Numerical modelling and experimental validation of laminar flame flashback in tube burners for H_2-enriched methane-air combustion

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Summary

The propagation of the flame upstream of its stable location in burners (i.e., flame flashback) is probably the main challenge in hydrogen combustion. Thus, the laminar flashback velocity of H_2-CH_4/Air flames is studied using experiments and CFD. The effect of changing the velocity profile is studied using a cylindrical inset, lowering the wall velocity gradient. An increased flashback resistance was observed for 60% H_2 enrichment. Results suggest core flow flashback rather than boundary layer flashback (as initially expected), which is confirmed by CFD.

Body

With the increasing interest in reduction of emissions from the automotive and industrial sectors, there has been a push towards greener fuels with H_2 being one of the leading candidates. Hydrogen offers carbon-free emissions as well as sustainable production pathways such as using solar or wind energy. However, combustion of hydrogen by itself is difficult due to its high laminar flame speed and its subsequent susceptibility to flashback, which raises safety concerns. An alternative is to use hydrogen blended fossil fuels, such as methane, taking advantage of the wide flammability range of H_2 allowing for ultra-lean combustion reducing both carbon and NOx emissions. The suitability of such fuel mixtures needs to be studied since this would guide the development of burners which can safely operate with increasing hydrogen content. The aim of this study is to determine the effect of the premixture velocity profile on the flashback propensity of a H_2-CH_4/Air mixture in a simplified tube burner using experiments and validate the use of CFD simulations in accurately capturing the flashback trends for this setup. The latter will then allow the development of newer burner designs based on simulations offering a rapid turnover rate from design to production. To the authors' knowledge, no similar study has been performed that might highlight the under or overprediction of flashback propensity of CFD simulations for a given design.

A simplified tube burner was used with a hole diameter of 4mm and a length of 30mm. The velocity profile was modified by inserting a hollow cylindrical inset with a wall thickness of 0.5mm. The inset is recessed 10mm within the tube which results in a velocity profile as shown in Figure 1. The fuel consists of 60% H_2 enriched premixed methane-air mixture at different air-fuel ratios: λ=0.75 and λ=1. Flashback was induced by slowly reducing the exit bulk flow velocity from a stable flame to a point where the flow speed becomes lower than the flame speed and the flame travels upstream into the tube. This was captured using a Genie HC 1024 camera with a 12 mm focal length lens and a MidOpt BP550-27 filter. A sequence of a flashback event, for λ=0.75, can be seen in Figure 2, which was captured by a Chronos 2.1 HD high speed camera paired with Hamamatsu C9016 intensifier unit.

The results show that for all cases, the addition of insets resulted in a reduction in flashback velocity, as shown in Figure 3. This is contrary to the a priori assumption that reducing wall velocity gradients would result in an increased propensity for flashback. For λ=0.75, the minimum velocity before flashback was reduced from 1m/s to 0.9m/s. At λ=1 the flashback velocity reduced from 0.75m/s to below the minimum allowable velocity (0.7m/s) for our available mass flow controllers. This result points to the flashback being a core flow flashback rather than a boundary layer flashback. This has previously been observed in simulations from Flores-Montoya et al. [1] and Fruzza et al. [2] where for mixtures with Lewis number greater than 0.5, a symmetric core flow flashback is observed. Thus, the increased core flow speed provided by the inset resulted in a decreased flashback propensity for this mixture. For lower Le, the maximum heat release rate moves towards the hotter surfaces, increasing the possibility of boundary layer flashback.

CFD simulations were further carried out for the case of λ=1 to verify the trends observed in the experiments. Based on the observations, a simplified steady laminar 2D axisymmetric model is used. Chemistry was modelled using a 17 species and 58 reactions model with a grid size of 30μm. The grid size was chosen to allow for at least nodes within the flame front, as calculated from 1D freely propagating flame using Cantera for this mixture. The simulations suggested slightly lower flashback velocities for both cases (with and without insets) compared to experimental results. However, the trends were similar and the case with insets had a lower flashback velocity compared to the case without insets. The small discrepancy in CFD simulations for this case can be attributed to the simplified 2D model which, as observed by Fruzza et al. [3], tends to underpredict flashback velocity compared to a 3D case.

Conclusion

The aim of this study was to both validate the prediction capabilities of CFD simulations in capturing flashback and to study the effect of velocity profile on the flashback propensity of a tube burner. Experimental results show that the addition of an inset (which results in an increased core flow velocity) provides better flashback resistance for a 60% H_2-CH_4/Air mixture. This behavior is in line with previous CFD simulations but further validation for different fuel mixtures is required.

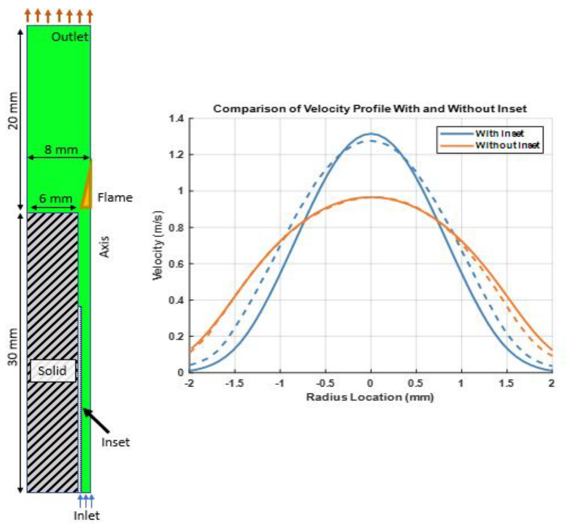

Figure 1 (Left) Schematic of the burner with inset (Right) Velocity profile at the exit of the burner (V_{avg}=0.5m/s), with and w/o inset. Dashed lines for hotwire measurements while solid lines for CFD simulations

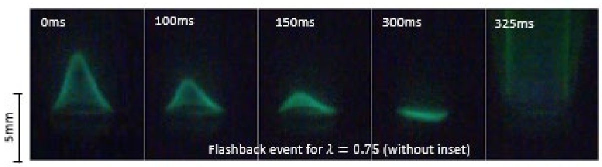

Figure 2 Flashback sequence for **λ**= 0.75 w/o inset

The CFD simulations for the case of λ=1 show a similar trend as seen in experiments with the flashback resistance increasing with the addition of insets. However, the minimum velocity for both cases was slightly underpredicted which, may be attributed to modelling assumptions.

This study was limited to 60% H_2 mixtures due to experimental constraints. Nonetheless, a clear trend can be seen and this will be explored in future studies with increasing H_2 fractions. Similarly, further CFD validation would be required for development of models and techniques suitable for capturing flashback of H_2 based burners.

References

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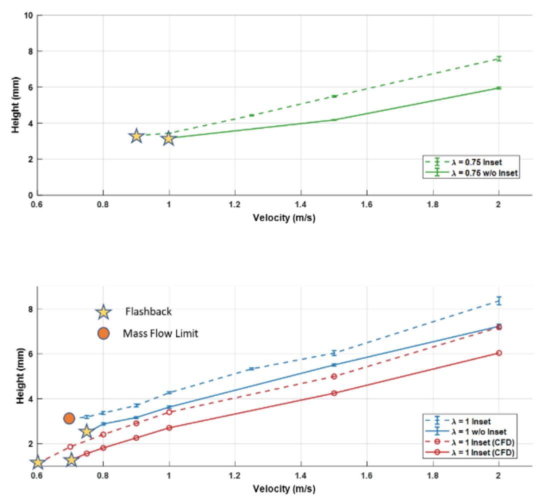

Figure 1 Comparison of flame progression towards flashback for λ=0.75 and λ=1. CFD simulations have been compared in the bottom figure for λ=1