Sub Topic: Microcombustion and New Combustions Concepts

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Experimental Evaluation of Swirl-Venturi Rapidly Mixed Tubular Burners for Hydrogen Combustion

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1. Introduction

In recent years, hydrogen has been in consideration for use as an alternative fuel. Hydrogen presents many favorable combustion characteristics; however, more research and development are needed before hydrogen can be widely adopted. Consequently, investigations of new hydrogen-air burner concepts suitable for stationary and aircraft gas turbine engines have become more prevalent.

Tubular flames represent a class of canonical combustion configuration proposed by Ishizuka [1] used for fundamental combustion studies and power generation [2]. Such flames present a characteristic extended longitudinal length and circular cross-section. Most early studies involving tubular flames were limited to systems where fuel and oxidizer were premixed prior to injection into the combustion chamber. However, due to flashback potential, interest in nonpremixed tubular systems, more specifically, opposed- and swirl-flow systems, has increased recently.

Nonpremixed opposed-flow tubular flames are obtained experimentally by inserting a porous cylinder installed along the axis premixed counterflow tubular burners [3]. The reactants flow radially into the system's annular section, forming a cylindrical flame. This simple configuration has only been used to characterize fundamental combustion parameters [4] as its geometry does not possess the characteristics necessary for practical combustion chambers. Alternatively, nonpremixed swirl-type tubular flame burners are obtained experimentally through a burner consisting of either one [5] or two concentric tubes [6]. In nonpremixed systems, fuel ejected from the porous cylinder reacts in the combustion chamber with swirling air.

Rapidly mixed tubular flames were introduced more recently to initially separate reactants in tubular combustion systems. The combustor utilizes the same injection concept devised for premixed swirl-type tubular flames, where reactants are issued from tangential injectors connected to the base of the system (Fig. 1). Premixed flames are obtained when a mixture of fuel and oxidizer is directed to all injectors (Fig. 1.a), whereas rapidly mixed tubular flames are generated if oxidizer and fuel are injected separately through the tangential holes (Fig. 1.b).

The first rapidly mixed tubular flame combustors employed burner diameters between 50 and 100 mm [7]. However, it was soon observed that burners with smaller diameters could also be experimentally realized, as the presence of swirling flows helps with the flame anchoring mechanism [8, 9]. As is other non-swirling systems, the rapidly mixed configuration is limited by wall quenching effects [10], restricting studies involving swirl-type flame to diameters of the order of

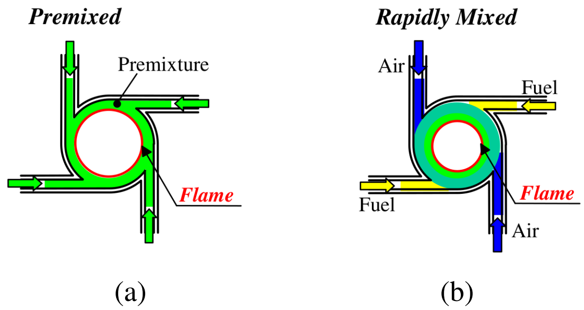

Figure 1: Original concept of rapidly mixed combustion in a swirl-type tubular flame burner [7]. (a) Rapidly Mixed, (b) Premixed. (Will be modified to avoid copyright issues in the final version.)

10 mm [11–18]. Another limitation of rapidly mixed burners is the relatively large dimensions of their injection system. Swirl injectors must be mounted tangentially to the burner inlet in the configuration. Moreover, further size reductions in the chamber diameter also influence the injection slit dimensions. To circumvent this issue, Sauer et al. [19] introduced a swirl-generator for the injection of rotating air and porous walls for fuel injection as replacements to the tangential slits from the original swirl-type tubular flame combustor based on the results from its nonpremixed liquid fueled counterpart [5]. In addition to reducing the overall burner size and further enhancements of swirl control, flames with injection equivalence ratios (Φ) near the lean methane-air flammability limit ($\Phi = 0.5$) were obtained.

Lean direct injection (LDI) employing swirl-venturi (SV-LDI) was extensively studied by Tacina and collaborators [20–27]. The converging-diverging venturi in SV–LDI uses a convergent section to provide a region of high-velocity air to aid in fuel mixing and divergence to help pressure recovery and promote a recirculation zone. In their systems, fuel is injected through a simplex fuel nozzle atomizer fitted within the hub of the air swirler, with its tip positioned to inject the fuel at the venturi throat [28]. However, the use of atomizers can mitigated if fuel injection through porous walls is considered, making the system also suitable for gaseous fuels without further modifications.

In the present study, a swirl-venturi rapidly mixed tubular flame burner is presented and evaluated experimentally. In this configuration, a Venturi tube enhances air and fuel mixing. Fuel is injected through porous walls at the throat of the Venturi tube. The radially injected fuel mixes and reacts with the swirling air from the bottom inlet. The flame is located in the combustion chamber downstream from the burner throat, where a straight tubular region follows the diverging section. Both time-independent and transient conditions are analyzed. The burner is evaluated based on the external flame structure produced in the tubular region.

2. Experimental Setup

A schematic of the burner is presented in Fig. 2. The system consists of a cylindrical quartz tube with inner diameter and length of 13 and 63.5 mm, respectively, and an aluminum base used for support. Fuel flows radially inwards into the combustion chamber through the walls of a 304 stainless steel porous cylinder with 6.9 mm, inner diameter 6.4 mm, and wall thickness 1.6 mm, positioned upstream from the quartz tube. The porous cylinder is made of a filter element rated

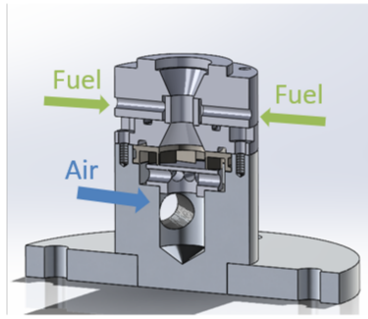

Figure 2: Schematic representation of the burner.

for removing particles up to 50 µm. The radial swirl generator is made out of multipurpose 304 stainless steel (with a vane angle of 12°), through which swirling air is supplied into the combustion chamber. The airflow is supplied axially and turned by the radial swirl generator to mimic the effect of the slits used in the original rapidly mixed tubular flame burner. The flow rate of compressed air is controlled by a mass flow controller (Omega, FMA5528A) calibrated with a bubble flow meter in the range 10 to 50 $\mathrm{L\,min^{-1}}$, while a second mass flow controller (Omega, FMA5420A), calibrated in the range 1 to 10 $\mathrm{L\,min^{-1}}$, is used to adjust the flow of methane. Hydrogen is added to the system through a rotameter (Aalborg, 042-15-GL-EA) calibrated from 1 to 35 $\mathrm{mL\,min^{-1}}$. The rotating reacting mixture flows upwards and exits from the upper open end of the burner, with the quartz tube allowing complete flame visualization. The volumetric flow rates of air, fuel, and hydrogen are varied independently to evaluate the generated tubular flame under several inlet equivalence ratios and H_2 dilution levels. A torch ignites the mixture at the combustor exit port.

Photographic images of the flame are captured by conventional DSLR (Nikon Z6 Mirrorless) cameras. One camera, mounted with its axis perpendicular to the tube centerline, is used to obtain images of the entire length of the tubular flame (front camera). A second camera captures photographic images from the top of the system using a mirror positioned at a 45° angle downstream from the burner exhaust.

3. Results and Discussion

The stability of the rapidly mixed tubular flame established in the burner varies depending on the inlet conditions. Unstable flames are characterized by oscillations in their luminous core that eventually lead to extinction, whereas the shape of stable flames does not vary significantly, remaining steady over the observed time length. The diameter of stable tubular flames varies, approximately, between 8 and 12 mm, depending on the inlet conditions. The characterization of the flame at different inlet equivalence ratios and flow velocities consists of a systematic procedure where the fuel flow rate is selected first, followed by an observation of the flame established in the system at an independently adjusted air flow rate for 60 s. At the end of the observation time, the DSLR cameras simultaneously obtain photographic images of the flame.

The observed flame configurations (Fig. 3) depend on the inlet flow rates of fuel and air, i.e., the system overall inlet equivalence ratio, Φ, and the hydrogen dilution conditions. To identify the operational limits of the system, as well as conditions for stable and unstable burning, a working-limit chart of the burner is presented and discussed.

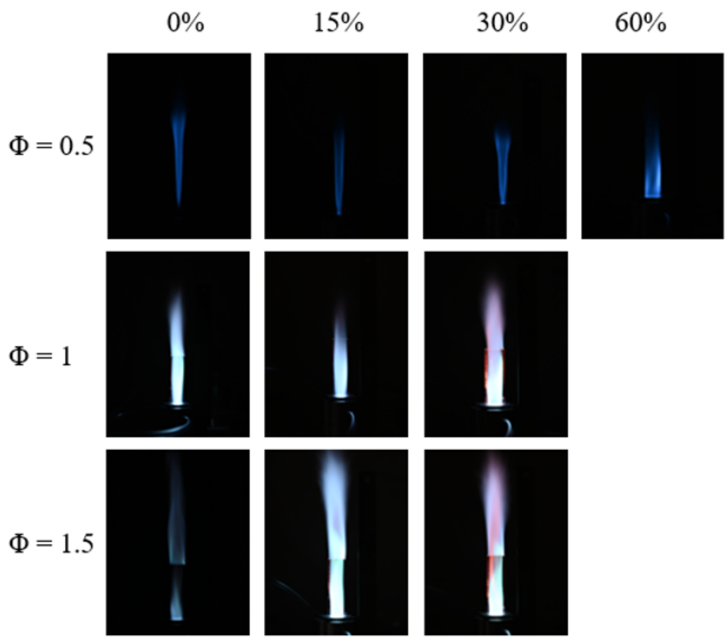

Figure 3: Characteristic photographic images of flames produced by the rapidly mixed tubular combustor. Images are shown for the front camera.

A working-limit chart of the system is shown in Fig. 4, where the abscissa and the ordinate represent, respectively, the inlet fuel and air flow rates. The solid line, denoting overall stoichiometric inlet conditions, separates the map into lean (upper) and rich (lower) operation zones. The working-limit chart shows that tubular flames are established for several conditions. Different flame structures are obtained depending on the inlet equivalence ratio. As shown in Fig. 4, the stability map can be divided into five subregions separated by different equivalence ratio limits by four different lines, where dotted, solid, long-dashed, and dashed lines represent Φ of 0.5, 1.0, 1.5, and 2.0, respectively. In each zone, a different characteristic flame structure is obtained.

When the system operates at inlet equivalence ratios greater than 2.0 (zone below the dashed line in Fig. 4), the amount of air supplied at the inlet is not sufficient for complete combustion inside the chamber (quartz tube). In that subregion, the system operates at conditions above the rich methane-air flammability limit of $\Phi = 1.68$ [29], and two luminous regions are formed (Fig. 3a). The flame near the air and fuel inlet has characteristics similar to swirl-type nonpremixed tubular flames, which seems to be caused by a poor mixture of reactants in that region. However, a more detailed flame analysis is necessary to characterize that reaction zone completely. A lifted flame is observed downstream from the burner outlet, consisting of diffusion flame formed by the unburned mixture and the ambient air. The separated luminous regions are connected by a rich, dim, tubular structure that becomes apparent when a larger amount of air is supplied to the system, i.e., by adjusting the system overall equivalence ratio to values closer to 1.5 (long-dashed line in Fig. 4). In the region of inlet equivalence ratios closer to the rich flammability limit (between 1.5 and 2.0), a uniform tubular flame is obtained, as shown in Fig. 3b. However, because of the excess fuel at the inlet, the luminosity of the flame structure shifts towards a characteristic green color, indicating that methane is not completely consumed inside the burner. The unburned mixture continues to react

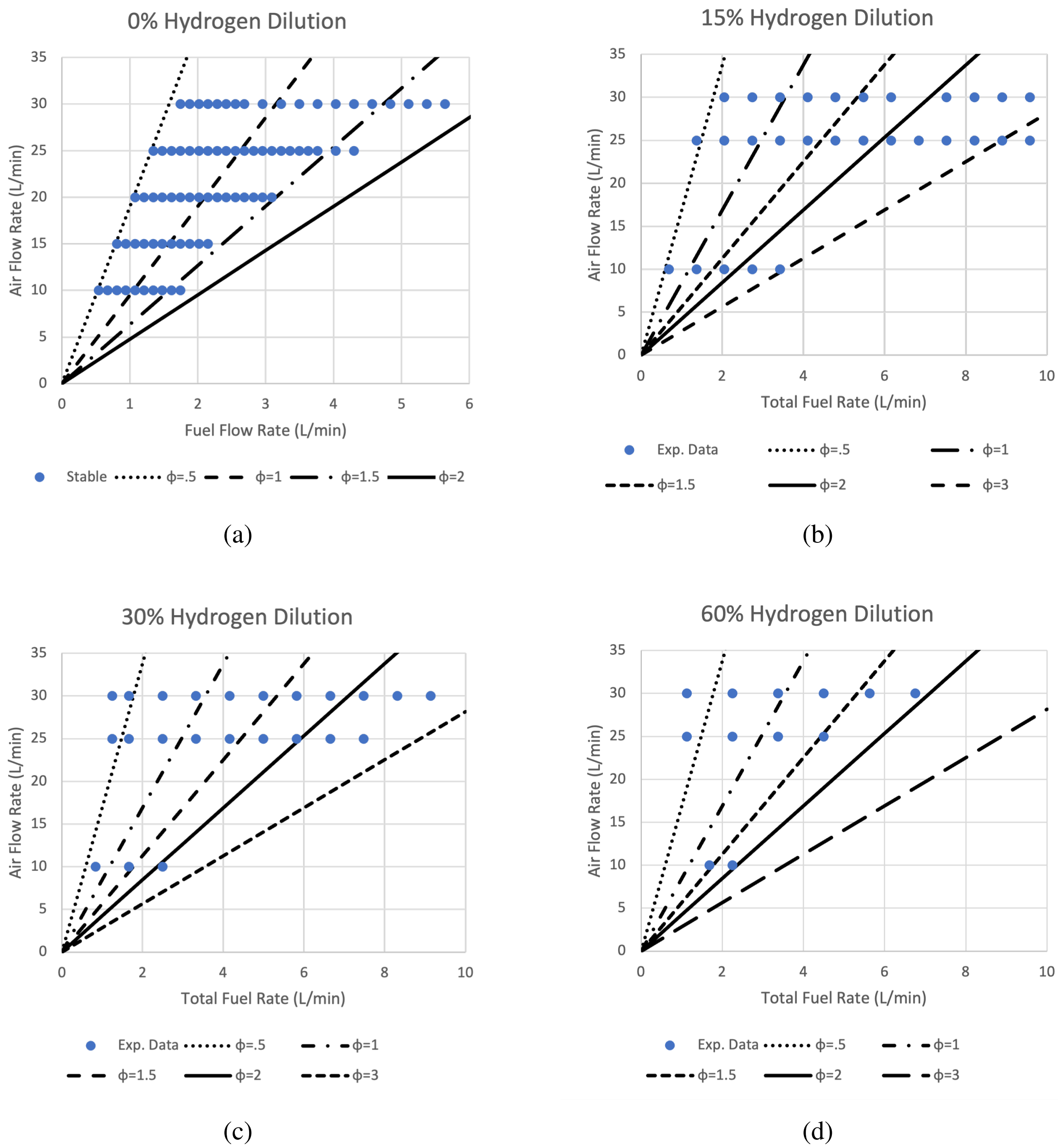

Figure 4: Combustor working-limit map. Hydrogen dilution of (a) 0%, (b) 15%, (c) 30%, and (d) 60%.

with the ambient air above the burner exhaust, prolonging the tubular flame structure downstream from the quartz tube. The flame luminosity transitions from green to blue as the equivalence ratio of the flame is reduced to values between 1.0 and 1.5 (Fig. 3c).

At inlet flow rate conditions near stoichiometric proportions, a tubular flame with intense luminosity is established in the burner (Fig. 3d). Although a relatively dim plume is found downstream from the burner exhaust – indicating that a portion of the air-fuel mixture continues to burn for a short distance –, most of the tubular flame structure appears to be confined in the quartz tube. At that condition, the diameter of the flame is increased, a behavior consistent with that from rapidly mixed flames established in burners with tangential inlet slits [7].

The zone to the left of the solid line represents lean inlet conditions in Fig. 4. The flames obtained in the lean region of the working-limit chart present a similar overall structure, characterized by an elongated tubular shape structure with increasing diameter along the flow direction, as shown in Fig. 3e. As the equivalence ratio decreases, the flame luminosity is further reduced, whereas the overall flame shape remains unchanged.

When the equivalence ratio approaches the lean methane-air flammability limit ($\Phi = 0.5$ [29]) – the upper region of the stability map –, the flame oscillates for a few seconds before extinguishing. This behavior is likely induced by the procedure employed in this investigation – where new inlet conditions are adjusted starting from a reference stable operation point. This instability seems to be limited to flames near the lean flammability limits at lower inlet fuel flow rates. However, a similar behavior was observed for flames at larger flow rates operating at equivalence ratios greater than $\Phi = 0.5$. Therefore, further investigation of flames near the lean flammability limit is still necessary to completely characterize the processes leading to combustion instability.

4. Conclusions

The modified rapidly mixed type tubular burner equipped with a swirl-venturi nozzle and a porous wall for injecting rotating air and fuel, respectively, demonstrates very promising combustion behavior compared with the original rapidly mixed combustor. The working-limit map of the system operating with methane and air shows that stable flames can be obtained for a wide range of inlet injection velocities, equivalence ratios, and hydrogen dilution levels. The new configuration will allow a reduction of the overall burner size and further enhancements of swirl control.

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