Miniature Fuel-Film Combustor: Flame Confinement and Stability

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1 Introduction to a new design

The concept on which this abstract is based is fastened to the potential for power mobility that fuel-film combustors have already demonstrated. Several promising configurations of fuel-film combustor have been developed [2] [3] since the concept of the fuel film was introduced [1] as an alternative to spray combustion systems at small scales. In particular, previous work has shown the possibility of creating combustors with diameter of one centimetre with the capability to burn liquid fuel from the inside wall of the chamber. Despite the successful demonstrations that have been made, more investigations are needed concerning the stability of the flame, the flame extension out of the combustion chamber and the possible further miniaturization of the overall dimensions of the chamber.

Examining these behaviors is the goal for a newly designed combustion chamber that is the subject of this paper. Specifically, the first step is to develop a strategy that confines the flame completely inside the chamber in order to realistically expect it to perform effectively with other components as part of a personal power system.

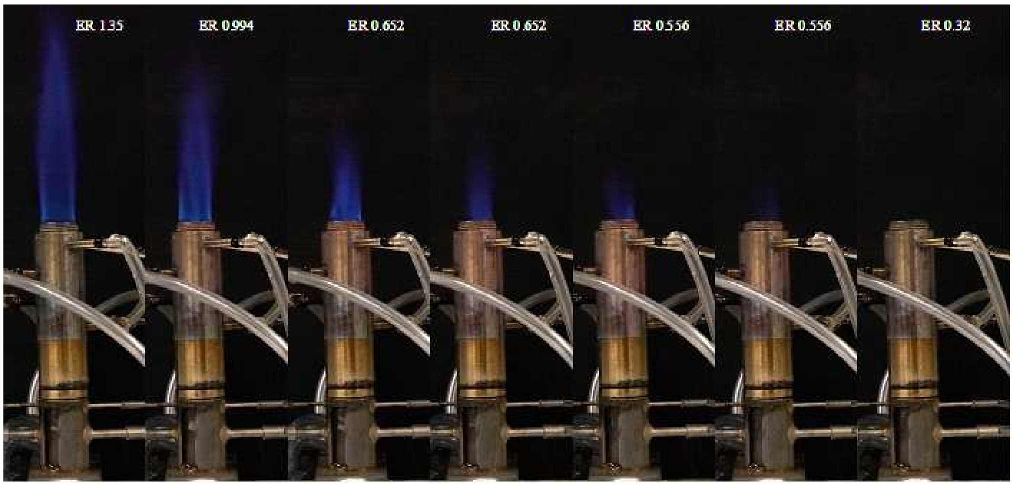

Fig 1: Effect of secondary air injection changing the air flow from 135 mg/s (equivalence ratio, ER 1.35) to 570 mg/s (ER 0.32) in different distributions of air injection between mid and top injectors.

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2 Phenomena description

Recent works on film combustors [2] [3] demonstrate that the length of the plume is correlated to the equivalence ratio and to the air flow. In all cases an increase of the equivalence ratio produces an incremental increase in the length of the external flame plume (see also Fig 1). Measurements show that the length of the flame's plume outside the chamber varies between a few centimetres to more then ten centimetres [2] for a fuel film combustor of one centimetre diameter and eight centimetres in height without secondary air injectors. This condition results from the fact that the triple flame structure identified as the flame stabilization mechanism [4] requires rich operation, hence the quantity of oxygen in the chamber is too low to fully burn the fuel. It is important, therefore to consider strategies that bring additional air into the combustor without affecting the flame holding mechanism and to enhance mixing and reaction rates downstream of the flame anchor point. The idea we examine in this paper is to introduce secondary air inlets in the middle and top of the chamber to ensure enough air flow for complete internal combustion. This concept was already used in large scale systems such as in the RQL gas turbine [8] where the air injection had the function to minimize the NO_x .

One important concept in fuel-film combustor operation is the film evaporation process. In fact fuel vaporization has the double function of ensuring a stable combustion process and protecting the wall by evaporative cooling from the flame heat transfer. The higher the heat flux from the flame the higher is the evaporation rate of the film. From the description above it appears that the stability of the flame is linked to the capacity of maintaining the flame inside the chamber through the local rich zone near the base that is required to form a triple flame. This condition is ensured by two air injectors at the bottom of the combustor. In addition, the swirling air flow and mixing that is generated near the air inlets at the base are diminished through the reaction zone both through the laminarizing effect of the decrease in Reynolds number with rising temperature and by the increasing dominance of the axial component of the flow. So secondary air injection is used also to increase the swirl of the flow in the middle and upper part of the chamber close to where the reactions take place.

During the combustion phase in very lean condition it was observed that a tubular flame could be forced completely inside the combustion chamber by the secondary air injectors. A very similar flame is studied by other authors [9] in a larger apparatus and usually with premixed mixtures. It appears that the fuel-film combustor here investigated obeys the principle that a swirl type tubular flame can be easily established in a tube where a fuel/air mixture is injected tangentially so that the exhaust gas exits axially [9].

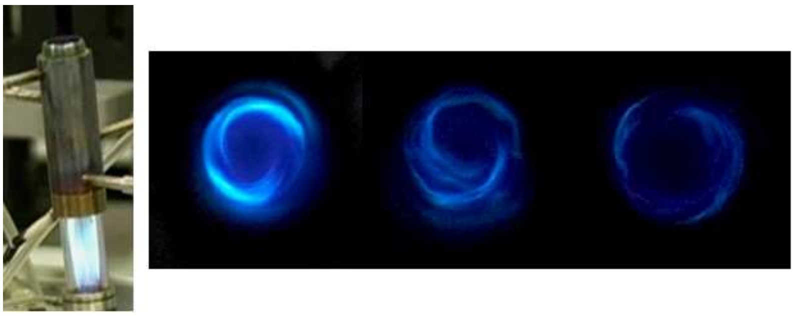

Fig 2 : Tubular flame images from side view through a sapphire window and from a top view with exposure time respectively (from left to right) of 0.001s, 0.00025s and 0.000125s .

3 Apparatus description

The combustor used in this research in composed of a bottom part with 2 air inlets and 2 fuel inlets with an inside diameter respectively of 2.7 and 1 millimetres [3]. The new chamber design includes a different middle section, 10 millimetres long, and a new top section that contains 4 tangential air injectors of 2.15 millimetres diameter. Threaded rings have been designed to connect the bottom section to the middle and top sections, all with stainless steel type 316. In this configuration the length of the chamber from the fuel injectors to the exit section is 58 millimetres and the overall length, comprising the bottom mixing section, is about 88 millimetres with a constant inside diameter of 9.7 millimetres (Fig 1). A transparent sapphire tube is also used as middle section, allowing visualization of the flame's anchor point that during regime operation is right above the fuel injectors (Fig 2). The combustion chamber as described above is the direct evolution of a first prototype that was built with some differences in the length of both middle and top sections as well as in injector diameters, material and the kinds of connections between the main chamber and the injectors.

An estimation for the swirl number has been made based on the Beèr and Chigier geometrical approximation [5] and formulations from Claypole-Syred [10] and Chigier-Chervinsky [11]. Results indicate a value of the swirl number S of about 2.7 from Beèr and Chigier and 1 for both Claypole-Syred and Chervinsky. The last equation gives a value that is between 0.9 and 1.4 due to some uncertainty regarding the flow's velocity.

The fuel feeding system is composed of two syringe pumps, one per each injector, and the air is supplied by a pressurized line where the air injectors are connected in groups of 2, one group from the bottom and two groups from the top section of the combustion chamber. Temperature measurements on the outside wall have been performed along the chamber at 6 different points, with K-type thermocouples; a Pitot tube was used for velocity and static pressure estimations at the exit of the chamber and a copper-vapor laser was used for visualization of the exhaust flow with shadowgraphy.

4 Results

A flammability investigation was performed over all the fuel and air flow range and the following graph contains a list of points and areas that define the stable operational limit for the configuration described above.

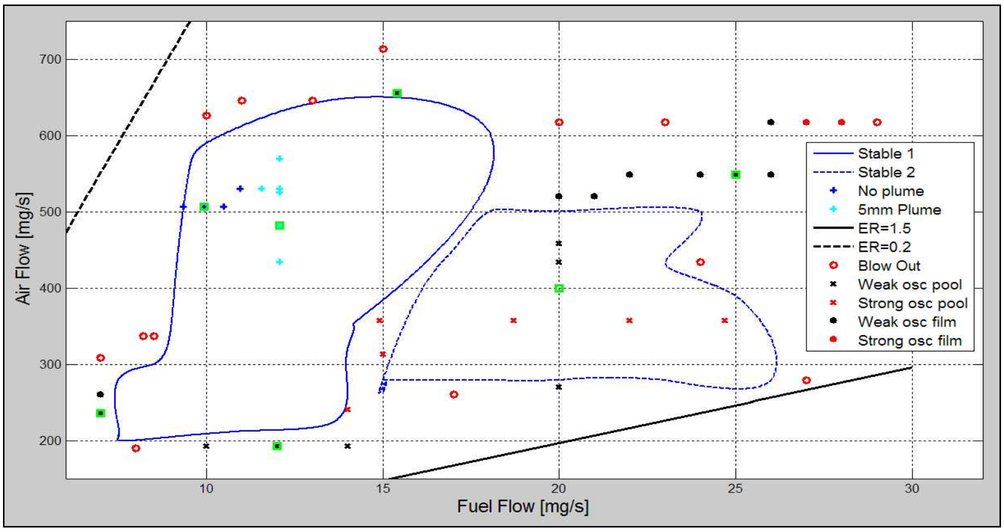

Fig 3 : Characterization of stable and unstable working areas in the fuel/air flow plane.

In Fig 3 two main regions can be seen, one with a continuous blue line that is used to indicates the most stable working area, and one with a dashed blue line (on the right) that is used to indicate a region where both stable and unstable points can exist depending on the distribution of the air flow in the injectors. Typically, with low ER values the blow out points take place very close to the stability area despite some regions where blow out points and stability regions are separated by instability points. The small blue crosses indicate operational conditions where there is no plume out of the combustion chamber so the entire combustion phenomenon occurs inside the chamber. It appears that this combustor is inclined to lean-mixture operation, specifically between 0.3 and 0.4 long run tests of about 1 hour could be made without blowoff.

Comparing the stable working area that corresponds to the bottom section with just a middle section but without secondary air injection [3] to the one in Fig 3, it is possible to see how the stable region is widened and extended to leaner mixtures. So it seems that the tubular flame can stabilize the combustion better than would occur with just air recirculation in the base. The green square points indicated in the flammability limit (Fig 3) were analyzed to estimate the heat loss, and in figure 4 the temperature profile along the chamber is plotted for each of those points. Using the measured temperature values a heat loss by radiation and convection from the wall is estimated to be maximum about 20 Watts when the heat generated by the flame is about 600 Watts.

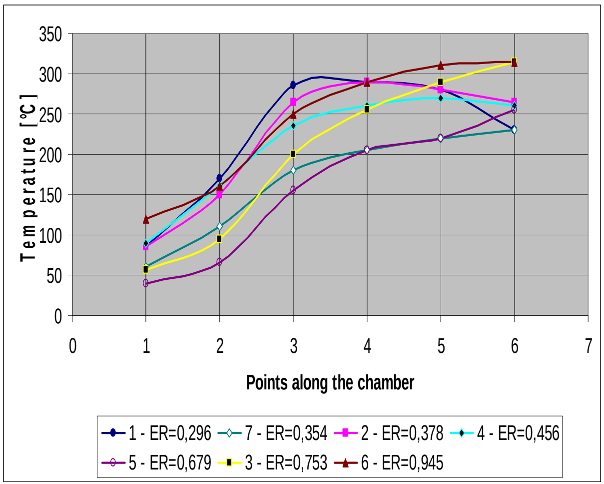

Fig 4: Temperature profile on the outside wall moving from fuel injectors (1) to exit section (6)

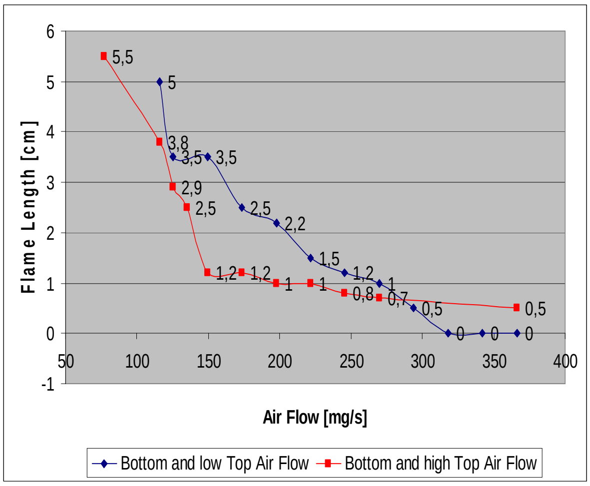

Fig 5: External plume length in centimetres caused by a variation of the air flow in the top injectors

Figure 5 shows the variation of the plume length caused by changing the air flow in the top two groups of injectors with a fixed fuel flow (12.5 mg/s) and fixed bottom air flow (77 mg/s). Square points refer to the group of two injectors located close to the exhaust; diamond points refer to the other two injectors closer to the middle section. Results show that different groups of injectors have different effects on the length of the plume and with respect to the bottom air injectors. Specifically the most sensitive position for the air injectors is the basement of the chamber, that is also closer to the anchor point. Next most effective is the low-top group that still controls the fuel-film evaporation more than the third group situated close to the exhaust.

Figure 6 shows the shadowgraphy images obtained with illumination from a copper-vapor laser with increasing air flow in the secondary injection respectively from 280 mg/s to 470 mg/s to 615 mg/s with fixed fuel flow at 12.5 mg/s. No recirculation at the exit section can be seen from this images though the value of the swirl number might suggest the opposite. Further examination of the exit flow will be accomplished in the future.

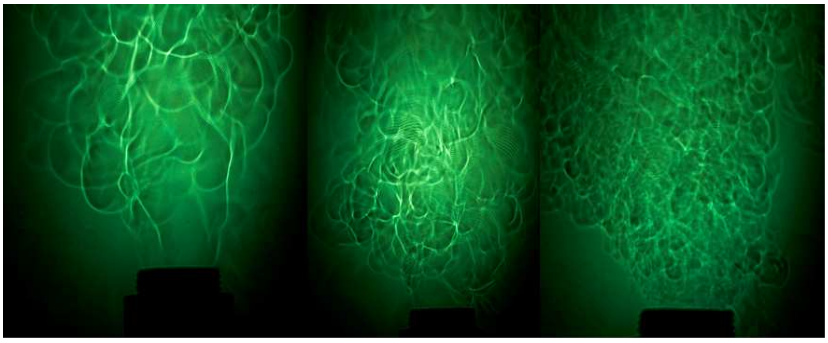

Fig 6: Shadowgraphy images of the exhaust hot gasses

5 Upcoming work

The first step will be the use of a four gas analyzer (HC, NO_x, CO, CO_2) for the analysis of the exhaust in the same 6 conditions explored for the heat loss estimation. This information, along with the exhaust temperature, will be used for the efficiency estimation. Three other middle sections with different lengths are ready to be used and compared with the purpose of understanding how the chamber length acts on the mixing and on the film evaporation in order to find the highest efficiency that can be obtained in the shortest configuration. Another secondary air injection section has been designed with a pressure gauge port. This port could also be used for water injection inside the chamber. The pressure measurements will be used with a set of nozzles and with a load cell for thrust measurements. Since oscillations at different frequency were observed in many points of the working area (Fig 3), a system for simultaneously acquiring temperature, pressure, and thrust data using a LabView interface is under development. This will allow the acquisition of three different signals and a frequency analysis, which should be helpful to understand the causes of the instability. The LabView acquisition will also be supported by an acoustic analysis of some of the instability points for confirmation of the critical instability frequencies. As a last point, an investigation will be done on a newly designed chamber with a critical size of 5 millimeters of inside diameter. This chamber has already been demonstrated to operate stably (Fig 7).

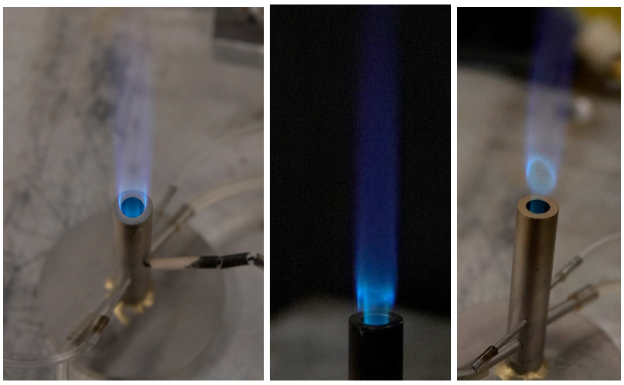

Fig 7: 5 millimetre diameter fuel-film combustor burning at ER = 1.5

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