Correlation of Tulip Flame Formation and CH Chemiluminescence Bursts in Confined Propane-Air Combustion

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Abstract: In this work, we studied how the fuel–air equivalence ratio changes the way propane–air flames propagate and become unstable in a rectangular chamber. For this, we used a high-speed camera (5000 fps) along with CH* chemiluminescence detection, so that flame images and heat release signals were recorded at the same time. The experiments were carried out for equivalence ratios between 1.1 and 1.47. From the flame images, we looked at how the flame front developed, its speed, and how the shape changed from finger type to tulip flame and further. The chemiluminescence signal (CH*) was tracked in time, and this was compared with flame development. It was noticed that with richer mixtures, the tulip flame formed earlier, and also the CH* signal was stronger, showing sudden bursts exactly when instabilities appeared. A clear relation was observed between the maximum CH* intensity and the key points of flame deformation. This indicates that CH* emission can be used as an early marker of instability for rich propane–air flames. The study adds a useful understanding of how heat release and flame dynamics are connected at higher equivalence ratios, which is important for designing and checking the stability of confined combustion systems.

1. **Introduction:**

The study of flame propagation in premixed combustible mixtures is important for understanding combustion stability, safety, and efficiency in confined chambers. Among different gaseous fuels, propane is widely used in industrial and domestic applications, yet detailed investigations on its flame dynamics at rich equivalence ratios are still limited compared to methane or hydrogen. The equivalence ratio plays a key role in deciding flame structure, burning velocity, and the onset of instabilities such as the well-known tulip flame formation.

Most of the previous studies have focused on global flame parameters or on lean-to-stoichiometric mixtures, whereas the flame behaviour at higher equivalence ratios ($\varphi \approx 1.4$–1.5) has not been explored in detail. In particular, the combined use of high-speed flame imaging and chemiluminescence diagnostics provides an opportunity to link visual flame morphology with heat release processes. The CH* radical emission near 430 nm is a commonly accepted marker for local heat release and can therefore be correlated with flame instabilities.

The present work addresses this gap by studying premixed propane–air flames in a rectangular chamber using simultaneous high-speed imaging and CH* chemiluminescence. The focus is on how increasing fuel richness affects flame propagation speed, morphology transitions (from finger-shaped front to tulip flame), and the timing of instabilities. By linking these features with the temporal evolution of CH* intensity, the work aims to provide new insights into the coupling of heat release and flame dynamics at elevated equivalence ratios.

2. Experimental Facility and Methodology

The experiments were carried out in a rectangular acrylic combustion chamber (400 × 40 × 40 mm) built in-house, with 12 mm thick optical windows on the front and back and 20 mm thick plates on the top and bottom for strength. A thin diaphragm on the right side acted as a safety vent. Propane and air were supplied through mass flow controllers to set φ between 1.1 and 1.47, and the mixture was allowed to mix for 10 minutes before ignition at x = 50 mm, w = 20 mm, h = 20 mm.

Flame propagation was captured using a Photron AX Mini 50 at 5000 fps (exposure = 1/frame rate). Under the same conditions, CH* chemiluminescence at 430 nm was recorded by mounting a bandpass filter on the same camera. The recorded videos were cropped to the propagation part and processed in ImageJ to track flame fronts along the centreline and walls. Pixel data were converted to position (mm) using calibration, and position–time and velocity–time plots were generated in Excel. Flame shape evolution (finger, tulip, oscillatory stages) was identified and marked. CH* intensity was integrated over time and compared with flame images at the same timestamps to relate heat release with flame dynamics. Preliminary efforts are also underway to approximate heat release rate from CH* signals.

3. Preliminary Results and Discussion:

Flame Front Evolution from Imaging: Figure 1 shows the direct flame images at two instants (12.8 ms and 28.0 ms), along with the corresponding CH* chemiluminescence images recorded at the same times. At 12.8 ms, the flame front in the direct image is smooth and finger-shaped, representing the early propagation stage. The CH* image at this instant shows a compact, bright emission zone confined to the leading edge of the flame, indicating that active heat release is localised in a much narrower region than the luminous flame thickness seen in normal imaging.

(a)

(b)

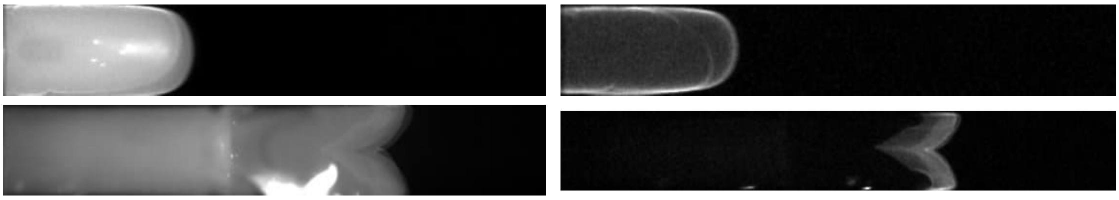
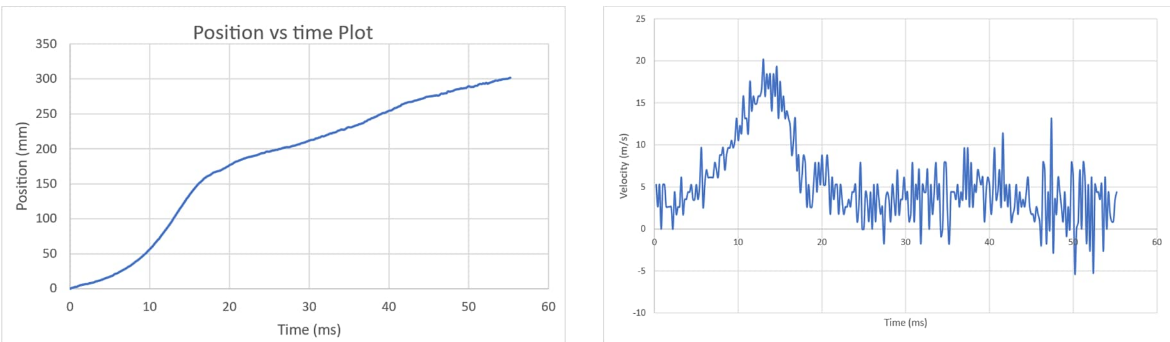


Figure 1. Comparison of flame images and CH* chemiluminescence at φ = 1.47. (a) t = 12.8 ms, finger flame; (b) t = 28 ms, tulip flame.

At around 28 ms, the normal flame picture shows the tulip flame very clearly, where the front has flipped in shape because of the chamber walls and pressure effects. In the CH* image at the same time, the light is brighter and not uniform. It looks patchy along the flame front. This means that when the tulip flame forms, the burning not only becomes stronger but also uneven in different parts of the flame.

Position–Velocity Characteristics at φ = 1.47: The position and velocity data of the flame front for equivalence ratio φ = 1.47 are presented in Figure 2. The flame advances steadily, reaching a maximum position of about 302 mm, close to the chamber end wall. The flame speed goes up quickly after ignition and reaches about 20 m/s at nearly 13 ms. After that the flame slows down as it travels toward the end of the chamber and starts to get unstable. This matches what is seen in the images, because the finger flame begins to turn into a tulip shape just after the velocity peak.



(a) (b)

Figure 2. Position–time (a) and velocity–time (b) plots of flame front for propane–air combustion at φ = 1.47.

Combined Interpretation: When we look at the pictures together with the velocity data, we can see the link more clearly. The highest speed at 13 ms also lines up with the time when the CH* signal begins to grow, so flame acceleration and heat release are happening together. Later, when the tulip shape appears around 28 ms, the CH* signal is not smooth anymore but scattered in patches, showing bursts of burning at different spots.

In summary, while the direct flame images give information about the overall shape and front movement, the CH* chemiluminescence highlights the chemically active zones and provides a more accurate picture of heat release. The velocity data bridges these two diagnostics by showing that mechanical flame acceleration and chemical activity peaks occur at closely linked times, particularly around instability onset.