Planar Laser-Induced Fluorescence measurements on a premixed bluff-body stabilized flame

1. OBJECTIVE

The objectives of this experiment are:

- To introduce Planar Laser-Induced Fluorescence (PLIF) technique
- To acquire data on a premixed, bluff-body stabilised, turbulent flame
- To study the flame structures from the PLIF images

2. INTRODUCTION

To reduce the formation of pollutants, namely soot and NO_X, aircraft propulsion systems have begun to switch to lean premixed combustion [1]. Nevertheless, designing and developing engines that stabilize lean premixed flames in a manner that avoids detrimental phenomena such as combustion instabilities, flashback, and lean blow off (LBO) is a considerable challenge.

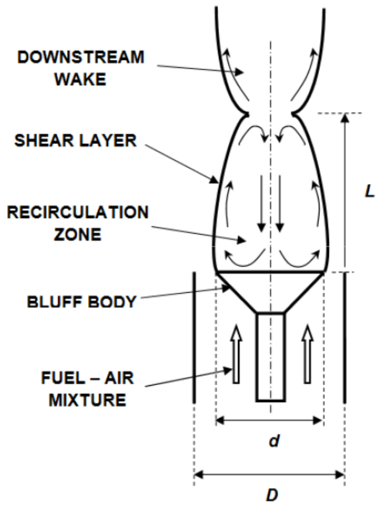


Figure 1: Schematic of the bluff body showing the recirculation zones [4].

A common way of stabilising lean premixed flames within the high Reynolds number conditions of practical devices is by generating a recirculation zone. Recirculation zones facilitate combustion within high speed flows by 1) creating a region of relatively low velocity, and 2) providing a continuous source of burnt products to back-support the flames (see Ref. [4] and those therein). Formation of recirculation zones within a stream of premixed reactants is often achieved by introducing a bluff body into the flow [1–3]. The effect of turbulence on the reaction zone and flame structure is significant for model validation. Previous experimental investigations of methane and ethylene flames stabilised by a bluff body showed that the flame changes shape from cylindrical at the stable condition to M shape close to blow off [4]. In those studies, near blow off the flame was found to close from the top and moved closer to the bluff body.

3. METHOD

3.1 Experimental apparatus

In this experiment, a bluff body burner, similar to that used in Ref. [4], is employed to study the behaviour of turbulent premixed flames, at stable condition and close to blow off. A schematic of this burner is presented in Fig. 2. The burner consists of a 300-mm long outer tube with an internal diameter of 35 mm. This tube is mounted to a small plenum and a small section of honeycomb is fitted within its center to facilitate flow straightening. To ensure smooth flow separation at the exit of the tube, its edge is tapered and filed to a sharp point. A conical shaped bluff body is mounted at the center of the outer tube via a small rod (outer diameter of~6.5 mm) that is positioned at the center of the tube. The bluff body possessed a 45° half angle and its widest diameter, which aligned with the exit of the outer tube, measured 25 mm.

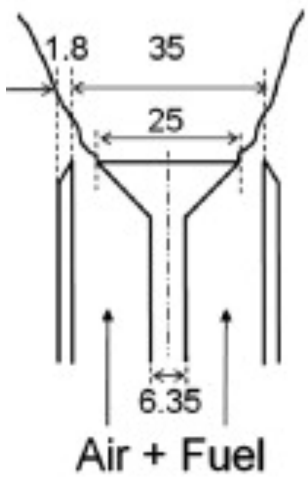


Figure 2: Schematic of the burner.

3.2. OH-PLIF system

Planar laser-induced fluorescence (PLIF) imaging of OH is performed as a means to visualize the topological structure of the flames considered here. In order to conduct these measurements, a SIRAH Credo high-speed dye laser (model 2400) is pumped by a solid state Nd:YAG laser (model JDSU Q201-HD), which output radiation at 532 nm with a power of 14 W at 5 kHz. The tuneable dye laser produces a beam at 566 nm, which is then frequency doubled using a BBO crystal to produce a beam with an average power of 300 mWat 5 kHz (60μJ/pulse). The frequency-doubled output was tuned near 283 nm to excite the Q1(6) line in the $A^1\Sigma-X^2\Pi$ (v' = 1,v" =0) band of OH. Sheet forming optics are used to produce a sheet with dimensions 20 (tall)×0.12 (thick) mm^2. A schematic of this optical setup is provided in Fig. 3. Fluorescence resulting from the incident laser light is collected by a Photron SA1.1 high-speed CMOS camera with a sensor possessing resolution of 1024×1024 $pixel^2$ and a two stage intensifier (LaVision). This camera was fitted with a 100-

mm f/2.8 UV lens (Cerco 2178) and a narrow bandpass filter of 310 ± 10 nm (Edmund, 34980). The camera is mounted perpendicular to the laser sheet and is operated with a gate of 300 ns. The region of interest in the image was 20 (tall) × 22 (wide) mm^2, giving a pixel projected size of ~37 μm.

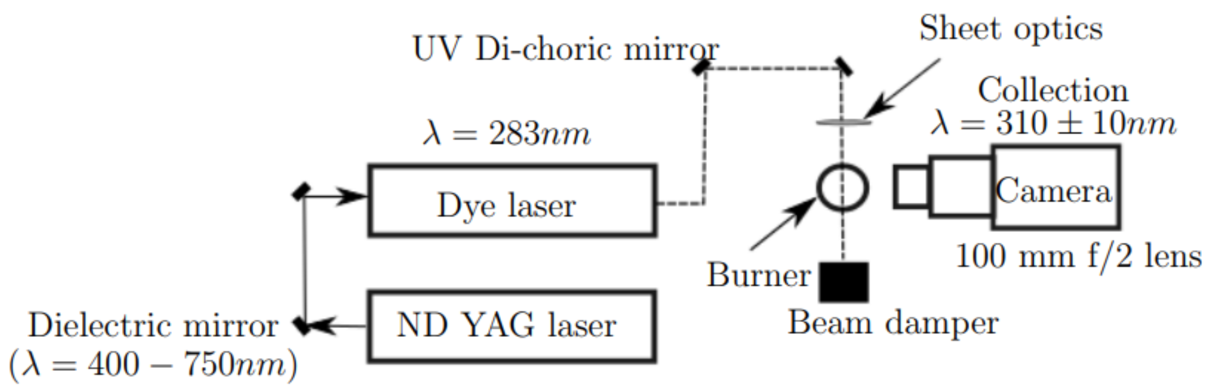


Figure 3: Schematic of the OH-PLIF system.

3.2 Experimental Procedure

SAFETY WARNINGS

- **Safety glasses to be worn by all in the experimental area.**
- **Laser googles for 283 nm with the appropriate filter density to be to be worn during alignment and full energy experiments.**
- **Don't remove the laser googles inside the lab at any time.**
- **Never change the apparatus without consulting the demonstrator.**
- **Never leave an open flame unattended. Be careful with paper sheets, sleeves and long hair!**

Part 1. Laser operation and system introduction

The system consists of a SIRAH Credo high-speed dye laser (model 2400) and solid state Nd: YAG laser (model JDSU Q201-HD). The Nd: YAG laser is used to pump the dye laser at a frequency of 5 kHz. The entire system is synchronised on the internal clock of the Nd: YAG laser. To achieve this, an output square electric pulse is sent from the laser to the camera and the controller of the IRO. The Intensify Relay Optics (IRO) is used to intensify the signal before it is acquired by the camera, to increase the signal to noise ratio. A power meter is used to measure laser power before starting the experiment. The laser beam is monitored using a PMT and an oscilloscope. The fine adjustment of the wavelength and power of the laser is obtained with the SIRAH software. The camera is controlled with the Photron software.

Part 2. OH-PLIF high speed images

Air and fuel flow rate are controlled with Bronkhorst and Alicat mass flow controllers, respectively. A mixture of methane and air at an equivalence ratio of φ = 0.75 (Case A1 in Fig. 4) is delivered to the burner, and the flame is ignited with the help of a blow torch. The camera is initially run in live mode, to check the signal intensity. In case the OH signal is not strong enough; the laser wavelength can be adjusted to try maximizing the signal to noise ratio. When everything is ready, we record 5000 images, extinguish the flame and then start transferring the images to the computer.
The same procedure will be repeated for a condition when the flame is close to lean blow-off (LBO) (case A4 in Fig. 4)

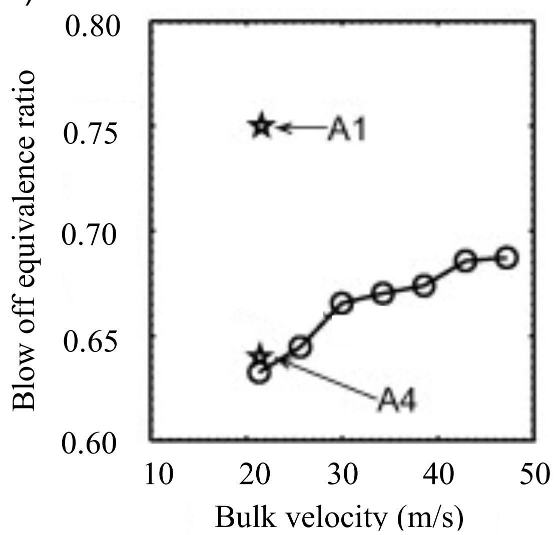
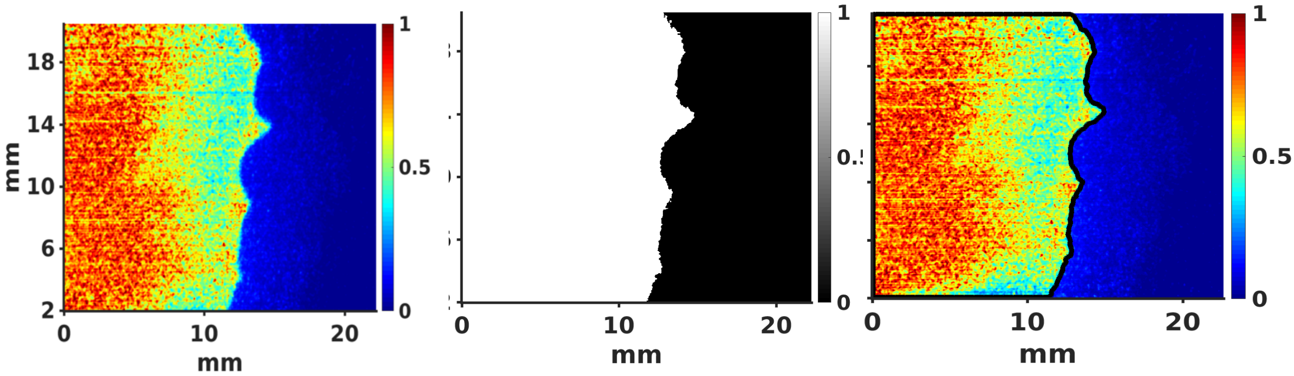


Figure 4: Blow off curve with methane flame [4].

3.3 Data analysis

A detailed routine should be employed to analyze the OH-LIF images. First, the average signal originating from the camera's dark current, laser background and flame chemiluminescence emissions need to be subtracted from each image. Following this subtraction, the images are median filtered to increase the signal to noise ratio.
A sample OH-LIF image that was subjected to the aforementioned correction process is displayed in Fig. 5a. These images can be further processed to obtain quantitative information on the flame, such as flame surface density (FSD) and 2D curvature. To calculate these quantities, you have to binarize the images to obtain the edge of the flame. The binarized image (using a threshold of 20% of the maximum intensity) and the corresponding edge image are shown in Fig. 5b and 5c. A detailed description of the methodology that can be employed to evaluate FSD and 2D curvature can be retrieved from these Refs. [4].



(a) (b) (c)

Figure 5: Images showing the instantaneous OH image after correction (a), binarized (b) and edge image (c).

4. Results

(a) Average the instantaneous images, using the software ImageJ. Visualise the flame structure and compare with instantaneous images. Use the high signal intensity regions to evaluate the reaction zone of the flame.

(b) Compare the flame structure at two conditions: stable flame, and close to lean blow-off.

(c) Which further information do you think can be extracted from these images? How can these experiments help in modelling the flame?

References:

1. Dunn-Rankin, D., Therkelsen, P., Lean Combustion: Technology and Control, Elsevier Science, 2016
2. Correa, S. M., "A review of nox formation under gas-turbine combustion conditions", Combustion Science and Technology, 87:329–362 (1993).
3. Echekki, T., Mastorakos, E., Turbulent Combustion Modeling: Advances, New Trends and Perspectives, Fluid Mechanics and Its Applications, Springer Netherlands, 2010.
4. Kariuki, J., Dawson, J.R., Mastorakos, E., "Measurements in turbulent premixed bluff body flames close to blow-off", Combustion and Flame 159:2589–2607 (2012).