EXPERIMENTAL STUDY OF LOW REYNOLDS NUMBER REACTING FLOWS: GAS-GAS LAMINAR FLAT PLATE DIFFUSION FLAME IN MICROGRAVITY

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EXTENDED ABSTRACT

Introduction

The study of highly exothermic reacting low Reynolds number flows has received nearly no attention in the past. The main reason being that highly exothermic reactions such as those common in combustion processes, result in buoyantly induced flow that generally characterised by Reynolds number greater than 1000. Motivated by fire safety concerns and the advent of long term micro-gravity facilities, a renewed interest in fire propagation at very low Reynolds number has arisen (Re<1000 is typical of spacecraft HVAC systems). Previous works show a need for fundamental combustion studies in micro-gravity to proper establish fire safety protocols in environments that become every day more challenging.

As a common fire scenario is that of a burning condensed fuel, we successfully started to study, some years ago, the global behaviour of gas-gas and gas-solid laminar flat plate diffusion flame in micro-gravity. In normal gravity, temperature gradients result in natural convection flows that are laminar when the scale is small and transition to turbulence as the size of the fuel increases. In spacecraft, where buoyancy is negligible, the flow is limited to that induced by the ventilation system. Characteristic HVAC velocities are of the order of 0.1 m/s, therefore the flow is expected to be laminar and parallel to the surface. The complex mixed flow (often turbulent) fire scenario observed in normal gravity is reduced to the classical combustion problem first described by Emmons [1]. It is the problem of a chemically reacting boundary layer flow over a flat plate, that of an incompressible boundary layer flow with blowing.

Numerous studies have followed the pioneering work of Emmons and particular attention has been given to the perturbations of the flow introduced by the flame. The importance of this perturbations is great since they affect the heat feedback from the flame to the fuel surface and thus the geometry, length and stability of the flame. All this parameters are of great interest to fire safety for space applications. Distortions in the flow field have been attributed to thermal expansion, buoyancy, leading edge geometry and flow properties but no conclusive evidence of the origin or the consequences of this distortions on the flame structure were resolved. The main reason was the natural constraint of buoyancy which forced an increase in flow velocity that masked all other effects.

In an initial stage, the condensed fuel was simulated by injection of a combustible gas. Although this precluded the self-similar solution it eliminated the heat feedback – pyrolysis coupling and thus allowed for shorter experimentation time and independent control of the fuel. In this stage the study of the effect of fuel injection and of the flame on the flow structure was emphasized. After showing the existence of different stability regimes and of extinction limits for both cases [1,2,3,4], we now like to better describe the structure of the reacting flow by still using optical diagnostics [2-5].

Experimental apparatus

For the use of ground based facilities, a burner is placed in the center of a combustion chamber of 320mm in diameter and 400mm in total length. The hardware, fully described elsewhere [3,4], was designed to be used at drop towers and parabolic flights, therefore is fully automated and leak proof. The burner is a 200mm x 95mm stainless steel plate with an aerodynamic leading edge to prevent separation of the boundary layer. For gas-gas experiments, a 60mm x 60mm x 5mm thick sintered bronze plate is placed, flush with the burner surface, 40mm behind the leading edge and centered in the burner plate. The distance from the leading edge of the burner to the leading edge of the porous plate was chosen to prevent separation according to [6]. Characterization of the flow without injection showed a two-dimensional boundary layer that corresponded well with classical theory predictions [7]. The fuel (pure ethane) is introduced into the porous burner through a controlled mass flow meter with a characteristic velocity V_F. The oxidizer characteristic velocity, U_∞ is also obtained through a mass flow meter, but corresponds well with hot wire anemometer measurements. A spark plug, placed at the trailing edge of the porous plate, serves as igniter. A thermocouple tree is attached to one side of the burner 10mm behind the trailing edge of the porous plate. Flow visualization are performed using a light sheet, originating from an argon laser, and an intensified CCD cameras. Seeding of the fuel is accomplished by means of incense smoke and of the oxidizer using zirconium oxide particles. Two other standard color CCD cameras provide side and top view of the visible flame. The drop tower at ZARM is equipped with a PLIF system to visualize OH radicals, i.e. the reaction zone, that was used to qualitatively validate the determination of flame length and stand-off distance by CCD cameras (Figure 1). The velocity field was characterized through PIV measurements. Moreover, a fast intensified CCD video camera, 50Hz, 256x256 pixels, with an interferencial filter centred at 532nm, is used to capture the CH emission and a high definition CCD video camera (1300x1000 pixels) for the PIV. During PIV measurements air is seeded with zirconium oxide 5µm particles lighted with a 26mJ mini-YAG. The pictures have been taken with a Δt = 4ms between two pictures for PIV during experiment carried out at the ZARM drop tower in Bremen with a very stable gravity level of 10^{-5}g, but after 3s of drop. At least 2s are needed to completely annihilate the influence of the initial buoyancy forces which introduce most of the disturbances.

Gas Injection Results

The objective of these experiments is to demonstrate the role of thermal expansion. Ethane was injected through the burner. Experiments were conducted for different forced flow velocities (U_∞ <0.15m), fuel injection velocities (V_F <10mm/s), and oxygen mass fraction (20% < Y_{O2} <55%). Dilution was done by means of nitrogen. Ignition was accomplished in normal and in micro-gravity conditions with similar results in both cases.

Flow visualization has shown that a three dimensional flow pattern is introduced by the injected flow, resulting in separation of the oxidizer flow and mixing zone detached from the porous plate. The mixing zone approaches the plate when increasing the Reynolds number and when decreasing the injection velocity. The flow characteristics correspond to a transitional regime but can be adequately scaled by an asymptotic, convection controlled, solution. Stable flames observed through this experiments, Figure 2, can be categorized in three regimes. Still images of representative flames corresponding to each region, are also presented in the figure. The different zones are delimited by the value of the ratio $C_Q = U_\infty/V_F$ and of V_F . For C_Q < 0.15, the flow field at the leading edge of the burner has a significant effect on the mixing zone, the flame is attached at both leading and trailing edges. For C_Q > 0.15 and V_F < 4mm/s , the flame is now detached from the trailing edge and the flow at the plane of symmetry is two dimensional and not affected by the side boundaries of the burner. The curvature of the leading edge is more pronounced than the curvature of flames in region

1. Flames in this region are blue close to the leading edge progressing towards yellow further downstream. However beyond the yellow zone the luminous intensity decreases as "x" increases and the flames significantly exceed the burner dimensions. Now for $C_Q > 0.15$ and $V_F > 4$mm/s, lateral entrainment results in a lift of the oxidizer boundary and therefore the physical boundaries of the burner have an effect on the structure of the mixing zone. This third region is characterized by a small blue and curve zone close to the leading edge followed by a linear yellow zone. The flame leading edge is positioned very close to the porous plate edge showing the parabolic nature of this region. At the trailing edge the flame is again fully detached from the burner and extinction can be clearly seen. As for region 2 the flames significantly exceed the burner dimensions.
For low flow velocities (both V_F and U_∞) thermal expansion plays a dominant role on the flame geometry and flow field. However a minimum fuel injection velocity is necessary for the flame to be stable. As both fuel and oxidizer velocities increase the importance of thermal expansion is reduced to the leading edge. Downstream of the leading edge convection transports fuel and oxidizer towards the mixing zone, within which diffusion of species dominates. Fuel injection forces separation of the free stream close to the leading edge. The present experimental observations raise many unanswered questions related to how fuel and oxidizer are transported towards the reaction zones, that are general to all low momentum non-premixed flames.
. Figure 3 corresponds to the seeding flow lighted by the laser, Figure 4 to the velocity field given by PIV, Figure 6 to the visible flame and Figure 7 to the CH emission from the reacting zone.
Figure 5 and 6 given by PIV confirm previous observations through direct flame visualisation [1,2] and the existence of a “convection” flame regime, for the range of fuel and air velocities considered. The gas thermal expansion in the flame zone distorts the stream lines, no particles can cross the flame boundary. The leading edge remains very close to the surface and stationary at the fuel edge, in contrast the trailing edge is completely detached from the surface. The reaction zones, corresponding respectively to the recording of the visible flame emission (Figure 5) and CH emission (Figure 6), are very similar but parallel, the CH zone being, as expected, slightly below the visible flame zone. In these conditions, the flame attains a stationary position and is nearly linear. Diffusion can be neglected and fuel and oxidiser are mostly transport towards the flame by forced convection.
The complete analysis of the different video and PIV recordings leads to a detailed description of the low velocity reacting flow, especially on the influence of the flame on the flow field, on the establishment of the flame and on the structure of the reaction.

Conclusion

The structure and the stability of a low Reynolds number laminar diffusion flame established over a flat plate was studied in micro-gravity. Different visualisation and optical diagnostics were successfully used to characterise the flow field and to properly located the flame. Three different domains have to be considered. Two stable regimes for blue and yellow flames and a transition regime between the two and the non-propagating or extinction zone. The development of a code, a DNS approach is currently under progress.

References

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Figures

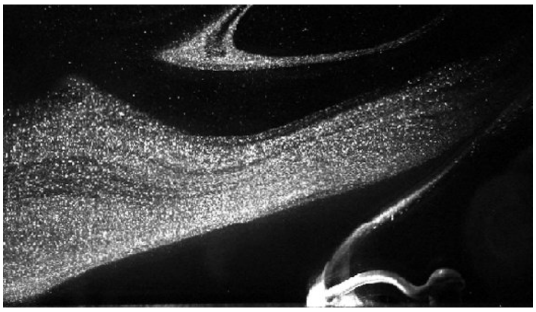


Figure 3

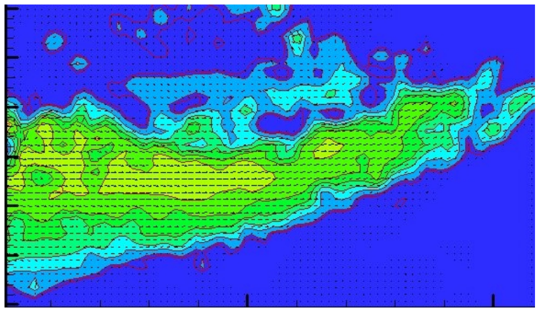


Figure 4

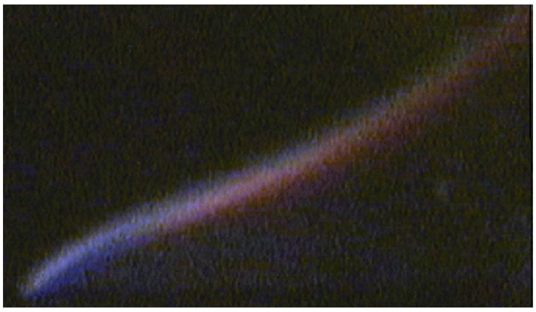


Figure 5

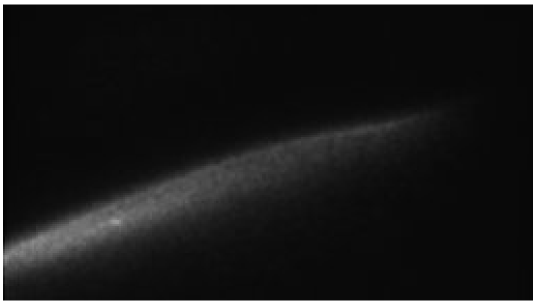
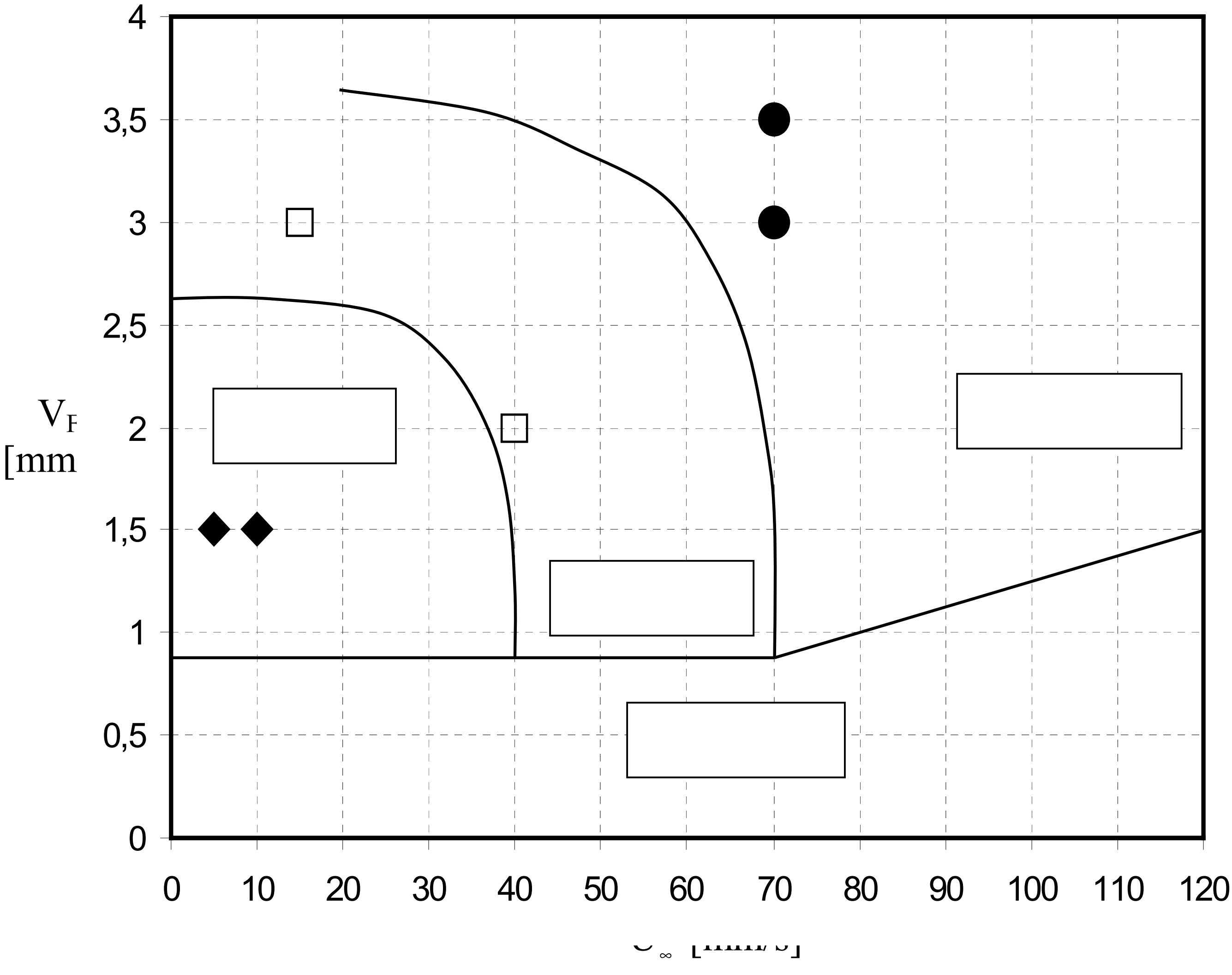


Figure 6

Figure 1 : Comparison between OH (PLIF) and visible flame emission

Figure 2a : Determination of the domain of stability of the flamme



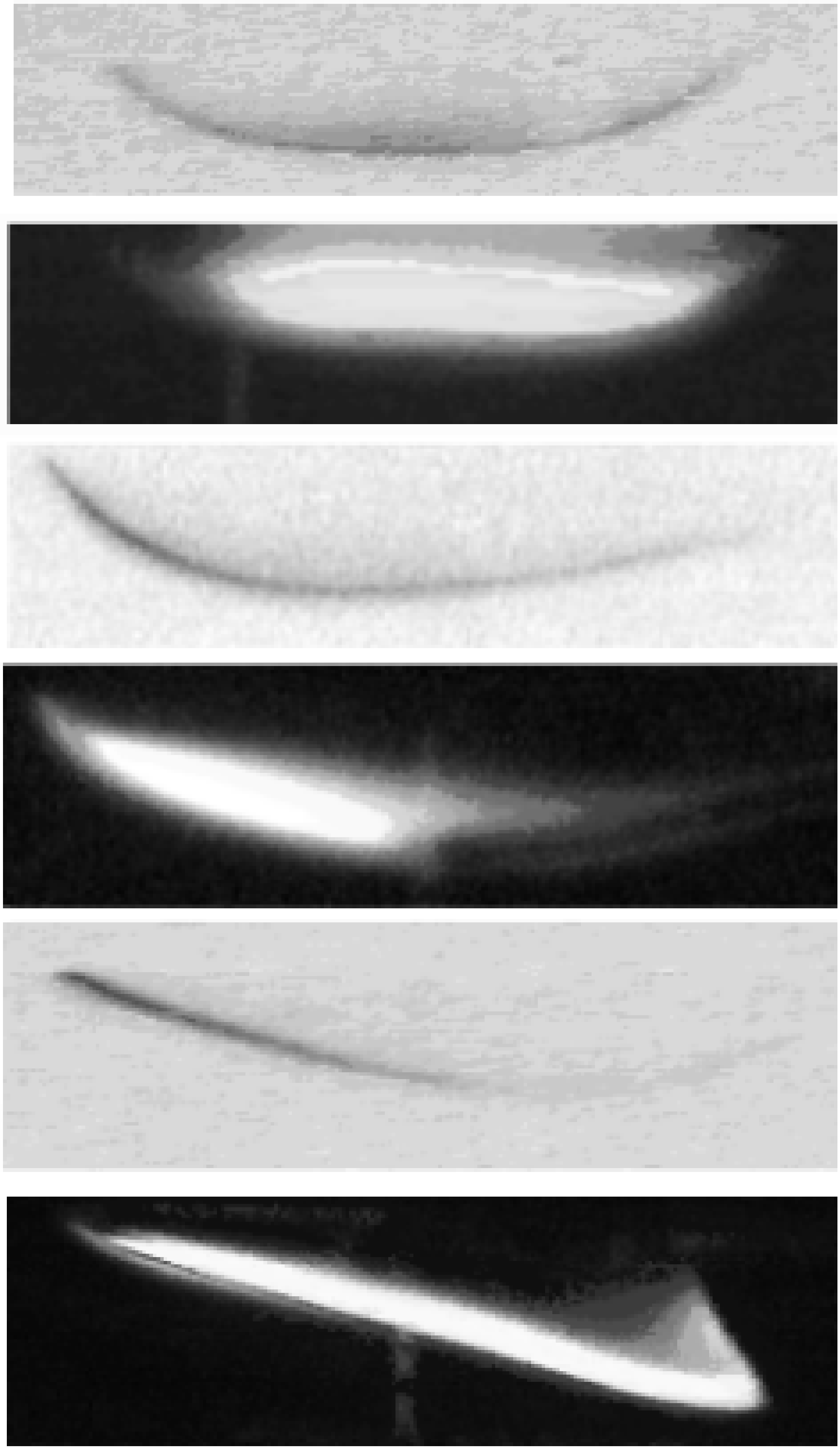


Figure 2b : Photographs of the flame (a) to (e) of the stability diagram