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Stability of Underexpanded Supersonic Jet Flames Burning H_2-CO Mixtures

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Abstract

Introduction

A wide variety of process gases, manufactured and utilised in the chemical and power industries, are stored and transported at high pressure. One such process gas attracting increasing interest is 'syngas', comprising a mixture of carbon monoxide and hydrogen, whose venting or accidental release into the atmosphere may pose a significant fire and explosion hazard. The precise nature of the hazard will depend, to a significant extent, on the stability of any jet flame resulting from the underexpanded fuel release. It has been established experimentally, for example, that both natural gas and hydrogen discharges, through circular orifices larger than a critical diameter, sustain stable lifted flames irrespective of the reservoir pressure driving the release [1,2]. At smaller diameters, however, stable burning will only be achieved at operating pressures higher than a particular, diameter-dependent, threshold. In the case of pure hydrogen, the critical diameter is approximately 1 mm, whilst for natural gas, predominantly methane, the value is 30 mm. Given the wide disparity of these values, the behaviour of multi-component mixtures involving hydrogen is then less readily predicted. Large differences in the combustion characteristics of mixture components - for example, in burning velocities and flammability limits - may be further compounded in extensively lifted flames by differences in molecular weights and, hence, transport properties. The present paper describes an experimental and computational investigation of the stability of underexpanded CO-H_2 jet flames over a range of driving pressures and mixture compositions.

Stability Correlations

Correlations describing the blow-off stability of subsonic releases from circular orifices have been developed, covering a range of single component fuels including, in some cases, inert diluents [3]. Fuel effects are incorporated comparatively simply through the maximum laminar burning velocity, relative density and kinematic viscosity. Extensions of such correlations to underexpanded supersonic jets have also been proposed, based on the introduction of a hypothetical 'effective' orifice diameter for the discharge. Kalghatgi [3] suggested, for example, that this diameter should be based on the equivalent exit diameter, d_{eff}, necessary to ideally expand the discharge to ambient pressure, namely -

$$d_{eff} = d \left\{ \frac{1 + \frac{1}{2}(\gamma - 1) M^2}{(\gamma + 1)/2} \right\}^{\frac{\gamma+1}{4(\gamma-1)}} M^{-\frac{1}{2}}$$

where M is the ideally expanded exit Mach number. In the case of natural gas releases, this relationship was observed to substantially overpredict the critical diameter for pressure-independent stability by almost 50%. Birch et at [4] proposed that the effective diameter be simply based on a notional expansion to ambient static pressure under essentially isothermal conditions, however, and reported good agreement with experiment.

In fig 1 these correlations are applied to releases of H_2-CO mixtures and compared with experimental measurements from the present study. The earlier observed behaviour in respect of predicted natural gas stability is now reversed - favouring the larger diameters emerging from the correlation due to Kalghatgi [3] - and the experimental data reveal a profound sensitivity to quite modest concentrations of CO (by volume) in the fuel mixture. Releases that might be expected to burn stably at small orifice diameters are, in fact, observed to blow-off, though the differences in laminar burning velocity of such mixtures, for example, are minor. These observations have prompted further investigations of the shock wave structure and turbulent mixing field between the jet exit and the flame stabilisation zone, both experimentally, using Schlieren photography and Raman spectroscopy, and computationally.

Jet Structure and Mixing

Experiment:

The possibility of substantial differential transport of the H_2 and CO components in the non-combusting regime immediately downstream of the exit has been examined using pulsed Raman spectroscopy. Since the small Raman scattering cross-section of the CO makes discriminating measurement uncertain, the CO was replaced by an equivalent concentration of the more spectrally distinct and larger cross-sectioned ethylene. Schlieren imaging indicates that ethylene cannot be directly substituted for the CO in the fuel mixture since there are minor changes occurring in the shock structure, reflecting small differences in the ratio of specific heats, γ. However, in terms of the differences in mixing for two component fuels, compared to single entity fuels, the overall shock structure is believed to replicate the hydrogen-carbon monoxide mixtures accurately enough to allow substitution for present experimental purposes.

The Raman measurements have been made using a pulsed Nd:YAG laser, at 355 nm, and an imaging spectrometer to capture both the Rayleigh scattering and the Raman spectrum. The total number density of the flow is gained from the simultaneous imaging of hydrogen, ethylene (C-H stretch), nitrogen and oxygen. The Rayleigh images are also collected for calibration purposes and to measure the density.

The concentration of hydrogen relative to ethylene is presented in fig. 2 for axial locations at 20, 30 and 40 mm. Images were collected in 10 mm increments, between 10 mm and 100 mm from the jet exit allowing the mixing region of the expansion to be investigated.

An illustrative set of blow-off limit data - critical diameter for varying CO concentration and driving pressure - are presented in fig.3. Under highly under-expanded conditions (P_0 / p > 20, say), once a strong Mach disc is established, the trends are slowly varying. At more modest pressure ratios, however, the changes are more dramatic and even the qualitative trends are poorly reproduced by the existing correlations.

Numerical Simulation:

In the absence of a comprehensive set of scalar and velocity measurements for these releases - reflecting the large volume flow rates and limited duration of experiments, amongst other factors - a number of non-combusting cases have also been simulated computationally using the CFD code FLUENT. Figure 4 and 5 compare the computed Mach number and fuel concentration distribution for a release at a pressure ratio of 22 with a long exposure (and therefore time averaged) Schlieren image at a pressure ratio of 18. Instantaneous images are dominated by small scale turbulent mixing and weak compressive disturbances that obscure the shock structure in the jet core. The flame lift-off height has been measured experimentally, immediately prior to flame blow-out, and the local jet properties identified from the computations at the corresponding location. Rates of turbulent mixing have been compared with the Raman measurements and incorporated in correlations to permit application across the wider data set of blow-out conditions.

Detailed discussion of the computed distributions of composition, mean velocity and turbulence properties, in the light of the flame stability observed experimentally, and the exploration of alternative stability correlations is deferred to the full paper.

References

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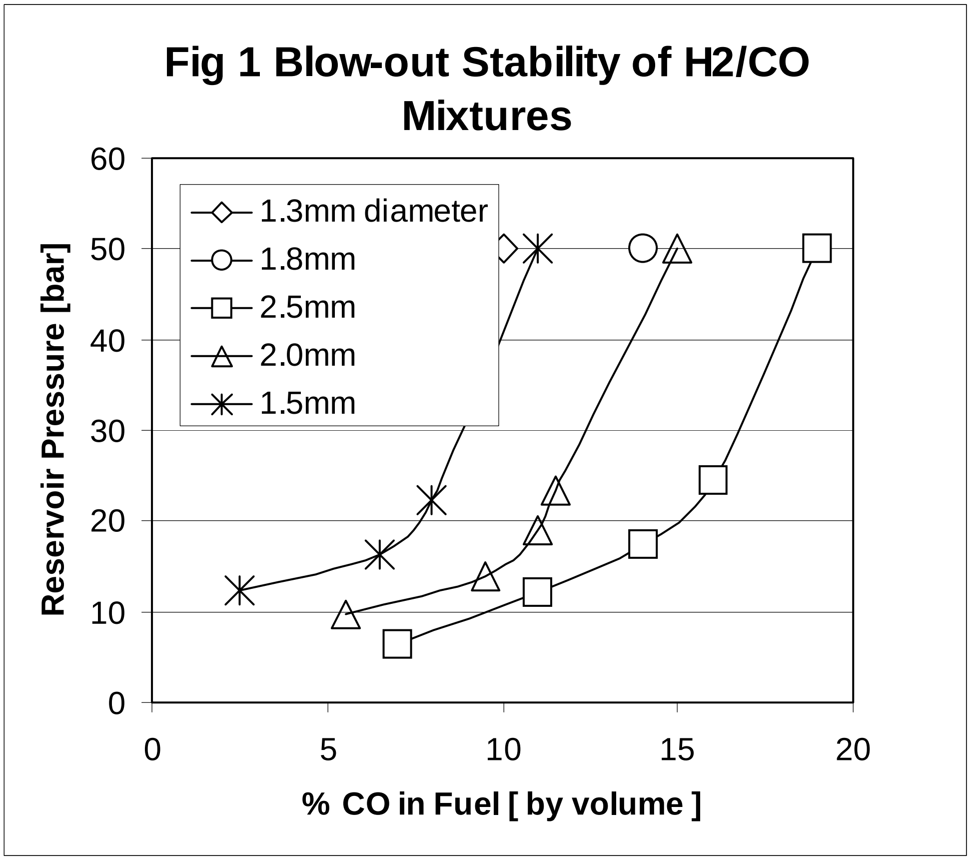

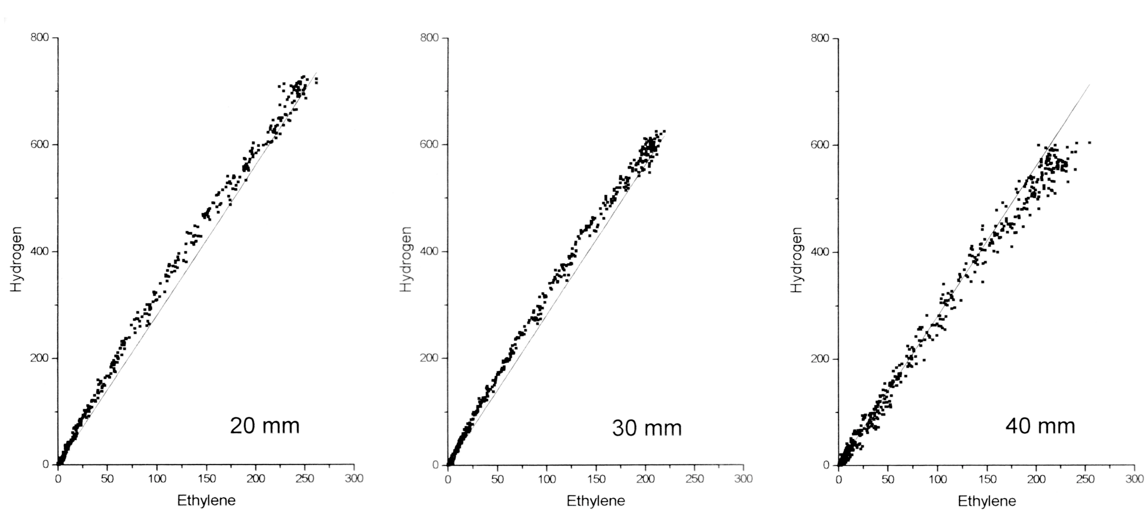

Figure 2 : Simultaneous pulsed Raman measurements of hydrogen and ethylene concentration at discrete axial positions (Pressure Ratio 16)

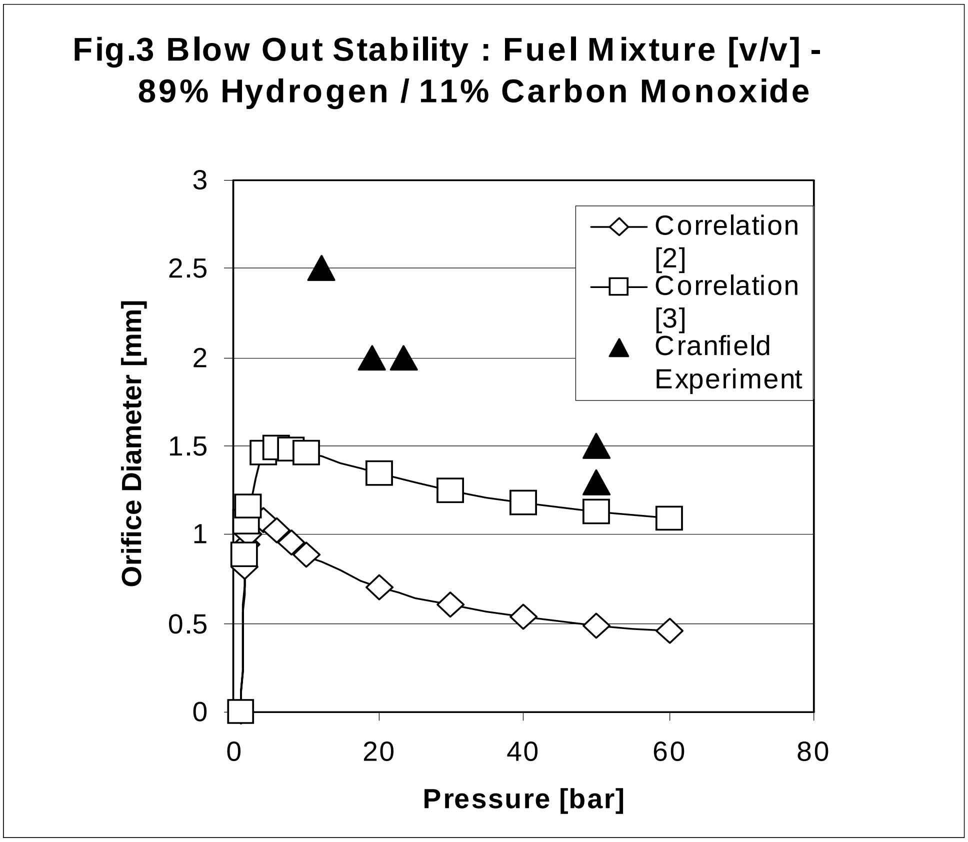

Figure 4 : Schlieren photograph H_2-CO (6.8 %) at 18 bar (reservoir pressure) diameter 1.5 mm

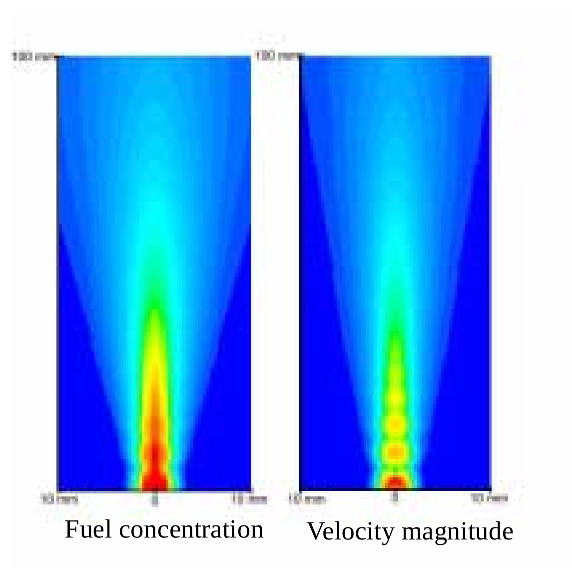

Figure 5 : Filled contours H_2-CO(2.1%) at 22 bar diameter 1.5 mm