Experimental Investigation of Turbulent Boundary Layer Flashback Limits for Premixed Hydrogen-Air Flames Confined in Ducts

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The concept of premixing fuel and oxidizer well ahead of the flame zone is omnipresent in today’s combustion technology. Its application spans from laminar premixed flames in domestic gas stoves and hot water tanks over the well-known laboratory Bunsen burner up to turbulent combustion in stationary gas turbines and even aircraft engines. All these premixed combustion devices share a common type of failure mode, which is associated with the detachment of the flame from its designated stabilization region and a rapid upstream propagation into the fuel supply. The term ‘flame flashback’ has been coined for this scenario, which usually has to be avoided by all means to guarantee safe and stable burner operation.

While the combustion literature distinguishes between several types of flashback, the underlying principle is always the same: The vector sum of flame consumption speed and flow velocity points upstream. A particularly interesting form of flame flashback occurs inside the velocity boundary layer close to solid walls. On the one hand, flow velocity drops due to the no-slip condition at the wall. On the other hand, reactions are slowed down by heat losses to non-adiabatic walls, resulting in a finite gap between wall and flame, the quenching distance, where the global reaction is extinguished.

Intuitively, a velocity balance between the local flow velocity and the local flame speed appears to be a proper basis for the correlation of wall flashback. This concept was elaborated by Lewis and von Elbe (1943) in their well-known research article on burner flame stability. They established the critical gradient model, which expresses the flashback limit as a balance between the flow velocity, simplified as the axial velocity gradient at the wall times a wall distance, and the flame speed just at the same wall distance. Very important to say here, an interaction between flow and flame was not accounted for in the critical gradient model, i.e. the velocity profile was assumed to be undisturbed or only weakly influenced by the exothermicity of the flame.

After its introduction by Lewis and von Elbe, the critical gradient model was used for almost 70 years to explain and to correlate flashback limits in a considerable number of numerical and experimental efforts for both laminar and turbulent flows, and has been included in many textbooks on combustion technology.

Ambitious goals and initial doubts

The work presented in our paper did not intend to challenge the critical gradient concept. The design of a flashback channel with rectangular cross-section was rather based on critical gradients from the literature to provide for a well-defined experiment. The rig was set up to deliver turbulent wall flashback limits for premixed H2-air combustion at high inlet Reynolds numbers by inclining the lower wall of the duct to form an asymmetric diffuser, reducing wall shear and thus the velocity gradient along the axial coordinate. However, first results from the rig were discouraging in the fact that its stability was much lower than expected and flashback could only be observed for extremely lean mixtures combined with the highest air massflow the supply was capable of.

The ambitious goal to merge a premixed combustion experiment with a boundary layer tunnel required some unconventional designs for flow straightening, avoidance of flashback in the edges of the channel as well as for full optical access through large quartz windows. The obvious suspicion was that some peculiarity of this complex setup distorted the experimental results. To have a direct comparison against flashback limits from the literature, which were almost exclusively recorded for zero pressure-gradient boundary layers of tube burners, the lower wall of the rectangular duct was adjusted horizontal, such that a straight channel could be investigated. However, in contrast to the literature setups where flames were burning on top of the tube burner in free atmosphere prior to flashback, the flame was stabilized yet inside the channel in the current setup shown in Fig. 1, which is more representative for the safety-critical failure case and has experimental advantages.

Straight channel and a tube burner experiment

Fig. 2 shows an intensified OH*- chemiluminescence image of a lean H2-air flame during turbulent wall flashback in the straight channel. The measurements resulted in critical gradients that lay up to an order of magnitude above literature values from comparable tube burner experiments. At the same time, it was known from extensive cold flow characterization inside the channel, using LDA and micro-PIV, that turbulent boundary layers were in a self-similar state and mean and fluctuating velocity distributions were quasi-2D in the center of the channel as intended. With these results on the table, the picture began to clear up. The fact that the flame anchor was not positioned outside of the channel, but confined by the channel walls, must have been responsible for the drastic decrease of flame stability against wall flashback.

At this point, one could think of two different explanations for the observation that a premixed flame which is confined inside a duct has many times the wall flashback propensity of a flame burning in free atmosphere: (1) The presence of the flame inside the duct may change the macroscopic axial velocity field, up to regions considerably upstream of the flame, which would distort the formerly quasi two-dimensional, canonical turbulent boundary layer of the isothermal flow in such a way that the near-wall region becomes retarded and velocity gradients decrease. However, since velocity gradients are computed for undisturbed flow, such changes would not be captured in the data processing. The Lewis and von Elbe model of a velocity balance in the near-wall region could then explain the large critical gradients observed in the channel. (2) The
presence of the flame inside the duct could only change the microscopic flow field in a small region upstream of the flame tip relative to unconfined flame holding. Since the Lewis and von Elbe model does not include a coupling between flame and flow, it fails to predict the flashback limit in this case, even if the wall velocity gradients on the duct wall are precisely known.

The channel experiment had an asymmetric flame configuration, as shown in Fig. 1. Thus, a macroscopic distortion of the channel flow profile seems much more feasible than for the axisymmetric flame holding of a circular geometry. For that reason, a tube burner experiment was set up to double-check the findings of the channel rig. The burner configuration is shown in Fig. 3. Unconfined flashback experiments were carried out by stabilizing the flame on top of the pilot burner in free atmosphere. A confined flame configuration was achieved by simply fixing a ceramic ring with a diameter higher by four millimeters on top of the pilot burner. Flashback measurements with unconfined flame holding neatly reproduced literature values for fully premixed, atmospheric H2-air mixtures and turbulent flow. Putting the ceramic ring on top was the decisive step in order to find out whether the critical gradient model of Lewis and von Elbe would still hold or not. The results of unconfined and confined tube burner experiments are plotted in Fig. 4 together with the channel results. The drastic decrease of wall flashback stability for confined flames was the very same for both, tube and channel.

**Conclusion**

The excellent match of confined wall flashback limits in tube and channel geometries rules out the explanation for increased limits by macroscopic flow distortion since such a strong upstream influence can be excluded for an axisymmetric tube burner arrangement (it was confirmed later on by high-speed micro-PIV in the wall region before and during flashback that this also holds for the channel setup). A microscopic interaction between the boundary layer flow field and the local pressure rise upstream of the flame obviously is a key process for the onset of wall flashback and should consequently be represented in any physically sound method for the correlation of flashback limits. The Lewis and von Elbe model, as intuitive and appealing as it appeared during almost 70 years, becomes obsolete at this point.

Figure 3: Tube burner setup.

Figure 4: Turbulent wall flashback Limits of confined and unconfined premixed atmospheric H2-air flames.