Liftoff Heights of N_2-in-H_2 Jet Flames in a Vitiated Co-flow Measured Using Schlieren Imaging

A North, R Dibble, J Y Chen, D Frederick, A Gruber*
University of California – Berkeley
***SINTEF Energy Research, 7465 Trondheim, Norway**
anorth@berkeley.edu

Keywords: Hydrogen, lifted flames, co-flow, schlieren, non-premixed

The development of gas turbine combustors that can reliably, efficiently and safely burn hydrogen in a lean premixed mode is one of the major challenges to be overcome before pre-combustion Carbon Capture and Sequestration technologies can be realized. Ensuring that the flame never propagates into or auto-ignites in the mixing section of the combustor is necessary for achieving reliable premixed operation. Research into the combustion characteristics of lifted jet flames facilitates understanding of the turbulence-chemistry interactions occurring during mixing. The lifted flame entrains air before the mixture ignites, similar to what happens during mixing in natural gas fueled turbine engines. UC Berkeley's Vitiated Co-flow Burner (VCB) is an effective apparatus for studying lifted jet flames under conditions similar to the environment in gas turbine combustors because the temperature and composition of the environment surrounding the jet can be controlled by varying the equivalence ratio of the co-flow.

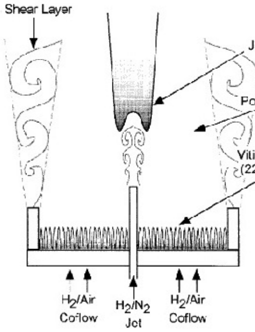

Figure 1: Conceptual drawing of Berkeley's Vitiated Co-flow Burner (VCB)

The goal of this research is to identify and determine key measurable combustion parameters that encompass the primary factors influential in determining whether combustion may occur in the mixing section, while still maintaining flame stability in the combustion section of gas turbine combustors. These combustion parameters can be used in the development, tuning and validation of numerical models that can later be used in the design of gas turbine combustors for hydrogen operation. In this research, the conditions under which the jet flame in the VCB is attached, lifted, unsteady, or blown out has been determined. The liftoff heights for the attached condition have also been measured for several operating conditions. Nitrogen dilution has been added to the hydrogen fuel, increasing the momentum of the jet and thereby promoting liftoff.

Prior work by Cabra et al (2005) examined one lifted N_2-in-H_2 jet flame condition in a vitiated co-flow environment in detail, using laser Raman, Rayleigh, and LIF measurements. Continued work by Gordon et al (2005) expanded this research investigating the effects on liftoff height by varying the co-flow equivalence ratio, jet velocity, and co-flow velocity using direct imaging with a 1 second exposure time. The current work examines a broader range of conditions using schlieren imaging for determining liftoff heights.

Schlieren imaging presents the opportunity for depicting flames with much higher frame rates than direct imaging because the intensity of the light is a tunable parameter with schlieren imaging, and for hydrogen, the amount of light available for direct imaging is weak. At shutter speeds sufficiently high for the capture of instantaneous images with direct imaging, flames with weak chemiluminescence are not visible. Alternatively with schlieren imaging, both the liftoff height and the variation of liftoff height in time can be accurately measured, providing statistical information describing flame dynamics which is useful in the development and validation of numerical models.

Diagrams showing the stability regimes have been generated for three jet velocities where the conditions under which the jet flame in the VCB is attached, lifted, unstable, or blown out are summarized. The nitrogen dilution mole fraction, y_{N2}, and the co-flow equivalence ratio, φ, were parameters varied in these diagrams. Once the stability regimes diagrams were developed, the liftoff heights for the range of conditions where a lifted flame exists were measured using an average of liftoff heights taken from five images for each set of conditions.

The inner diameter of the jet tube is d = 2.4 mm and the outer diameter of the co-flow is D =10 cm. The co-flow is generated with a perforated plate consisting of 1.6 mm diameter holes drilled into a brass plate arranged in a hexagonal pattern with 4.8 mm separation between perforations. The overall blockage is 0.89. For this study, the exit of the jet tube extends 25 mm above the base of the co-flow, but this parameter can be varied if it is of interest in future studies.

Nitrogen dilution mole fraction and co-flow equivalence ratio were variable for this study. For all experiments, the jet fuel temperature was approximately T_j = 293 K and the co-flow bulk velocity before combustion was held constant at u_{cfb} = 0.65 m/s. The stability regimes diagram for a 500 m/s jet velocity is shown on the left side of Figure 2:

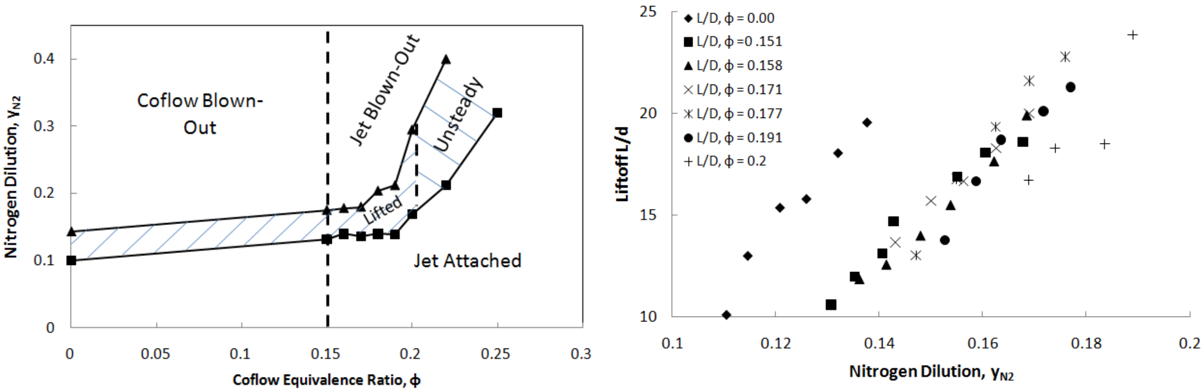

Figure 2: Stability regimes diagram for a jet velocity of 500 m/s (left); liftoff heights as a function of nitrogen dilution and co-flow equivalence ratio (right).

Similar diagrams were produced for V_{jet} = 300 m/s and 400 m/s. Once the stability regimes diagrams were developed, the normalized liftoff heights, L/d, for the range of conditions where a lifted flame exists were measured using an average of L/d values taken from five images for each set of conditions. The liftoff height measurements for a jet velocity of 500 m/s are given on the right side of Figure 2.