



# Notes on Hydrogen Combustor Flame Stability Under Lean Premixed Conditions

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## Abstract

Lean premixed combustion is the established route to low nitrogen oxide emissions in gas turbines, and it is the obvious starting point for engines intended to burn hydrogen. The difficulty is that the stability limits of a lean premixed combustor were drawn for natural gas or kerosene, and hydrogen moves every one of them. This short communication is a technical note, not a report of new measurements. It collects what the published literature establishes about the four stability problems of premixed systems, namely flashback, lean blowoff, autoignition in the premixing passage and thermoacoustic oscillation, and explains how the distinctive properties of hydrogen act on each. High laminar flame speed and a small quenching distance make boundary layer flashback the dominant constraint. A Lewis number below unity strengthens lean flames under stretch and widens the blowoff margin, while changing how flames respond to turbulence. A shorter, more compact flame alters the time delays that govern acoustic coupling. The note summarises the design responses now being pursued, chiefly the replacement of large swirl-stabilised flames by arrays of small jets, and lists the observations that would most help designers and that early test campaigns should aim to record.

**Keywords:** *Hydrogen combustion, Lean premixed combustor, Flashback, Lean blowoff, Thermoacoustic instability, Gas turbine*

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## 1. Introduction

Burning hydrogen in a gas turbine removes carbon dioxide from the exhaust but not nitrogen oxides, which form from atmospheric nitrogen wherever the gas is hot enough for long enough. The remedy used for hydrocarbon fuels is to premix fuel and air to a lean mixture, so that the flame temperature stays below the level at which the thermal mechanism becomes rapid (Lefebvre and Ballal, 2010). The price is a narrow operating window. A lean premixed flame sits between blowing off the stabiliser and propagating upstream into the premixer, and it is prone to coupling with the acoustics of the chamber.

Hydrogen differs from methane in almost every property that sets those limits. Lieuwen et al. (2008)

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organised the consequences of fuel composition under four headings: blowout, flashback, autoignition and dynamic stability. This note follows the same division. It reports no experiments of its own. Its purpose is to set down, briefly and for readers approaching hydrogen from conventional combustor practice, what is already established and what remains to be observed.

2. Properties That Set Hydrogen Apart

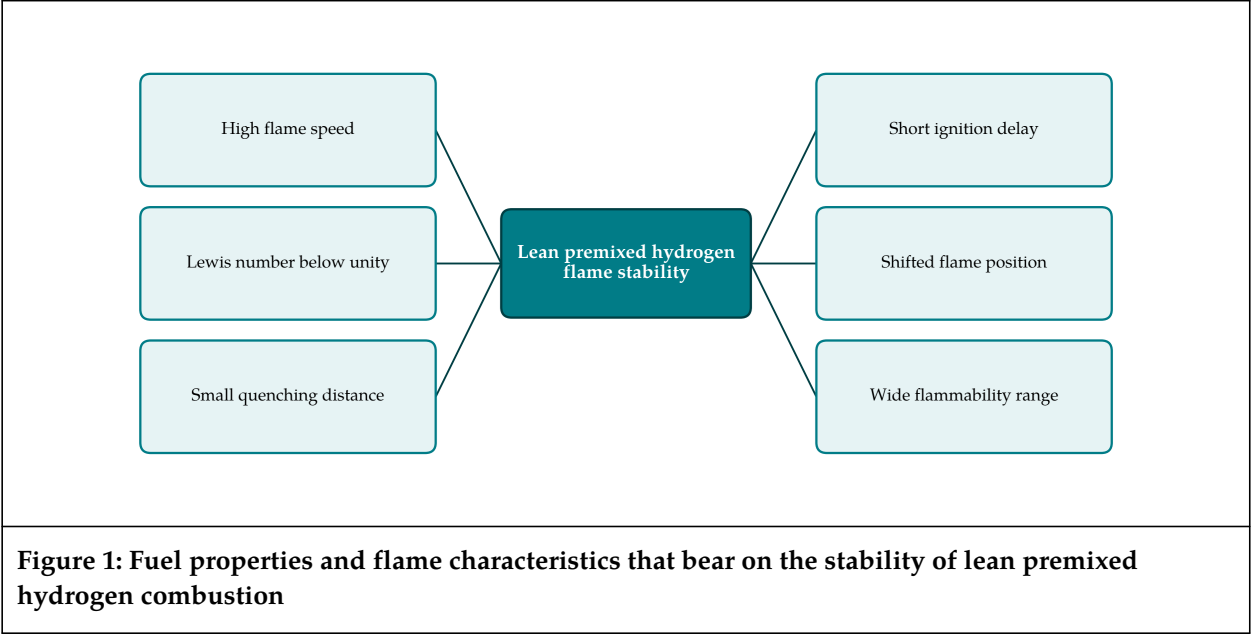
The laminar burning velocity of a stoichiometric hydrogen-air mixture is several times that of methane-air, and it remains comparatively high in lean mixtures. Flammability limits are much wider, the minimum ignition energy is roughly an order of magnitude lower, and the distance within which a cold wall quenches the flame is smaller (Law, 2006). Hydrogen also diffuses far faster than heat in a lean mixture with air, so the Lewis number of the deficient reactant is well below one. A lean flame bulging towards the reactants then gathers fuel faster than it loses heat and burns more intensely at the bulge. Such flames are thermodiffusively unstable, wrinkle spontaneously, and respond to stretch and turbulence in a way that the unstretched laminar flame speed alone does not predict (Lipatnikov and Chomiak, 2005). Figure 1 gathers these properties around the stability problem they jointly shape.

3. Four Stability Problems

Each of the four limits responds differently to these properties. Table 1 summarises the direction of the change and the usual design response.

3.1. Flashback

Flashback can occur through the core flow, through the wall boundary layer, through combustion-induced breakdown of a swirling vortex, or during a pressure oscillation (Lieuwen et al., 2008). For hydrogen the boundary layer route is the most troublesome. The classical criterion of Lewis and von Elbe (1943) holds that a flame enters a duct when the velocity gradient at the wall falls below a critical value that rises with flame speed and falls with quenching distance, and hydrogen is unfavourable on both counts. Experiments in turbulent boundary layers have shown, further, that a flame confined in the duct flashes back far more readily than the unconfined flame the classical model assumes, because the flame itself decelerates the approaching near-wall flow (Eichler and Sattelmayer, 2011). The mechanisms and the correlations proposed for them are reviewed by Kalantari and McDonell (2017).



3.2. Lean blowoff

At the lean limit hydrogen helps. Blowoff of a bluff-body or swirl-stabilised flame is preceded by local extinction along the shear layers, where the flame is strongly stretched (Shanbhogue et al., 2009). A flame

with a Lewis number below unity resists extinction by stretch, and adding hydrogen to methane has been shown to extend the lean stability limit of a swirl burner and to change the flame shape as it does so (Schefer *et al.*, 2002). The gain is real but should not be read as licence to keep an existing stabiliser, since the features that hold a methane flame also invite hydrogen flashback.

**Table 1: Stability problems of lean premixed combustors, the effect of hydrogen on each and common design responses**

| Problem         | Effect of hydrogen                                              | Common design response                                       |
|-----------------|-----------------------------------------------------------------|--------------------------------------------------------------|
| Flashback       | Much greater risk, especially along walls and in swirling cores | High passage velocity, thin boundary layers, small injectors |
| Lean blowoff    | Margin widens; flame holds at leaner mixtures                   | Operate leaner; revisit staging schedules                    |
| Autoignition    | Ignition delay shortens at high pressure and temperature        | Short premixing length and residence time                    |
| Thermoacoustics | Flame shortens; unstable frequencies and modes shift            | Re-tune dampers; spread convective delays                    |
| Emissions       | Higher flame temperature at equal equivalence ratio             | Leaner operation and rapid, uniform mixing                   |

### 3.3. Autoignition and thermoacoustic oscillation

Premixing takes time, and the mixture must not ignite before it reaches the flame. At the high inlet pressures and temperatures of modern engines the ignition delay of hydrogen-air mixtures shortens, which narrows the gap between delay and premixer residence time and makes the result sensitive to local hot spots and rich pockets. Thermoacoustic behaviour changes for a different reason. Oscillations arise when heat release fluctuations are in phase with pressure, and the phase is set largely by the time a disturbance takes to travel from the injector to the flame (Lieuwen, 2012). A hydrogen flame is shorter and anchors closer to the injector, so that delay falls, and a combustor that was quiet on natural gas may become unstable in a different, often higher-frequency, mode. A review of fuel flexibility in hydrogen-rich premixed combustion reaches the same conclusion for syngas and blended fuels (Taamallah *et al.*, 2015).

## 4. Design Responses

The dominant response has been to abandon the single large swirling flame. If the fuel cannot be trusted in a long premixing duct with thick boundary layers and a central recirculation zone, the duct is made short and narrow and the number of injectors is multiplied. Micromix and multi-tube concepts burn the fuel in a great many small flames, each fed at a velocity high enough to prevent upstream propagation and each too short for much nitrogen oxide to form (Funke *et al.*, 2019). Small scale brings its own concerns: manufacturing tolerance, blockage, pressure loss, and the acoustic interaction of many closely spaced flames, which need not behave as the sum of single ones.

## 5. Observations Worth Recording in Early Tests

Much published work has been done at atmospheric pressure, on blends and not pure hydrogen, or on single injectors. Four kinds of observation would be especially useful from early combustor tests. One is the flashback limit at engine pressure and preheat, reported with wall temperature and with the velocity profile at the injector exit, since both enter the critical gradient. Another is the flame position and shape across the operating range, without which the measured acoustic response cannot be interpreted. A third is the behaviour during transients, when fuel composition or flow changes faster than the hardware temperature. The last is sensitivity to imperfect mixing, because small rich regions burn fastest and set both the flashback and the emissions outcome. Test reports that give these alongside the usual emissions and pressure-loss figures would allow results from different rigs to be compared.

## 6. Conclusion

Hydrogen does not make lean premixed combustion unstable so much as relocate its limits. Blowoff recedes, flashback advances, autoignition margins shrink and the acoustic character of the chamber changes. Of these, boundary layer flashback places the tightest constraint on injector design, and the move to arrays of small, fast jets is a direct answer to it. Established combustion theory explains the direction of every effect. The magnitudes at engine conditions, and the interaction of many small flames, are where careful observation is still needed.

## Conflict of interest

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