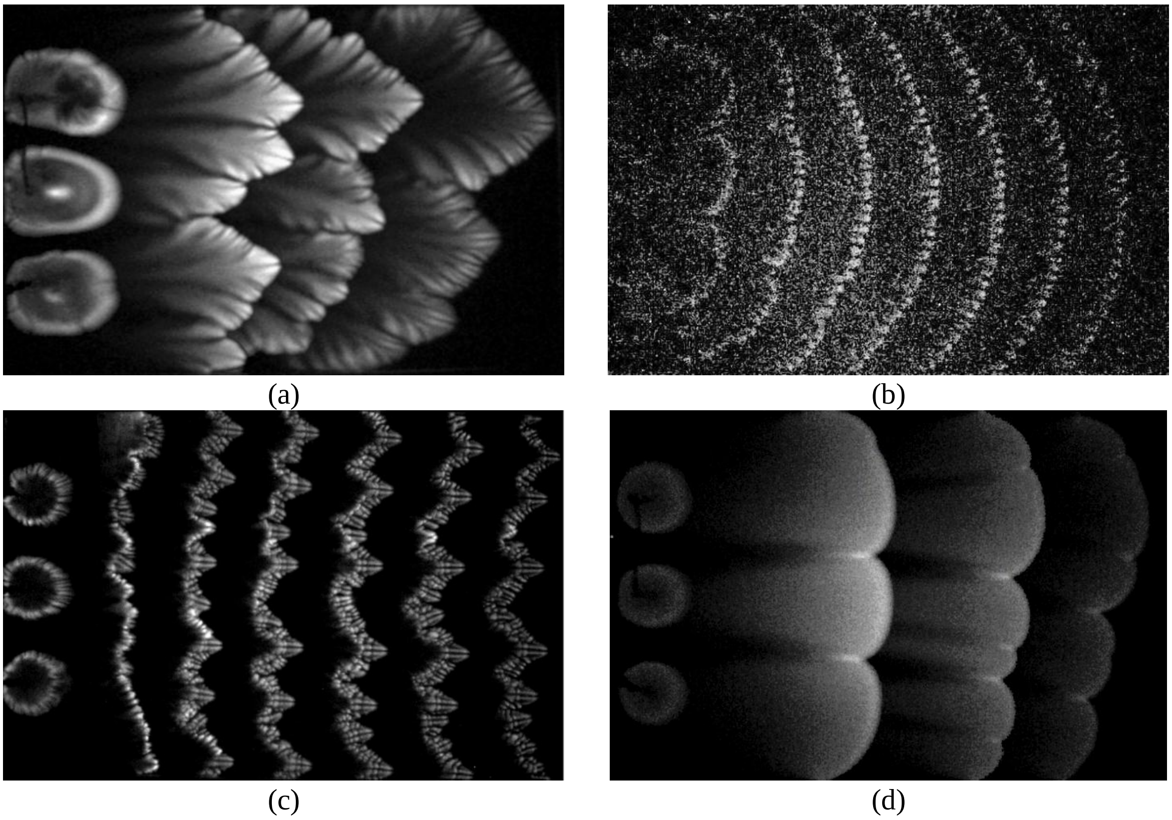

Figure 2. Superimposed images of flame fronts in H_2-O_2-inert mixtures. (a) equivalence ratio = 0.8, adiabatic flame temperature = 1300 K, horizontal propagation (b) equivalence ratio = 0.45, adiabatic flame temperature = 900 K horizontal propagation (c) equivalence ratio = 0.35, adiabatic flame temperature = 1050 K, downward propagation (d) equivalence ratio = 2.0, adiabatic flame temperature = 1300 K, horizontal propagation

flames (low equivalence ratio, Fig. 4). In contrast, for high-Le flames (high equivalence ratio, Fig. 5), there is a substantial effect which, as expected, diminishes for faster flames (higher adiabatic flame temperature) because for the faster flames buoyancy-induced convection velocities, i.e. RT effects, becomes slower relative to flame propagation speeds.

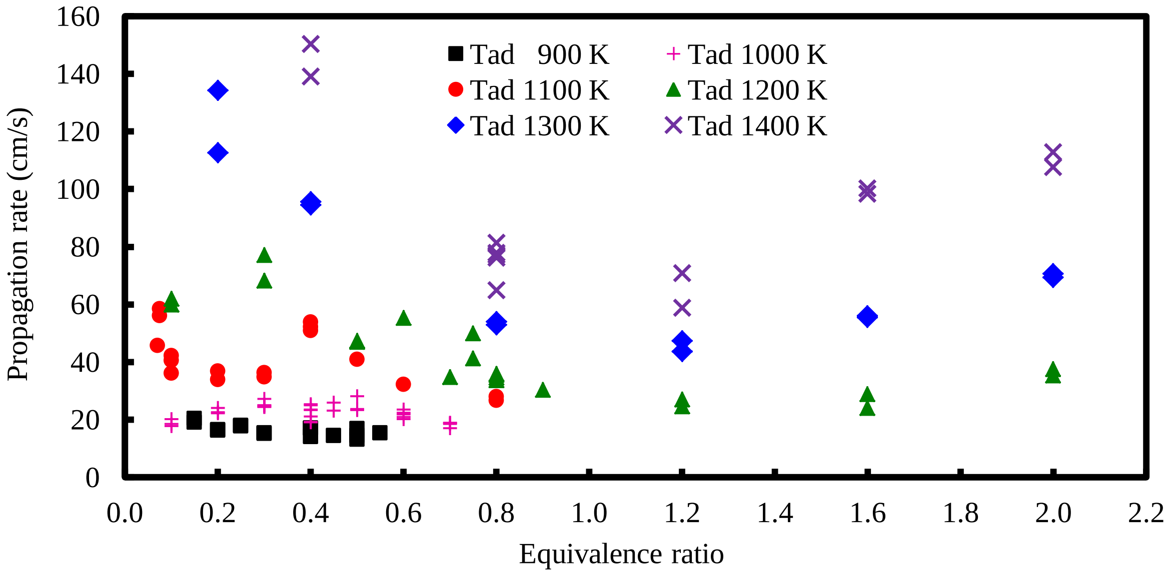

Figure 3. Effect of equivalence ratio and adiabatic flame temperature on flame propagation rates.

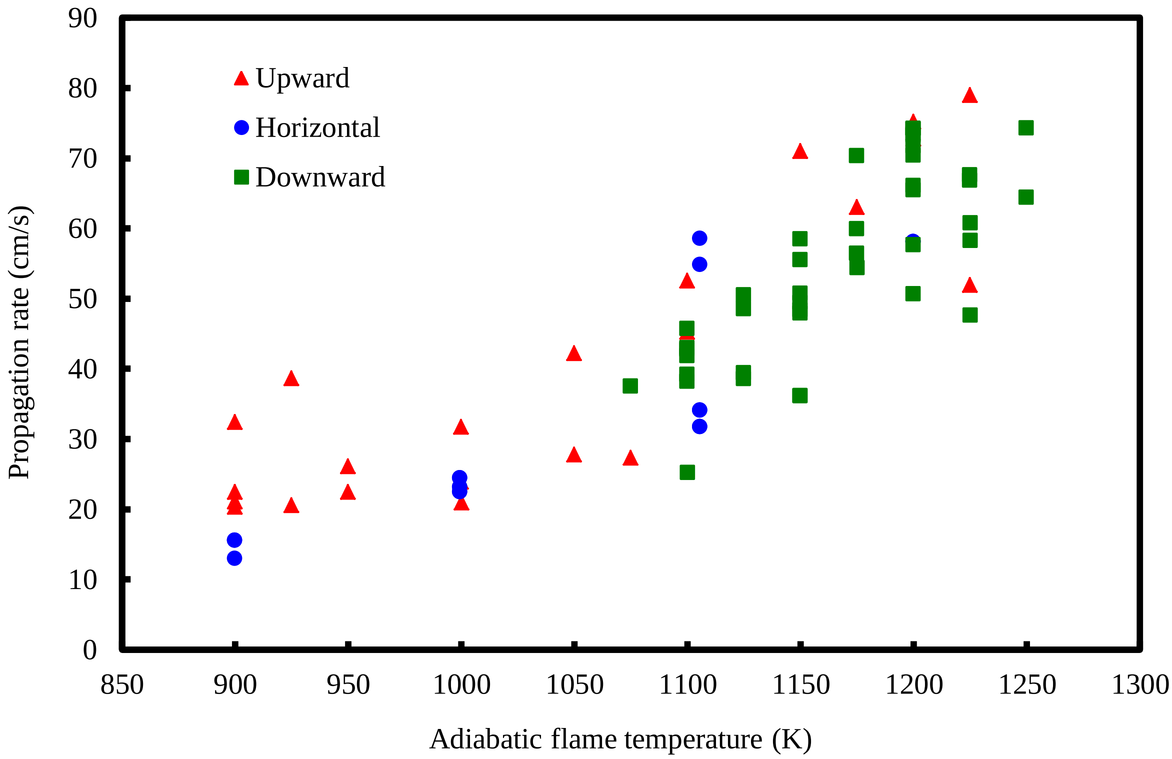

Figure 4. Effect of adiabatic flame temperature and propagation direction on flame propagation rates at equivalence ratio 0.2.

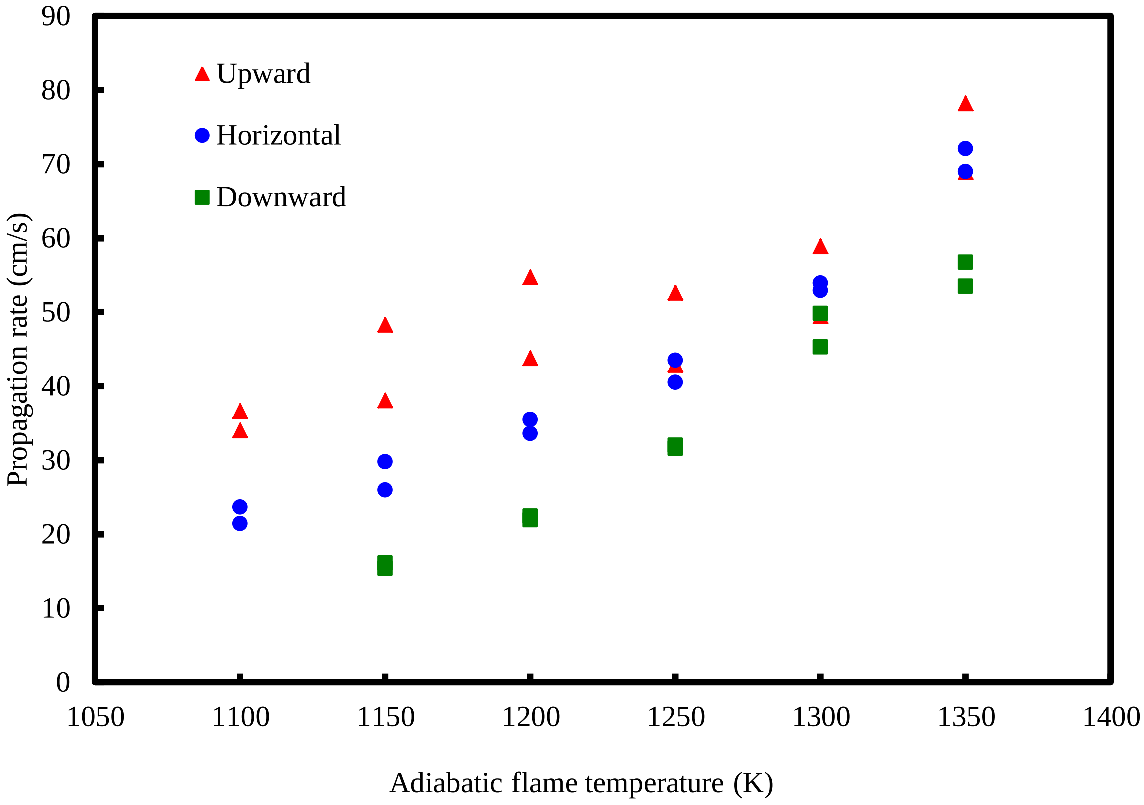

Figure 5. Effect of adiabatic flame temperature and propagation direction on flame propagation rates at equivalence ratio 0.8.

5 Conclusions

Flames in H_2-O_2-inert mixtures propagating in narrow channels exhibit a wide range of behaviors including the combined effects of Darrieus-Landau (DL), Rayleigh-Taylor (RT), Saffman-Taylor (ST) and diffusive-thermal (DT) effects, both in terms of flame shapes and propagation rates. These in particular, thermal expansion (DL) effects are always present, except for very weak mixtures. Buoyancy (RT) effects are destabilizing/stabilizing at long wavelengths for upward/downward propagation. Heat loss has little effect except where the effect is so strong as to suppress thermal expansion. There is clear evidence of both DL and DT instabilities. Moreover, some new phenomena have been observed, e.g. angular large-scale structures (Fig. 2a) vs. cusped for $Le \geq 1$) (Fig. 2d) as well as very stable "sawtooth" patterns for downward propagation (Fig. 2c). Finally, we remark that most experiments are conducted in open flames (Bunsen flames, counterflowing jets, etc.) where gas expansion (DL effects) are at least partially relaxed in the 3rd dimension, whereas most practical applications are in confined geometries, where unavoidable thermal expansion (DL) instabilities cause propagation to be higher than the laminar burning velocity even when heat loss, Lewis number and buoyancy effects are negligible.

6 Acknowledgements

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