Porous Wall Fed Liquid Fuel Nonpremixed Swirl-Type Tubular Flames

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1 Introduction

A tubular flame is a classical configuration used in fundamental studies in combustion science. Its characteristic shape, circular in cross section and long in the perpendicular direction, was first reported by Ishizuka [1]. The most common tubular flame configurations — the swirl type and the counterflow type — have been mainly applied to the analysis of premixed systems. After the introduction of nonpremixed counterflow tubular combustion [2, 3] the interest in the tubular configuration has increased. However, studies involving tubular flames are limited primarily to gaseous fuels, despite the fact that volumetric heat release from combustion of liquid hydrocarbon fuels has much higher energy density available for power generation [4].

The nonpremixed counterflow (often called opposed-flow) tubular flame is obtained experimentally using a modified premixed counterflow tubular burner [5]. The burner is altered by installing a porous cylinder along the center axis from which one of the reactants flows outwardly in the radial direction [2]. The outer contoured nozzle issues inwardly the other reactant. Another type of tubular flame configuration in which the reactants are injected separately is the rapidly mixed burner [6]. This configuration consists of an injection system in which reactants are issued tangentially in a tube through four slits located at its closed end and a downstream transparent tube allowing flame visualization. However, a Damköhler number analysis suggests that this type of flame can only be established for mixing times shorter than the reaction time, effectively resulting in premixed tubular flames [7].

The combustion of liquid fuels is much more complex compared to gaseous fuels. In the combustion of condensed fuels the reaction zone is located in the gas phase, such that a portion of the heat generated by the chemical reactions is conducted towards the liquid phase to provide the latent heat of vaporization of the fuel [8]. The gas phase reaction is accompanied by a number of complicating parameters at the liquid/gas interface such as the pyrolysis of the fuel, formation of condensed products, phase transitions, etc., which makes the development of new combustion systems employing condensed fuels challenging, particularly at small scales. Nevertheless, burner configurations involving liquid fuels are potential alternatives to systems

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that otherwise would be limited by the difficulties inherent to pre-processing the condensed fuel. At the same time, the condensed fuel can offer protection from heat losses and quenching since the temperature of the walls where a liquid layer develops does not exceed the boiling point of the fuel.

The liquid film combustor is one of the few tubular flame configurations in which condensed fuels have been considered [9]. The system takes advantage of the fact that for miniature systems a condensed fuel layer can offer a surface area for vaporization as high as in vaporizing sprays [1]. In this configuration the liquid fuel is injected tangentially into a tube creating a thin film on the surface of the wall. A swirling air flow is introduced from the closed end of the tube through a swirl generator [10]. The injection of swirling air creates a rotational movement of the flow field which helps to spread the fuel and stabilize the film on the combustor inner surface [11].

This current study explores a configuration in which a permeable material is used to deliver fuel to the combustion chamber. Porous materials have been employed in reacting system for many years. More specifically, in the case of liquid fuels, porous inert media were used in the development of radiant burners [12], for control of noise and instabilities in a swirl-stabilized combustor [13], to examine flame spread over fuel-soaked ground [14], among others. One of the drawbacks of analyses involving permeable media in combustion is the fact that the porous matrix prevents optical access to the combustion chamber. Therefore, flame visualization and, consequently, the discussion on flame structure and stabilizations mechanisms are not possible with the combustion diagnostic tools currently available.

The nonpremixed swirl-type concept presented herein is based on injection of fuel through porous walls, and takes advantage of the combined advances in liquid fuel film and classical tubular flame burners. In this new configuration, instead of developing a layer of liquid on the walls, the condensed fuel is injected through the permeable burner walls. The condensed fuel vaporizes and becomes the gaseous fuel source for the chemical reaction with the swirling air coming from the bottom inlet. The flame is located in the combustion chamber between the burner walls and the exhaust gas at the core of the chamber.

2 Experimental Setup

A schematic of the burner is presented in Fig. 1. The system is composed of two concentric cylindrical tubes and an aluminum base used for alignment and support. The liquid fuel flows into the combustion chamber — the hollow central region of the tube — through the walls of the inner tube, which are permeable. The porosity of the walls allows the surface tension to spread the liquid over its volume. The outer tube is solid, made of aluminum. Fuel is delivered to the porous medium trough an orifice that ends in a small gap between the outer and inner tubes indicated in Fig. 1 as "Fuel Inlet". The small annular space drives the fuel upwards though capillary effect. Air is injected axially from the bottom of the combustion chamber through a swirl generator. The jetted photopolymer rapid prototyping machine is used to produce the swirl generators, which consist of three blades with a vane angle of $15°$.

The porous tube consists of a commercial stainless steel filter element with internal diameter $12.7\,\mathrm{mm}$. The tube is made of stainless steel meshes formed into cylinders and sintered together. A $20\,\mu\mathrm{m}$ pore size is considered in the evaluation of the burning conditions. The length the combustion chamber, which is slightly longer than the height of the porous tube, is $57.5\,\mathrm{mm}$.

The flow rate of compressed air is controlled a rotameter calibrated with a bubble flow meter in the range of 10 to $40\,\mathrm{L\,min^{-1}}$. A continuous syringe pump controls the flow of liquid n-heptane. The volumetric

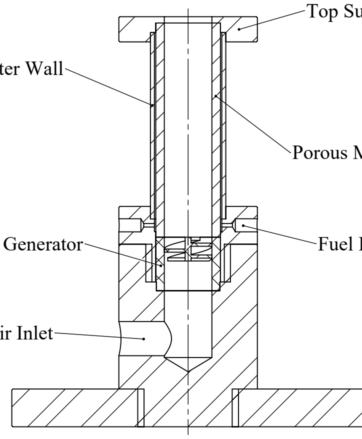


Figure 1: Schematic section of the system.

flow rates of air and fuel are varied independently such that several inlet equivalence ratios are considered. Namely, lean, stoichiometric and rich conditions.

The temperature of the outer wall is measured by K-type thermocouples located a at several heights on the burner external wall and with an infrared camera FLIR SC660.

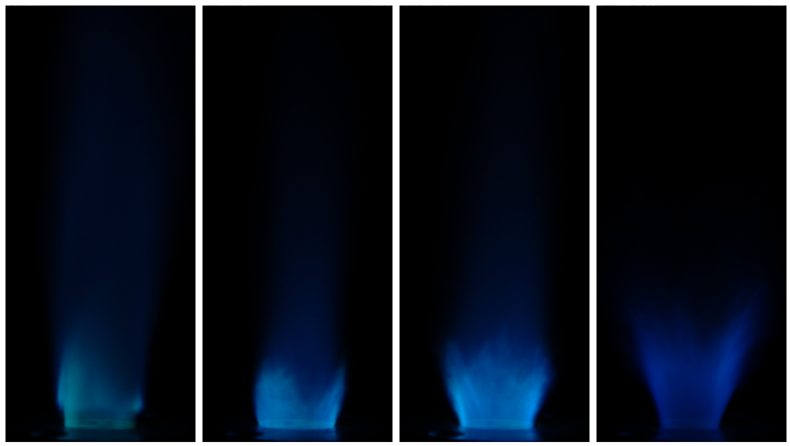
3 Results and Discussion

During stable operation conditions a single continuous steady flame structure with varying shape is observed. The flame shape changes depending on whether the observed region belongs to the luminous core inside or outside the combustion chamber, i.e., bellow or above the top support show in Fig. 1. In the internal region, the flame possesses a shape that resembles a cylindrical structure observed in the counterflow-type tubular burner [2]. In the region formed above the rim the flame shape is changed by the expansion of the internal structure into an external conical shape (with axially increasing radius), mainly because of the unconfined swirling conditions. In this way, some of the unburned mixture continues burning above the rim and some of it reacts with the outer ambient air. Visual inspection shows no discontinuity when the flame transitions from the tubular to the conical shape.

The porous matrix does not allow further observations on the structure of the internal flame. Thus, a detailed analysis of the internal flame characteristics such as anchoring mechanisms, chemical species and temperature profiles, etc., is not possible. However, externally observable characteristics can be used in order to evaluate qualitatively the system. The internal and external flame correspond to two regions of a single flame structure, such that the existence of an external flame is sufficient for a complete flame structure being established in the combustion chamber under the experimental conditions considered in this study. As a consequence, flame stability conditions based on fuel and air injection flow rates can be derived. At the same time, the temperature of the outer wall indicates whether the liquid fuel has been completely vaporized and heated up in the annular region between the inner and outer tubes. External wall temperatures higher than the fuel dew point correspond to fuel in vapor phase flowing into the porous medium. On the other hand, temperatures measurements of the external wall close to the fuel dew point indicate saturated fuel flowing into the porous matrix.

3.1 Stability Limits

The system operates in a broad range of conditions for the inlet equivalence ratio. For different combinations of fuel-air inlet flow rates, distinct external flame shapes are obtained. The observed flame configurations presented in Fig. 2.



(a) (b) (c) (d)

Figure 2: Photographic images of the experiment. (a) Torch flame; (b) Conical flame; (c) Open flame (d) Unstable flame.

In order to identify the operational limits, stability of burning conditions and observed shapes of any secondary flame, working-limit charts are presented in Fig. 3, where the abscissa represents the inlet liquid fuel flow rate and the ordinate the inlet air flow rate. The black line denotes an overall stoichiometric inlet condition (though the reaction is non-premixed so we presume that any reaction interface is always stoichiometric). The regions above and below the black line, which represents stoichiometric inlet conditions, separates the map into global lean (upper) and rich operation zones (lower). The map shows that all measured points lie in the region of stoichiometric or rich conditions. Depending on the amount of air introduced into the chamber it is possible to change the flame shape and combustion behavior. Three stable regimes — denoted torch flame, conical flame and open flame in Fig. 2 — and one unstable regime (Fig. 2(d)) are observed. When the flame is in the stable region, oscillations are not observed and the shape of the external luminous core can either resemble a torch (Fig. 2(a)), a cone (Fig. 2(b)) or an open structure (Fig. 2(c)), represented in Fig. 3 by circles, triangles or squares, respectively. Torch flames are observed in richer regions of the map, and characterized by a long external structure mainly due to the lack of oxidizer in the combustor, which allows an excess of unburned fuel to leave the burner and react with ambient air. Conical flames are longer and wider than open flames, and they are commonly observed in leaner regions. In the unstable region, represented by diamonds in Fig. 3, the flame cannot sustain its shape for long periods of time (when compared to the stable regime), and its shape resembles the premixed low-swirl burner developed at the Lawrence Berkeley National Laboratory [15].

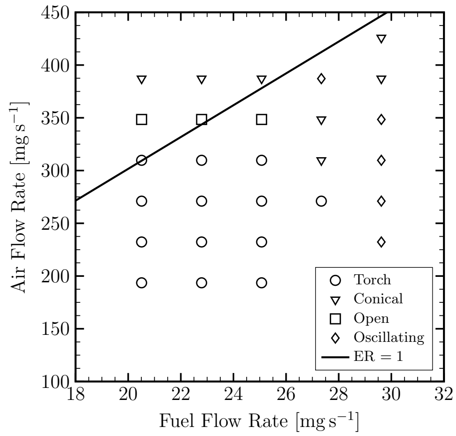


Figure 3: Combustor working-limit map.

3.2 External Temperature

The external temperature of the burner at specific locations is obtained using K-type thermocouples. In order to evaluate the temperature field over a larger surface area of the burner an infrared camera is used. Reflection of infrared radiation from the surroundings by the burner surface is avoided by applying a high temperature black coating. Thermocouple measurements at different heights show that the external temperature remains lower than $40\,°\mathrm{C}$ even after extended operation. The temperature over the external wall surface shown Fig. 4 corroborates the data obtained from the thermocouples. The measured temperatures on the external wall are considerably lower than the boiling point of heptane (around $98\,°\mathrm{C}$), which indicates that the fuel from the annular injection points enters the porous wall below its saturation condition.

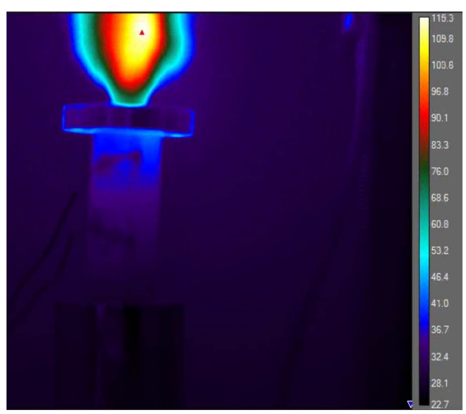


Figure 4: Infrared images of the burner.

4 Conclusions

The porous based non-premixed tubular burner demonstrates very promising combustion behavior as compared to mesoscale film combustors. Operating limits are expanded and the burner walls remain cool. Further details of combustion efficiency and emissions will be included in the full paper.

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