Interaction of an Isolated Vortex Ring with a Non-Premixed Flame

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Abstract

An experimental investigation analyzes some fundamental features of a diffusion flame interacting with a vortex ring. A steady non-premixed counterflow flame of air and hydrogen diluted with nitrogen is first established. A vortex ring is generated from a tube installed in the lower combustor nozzle and impinges on the flame. In the experiment described herein, the vizualisation of the cold vortex structure is achieved by planar laser induced fluorescence on acetone. The difficulty to generate small vortices and high-strength vortices is emphazised. Then, the visualization of the flame front is achieved by simultaneous OH planar laser induced fluorescence (PLIF) with planar Rayleigh scattering or simultaneous OH planar laser induced fluorescence (PLIF) with PIV. A detailed description of the interaction is given, showing a global enhancement of combustion due to the interaction with the vortex. Extinction processes occurring later are also described. Vorticity fields are extracted from the PIV measurements and flame-induced vorticity is studied carefully. Finally, all the measurements are gathered in a spectral diagram of flame/vortex interactions.

Introduction

The flame/vortex interaction is a fundamental mechanism of turbulent combustion. In many circumstances, vortices also drive various types of instabilities. Most experimental investigations have been concerned with premixed flames, some including the study of flame propagation in a vortex ring for both premixed and non-premixed configurations or the interaction of a branch of a V-shaped premixed flame with a Kàrmàn vortex street [1–3]. Recent experiments have incorporated the generation of an isolated vortex. Rolon and coworkers proposed a counterflow burner in which a diffusion flame is stabilized and a toroidal vortex is directed into the reactive sheet [4–11]. This configuration was recently extended to the premixed case [12]. Jarosinsky et al. designed an experiment in which a premixed flame propagates upward and a vortex ring travels downward to interact with the flame [13]. This configuration has been extensively studied by Driscoll and coworkers [14–16]. In another configuration designed by Samaniego, a vortex pair interacts with a V-shaped flame. [17].

Apparatus

The experiments in the present study rely on the Rolon burner configuration shown in Fig. 1. Each injection nozzle is 25 mm in diameter and is surrounded by an annular nozzle with an outer diameter of 49 mm. The reactants are injected through the central nozzle, and the outer sheet of nitrogen insulates the reactive stream from external disturbances. The lower nozzle is fed with air, while the upper nozzle delivers a mixture of hydrogen (or propane) and nitrogen at ambient temperature and pressure. On the axis of the lower nozzle, a cylindrical tube (internal diameter d=10, 5, 2, 0.6, 0.5 mm) connected to a cylindrical plenum chamber (diameter D=25, 8.1, 4.8, 3.2, 1.2 mm) generates a single laminar vortex ring by the displacement of a piston in this chamber. The actuator, that moves the piston, is excited by a voltage ramp with a rise time τ_r that can take any value greater than 0.1 ms. An extensive description of this burner is given in Ref. [4].

The high reproducibility of the interaction (time resolution of about 10 μs) is demonstrated in Ref. [10] which also includes a detailed description of the measurement experimental setup. A classical problem encountered in PLIF is to characterize flame extinction. In a recent paper, Renard et al.

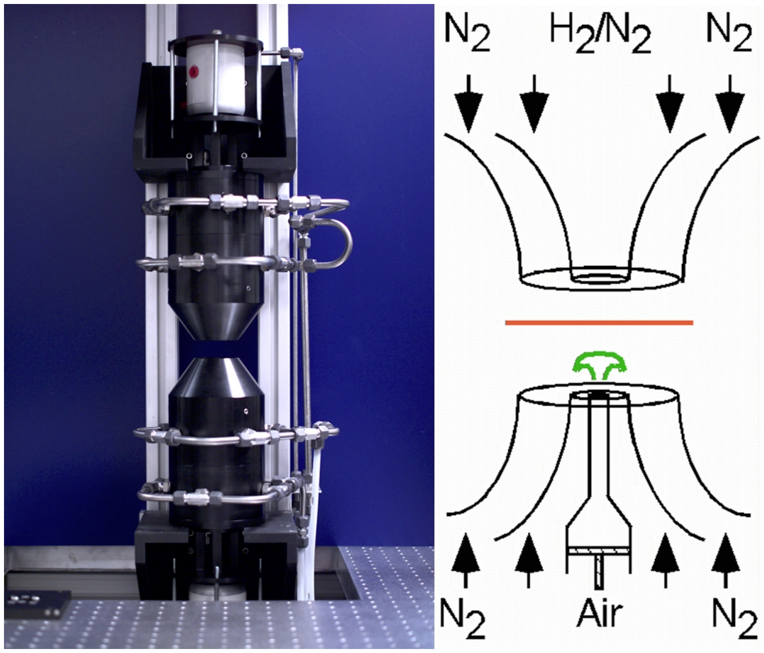


Figure 1: Experimental Setup.

showed that OH may be a good tracer for this configuration provided some precautions are observed [11]. The conclusion they made is that a fluorescence signal lower than 5 % of the maximal signal in the unperturbed flame front ensures that the flame is locally extinguished there.

Characteristic aspects of the interaction

PLIF acetone visualizations are used to study the quality of the vortex structure. If the amount of fluid injected is excessive, a starting jet is generated rather than a ring (Fig. 2). This jet may disturb the reconnection processes: while the flame/vortex interaction may appear to be complete once the ring crosses the reactive layer completely, a jet/flame interaction may follow the flame/vortex event. Furthermore, a limit exists beyond which the toroidal vortex cannot absorb additional vorticity, resulting in the formation of other vortex rings behind the first one (Fig. 3). This multiple vortical structure and

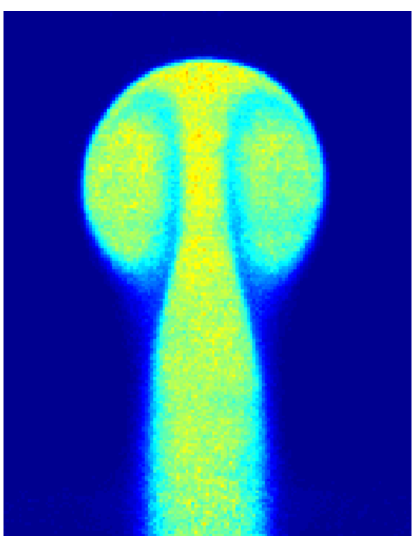


Figure 2: The vortex ring evolves into a starting jet.

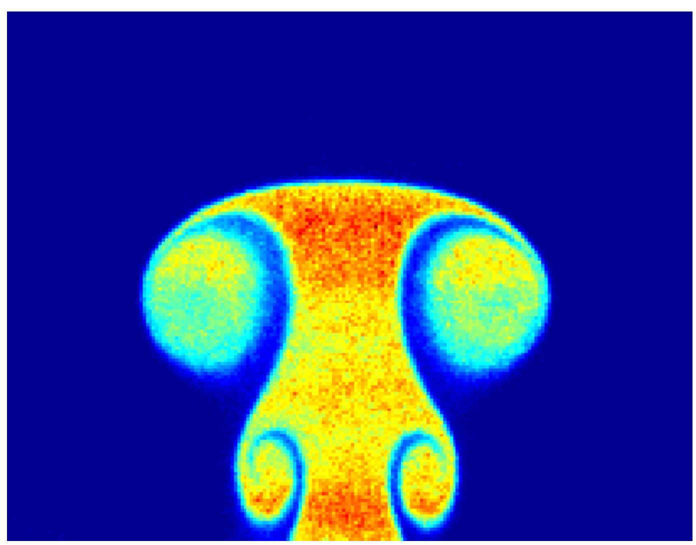


Figure 3: Formation of a secondary vortex.

leapfrogging phenomenon can complicate the structure of the hydrodynamic perturbation.

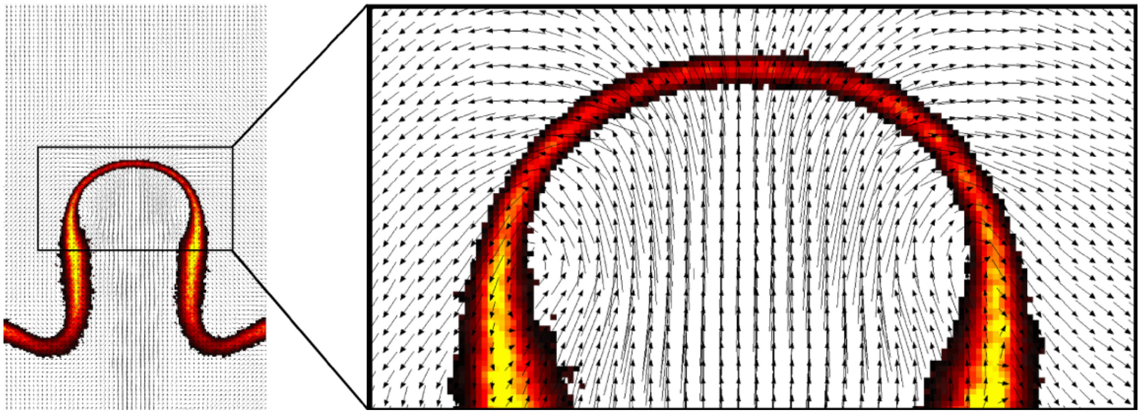
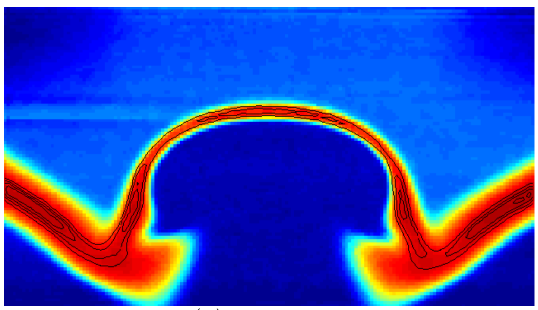
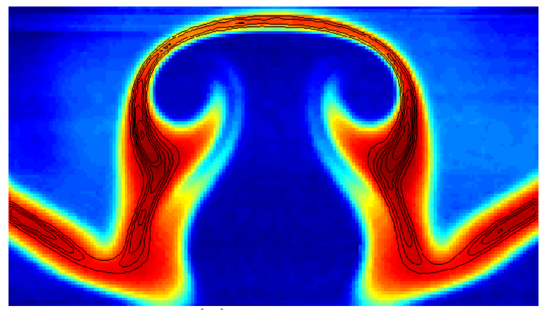


Figure 4: Typical example of simultaneous visualization of velocity field (PIV) and flame front position (OH PLIF).



(a) $t = 22$ ms



(b) $t = 27$ ms

Figure 5: Typical example of simultaneous visualization of temperature field (field of Rayleigh scattering) and flame front position (isolevels of OH PLIF).

Several injectors with different diameters are used to explore a large spectral range of vortices (the ratio of the largest diameter to the smallest one is 20). Vortex quality is examined for each injector diameter. Previous analysises obtained using the 5-mm nozzle in Ref. [6] are extended to these new diameters. It is observed that, under certain vortex and H_2-flame conditions, extinction in the OH layer can occur in an annular pattern as predicted in Ref. [9]. Thanks to PLIF, PIV, and Rayleigh scattering measurements, several kinds of flame/vortex interactions are characterized (Figs 4 and 5). The influence of the flame front on vorticity generation is emphasized. Comparisons between temperature and OH field dynamics are also provided.

Conclusions

Interactions of a non-premixed flame and a vortex ring are observed experimentally. Results are obtained for different vortex diameters. The influence of the vortex strength and the global mixture ratio on combustion dynamics is emphasized and confirms the results previously obtained using the same configuration [10,11]. The large volume of data is now being analyzed to construct a spectral diagram of flame/vortex interactions in an approach similar to Ref. [6]. This may be a basis for a turbulent non-premixed combustion diagram.

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