Experimental and Numerical Evaluation of Pressurized, Lean Hydrogen-Air Flame Stability with Carbon Dioxide Diluent

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ABSTRACT

The potential to combine steam-methane reforming for large-scale hydrogen production with CCS provides two unique vectors (H_2 and CO_2) for utilization in decarbonized gas turbine power generation. Therefore, a study has been conducted to evaluate the use of CO_2 as an additive in lean premixed (LPM) H_2-air swirl flames. Chemical kinetics modelling indicates that the use of CO_2 in the premixed reactants reduces H_2-air laminar flame speed (S_L) and adiabatic flame temperature (AFT) within the well-characterized range of preheated LPM CH_4-air flames, albeit in markedly different proportions; nearly 70% vol CO_2 in the fuel is required for a reduction in S_L to equivalent CH_4-air values, while approximately 30% vol CO_2 in the fuel is required for an equivalent reduction in AFT, impacted by the increased heat capacity of CO_2. A generic gas turbine swirl burner is therefore utilized to experimentally investigate the influence of CO_2 dilution on pressurized (25 kW/bar), preheated (573 K), LPM H_2-air flame stability using high-speed OH* chemiluminescence and dynamic pressure sensing. The influences of extinction strain rate and Lewis number are suggested to characterize, both experimentally and numerically, the observed lean flame behavior, in particular as extinction strain rate has been shown to be non-monotonic with pressure for highly-reactive and diffuse fuels such as H_2.

INTRODUCTION

The use of hydrogen in lean premixed gas turbine power generation presents a number of interesting challenges for the use of established burner technologies. An experimental and numerical study is therefore conducted in a **fully premixed, preheated (T2 = 573 K ± 5 K), pressurized (25 kW/bar)** generic swirl burner to investigate the use of CO_2 as a premixed fuel additive, given its ability to moderate the combustion process; for example, as shown in **Figure 1**, which plots modelled laminar flame speed, S_L, as a function of fuel CO_2 (%vol) and equivalence ratio (φ) with the equivalent CH_4-air flame speed at $\varphi = 0.6$.

In addition to the increase in reactivity observed in Figure 1, H_2-air flames also exhibit enhanced thermodiffusive effects, making them less resistant to extinction under highly stretched conditions. This effect, however, has been shown experimentally to be non-monotonic with pressure, as shown in **Figure 2**, by Niemann et al. [3,4].

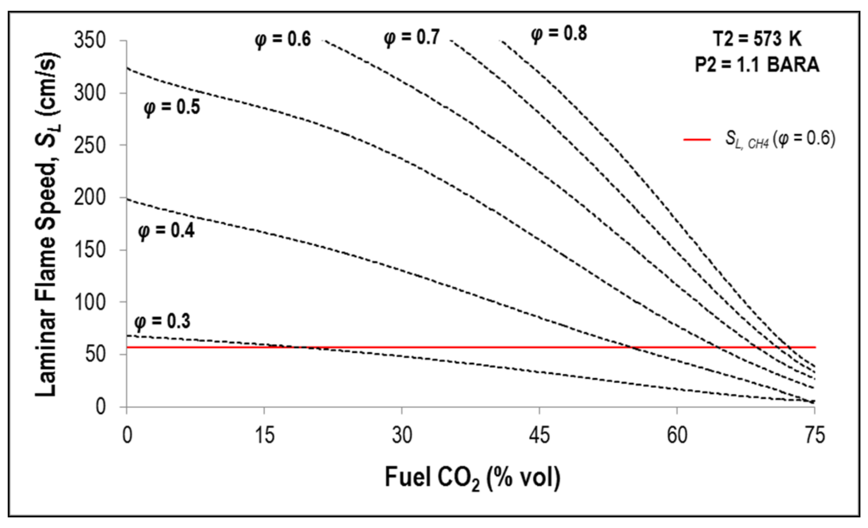

Figure 1: Laminar flame speed (S_L) modeling of CO_2 dilution effects on H_2-air flame and comparison with equivalent CH_4-air flame at $\varphi = 0.6$ (red line), using Li et al. [1] and GRI-Mech 3.0 [2] mechanisms, respectively

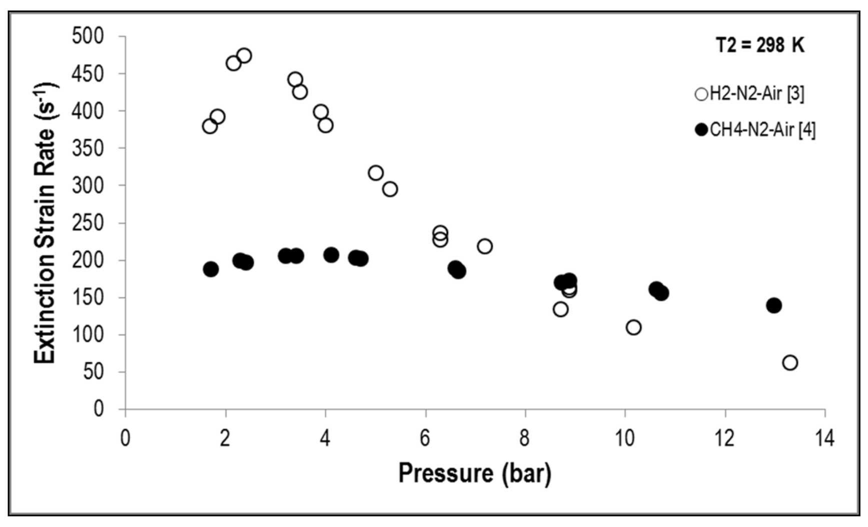

Figure 2: Experimental extinction strain rate measurements for CH_4-N_2-air and H_2-N_2-air counterflow diffusion flames at elevated pressure [3,4]

EXPERIMENTAL METHODS

A comparison of burner operability between CH_4-air and H_2-CO_2-air flames is first conducted at near-ambient burner inlet pressure (P2 = 1.1 bara) with flame stabilization mechanisms and flame instabilities identified using high-speed OH* chemiluminescence (4 kHz, 10 μs gate, 4.65 pix/mm) alongside in-burner dynamic pressure measurement (4 kHz). Then, a single lean equivalence ratio ($\varphi = 0.25$) is selected to investigate the influence of P2 on lean H_2-CO_2-air flame stability and stretch behavior. Refer to **Table 1** for experimental operating conditions.

Table 1: Experimental operating conditions for fully premixed CH_4-air and H_2-CO_2-air flames

Premixed Reactants	$\dot{m}_{air}$ (g/s)	$\dot{m}_{fuel}$ (g/s)	$\dot{m}_{CO2}$ (g/s)	T2 (± 5 K)	P2 (bara)	P_{therm} (kW)	φ	Re ($x10^3$)
CH_4-air	10.8 - 16.4	0.5	0	573	1.1	25	0.53 - 0.80	12 - 18
H_2-CO_2-air	10.0 - 71.5	0.2 - 0.52	0 - 14.37	573	1.1 - 2.75	25 - 62	0.25 - 0.72	27 - 90

All experimental work has been conducted utilizing the 2nd Generation High-Pressure Generic Swirl Burner (HPGSB-2) installed within the High-Pressure Optical Chamber (HPOC), refer to **Figure 3** and **Figure 4**, respectively.

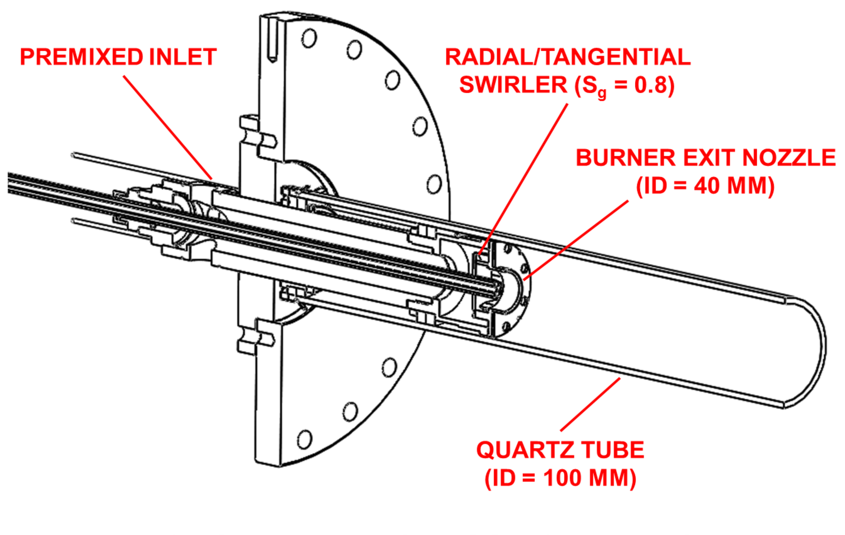

Figure 3: Schematic of HPGSB-2 assembly with critical features identified

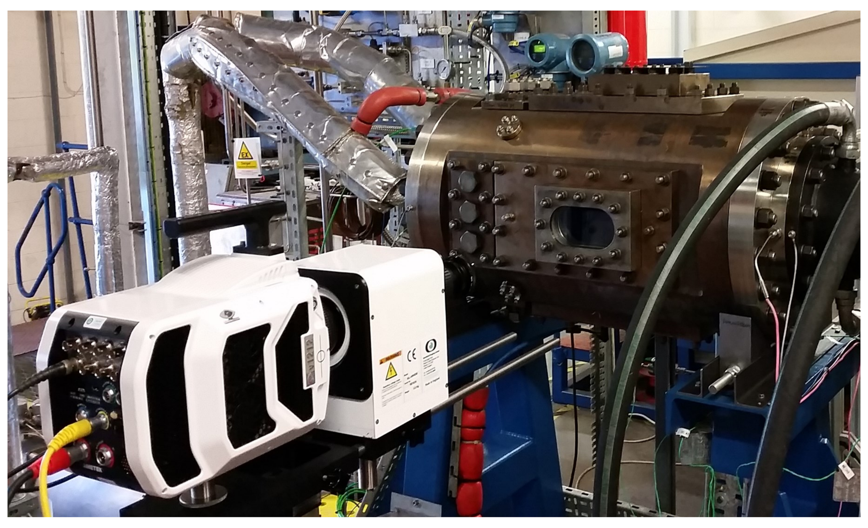

Figure 4: Photograph of HPOC with HPGSB-2 and high-speed OH* chemiluminescence system (Phantom v1212 camera, SIL-3 image intensifier, 78 mm UV lens and 310 nm bandpass filter)

RESULTS

Figure 5: The use of H_2 reduces the lean blowoff (LBO) equivalence ratio and requires stabilization at higher *Re*. Up to 40% vol CO_2 in the premixed reactants at $\varphi > 0.70$ is achieved.

Figure 6: For increasing φ, the achievable CO_2 dilution increases, but the stable operational range reduces. At $\varphi < 0.3$, pure H_2-air flames were stabilized, however burner exhaust temperatures were insufficient (<1100 K), suggesting a future increase in 25 kW/bar scaling.

Figure 7: With increasing pressure, the CO_2 dilution level at LBO is nonmonotonic, which suggests a relationship with the extinction strain rate (see **Figure 2**) due to the high turbulence.

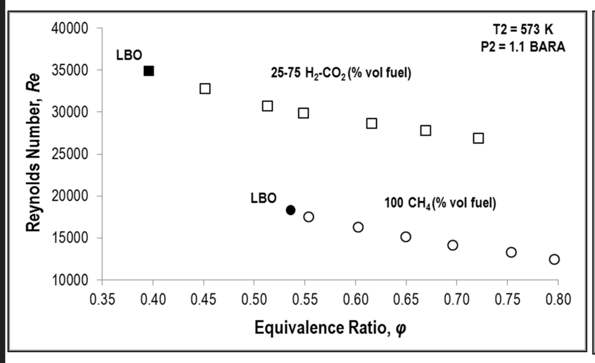

Figure 5: Required Reynolds number for stable operation of atmospheric CH_4 and 25-75 H_2-CO_2 flames

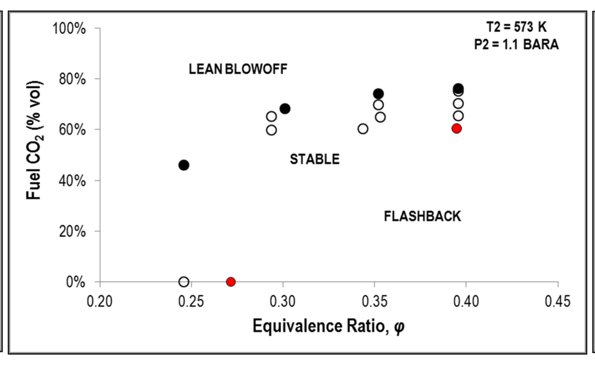

Figure 6: Required fuel CO_2 levels for atmospheric H_2-CO_2-air flame stability with varying φ

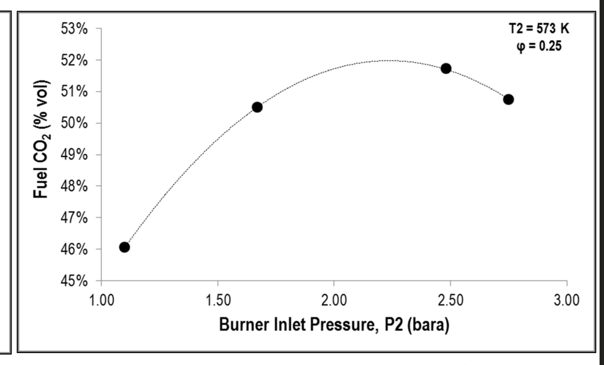

Figure 7: Non-monotonic influence of pressure on achievable fuel CO_2 (%vol) levels near LBO

Figures 8 and 9: Flame stabilization prior to LBO is characterized by flame attachment (8.a and 8.d) and detachment (8.b and 8.c) from the burner exit nozzle, with significantly reduced OH* intensity in the H_2-CO_2-air case. CH_4 heat release (9.a) and dynamic pressure (9.b) fluctuation near LBO have similar peak frequencies, with heat release fluctuation damped in H_2-CO_2 flames.

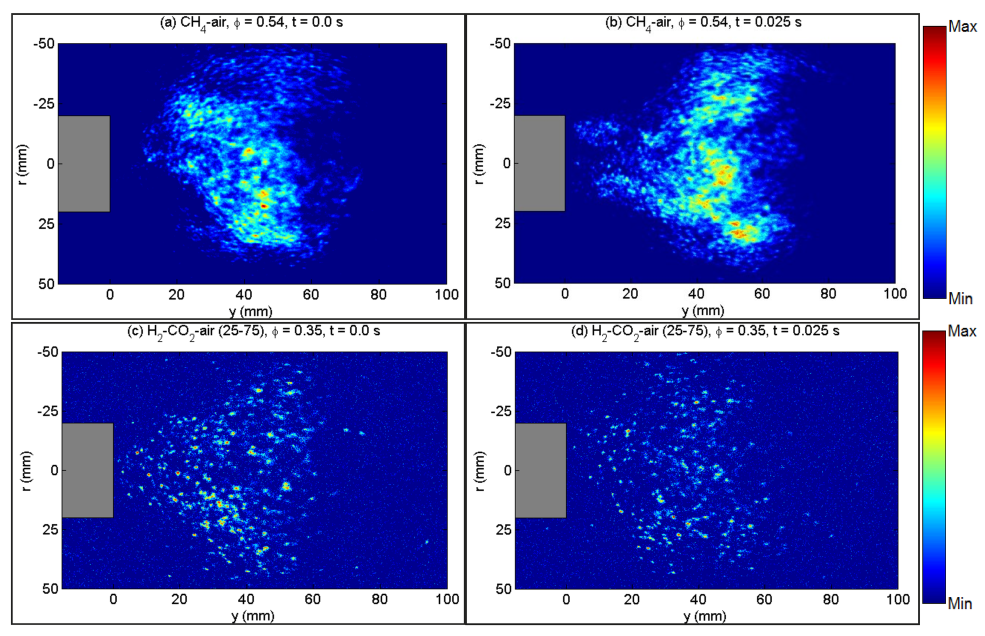

Figure 8: Instantaneous OH* chemiluminescence images near LBO for CH_4-air (a,b) and H_2-CO_2-air (c,d) flames. Note burner exit nozzle in grey, flow from left to right

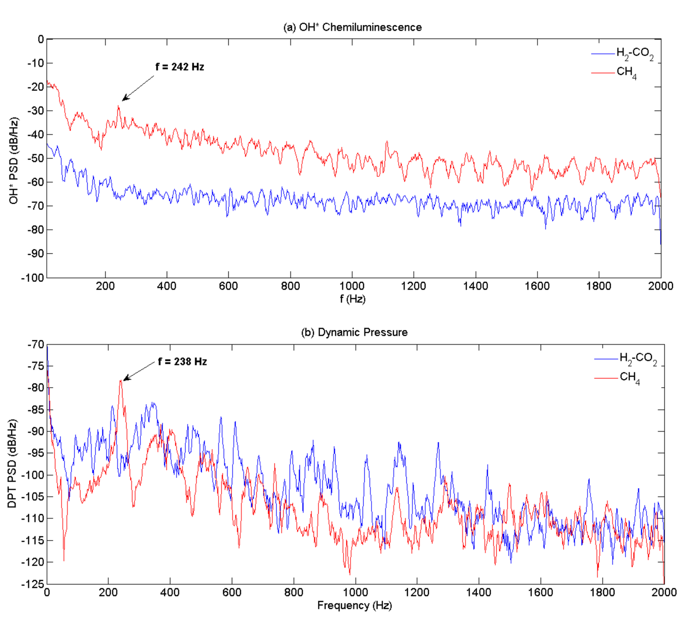

Figure 9: Power spectral density of OH* chemiluminescence fluctuation (a) and dynamic pressure fluctuation (b) at near LBO conditions from Figure 8

CONCLUSIONS AND FUTURE WORK

- Fully premixed, lean H_2-air flames were successfully stabilized in a swirl burner with sufficient levels of CO_2 dilution (up to 75% vol fuel / 40% vol premix) and turbulence ($Re_{H2} \approx 2*Re_{CH4}$). Fully premixed, pure H_2-air flames were successfully stabilized at low equivalence ratios ($\varphi < 0.3$) with sufficiently high burner exit nozzle velocity.
- Flame attachment and detachment from the burner exit nozzle precedes lean blowoff, with heat release fluctuations and pressure fluctuations near LBO dampened by the addition of CO_2 in the premixed reactants.
- Maximum levels of CO_2 dilution in H_2-air flames near LBO exhibit a non-monotonic influence of pressure, suggesting that thermodiffusive effects dominate under these highly stretched conditions, in agreement with the work of Niemann et al. [3,4].
- Future work to include operation with higher CO_2 mass flow at higher φ to achieve representative GT burner exit temperatures, operation at higher pressures to further evaluate stretch effects, an evaluation of NO_x/CO emissions, and the development of a pressurized counterflow burner system for fundamental study of H_2-CO_2-air extinction behavior.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding for this work provided via the UK Engineering and Physical Sciences Research Council (EP/M015300/1) for research in "Advanced Gas Turbine Cycles for High Efficiency and Sustainable Future Conventional Power Generation."

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