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Flame dynamics of a meso-scale heat recirculating combustor

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A B S T R A C T

The dynamics of premixed propane–air flame in a meso-scale ceramic combustor has been examined here. The flame characteristics in the combustor were examined by measuring the acoustic emissions and preheat temperatures together with high-speed cinematography. For the small-scale combustor, the volume to surface area ratio is small and hence the walls have significant effect on the global flame structure, flame location and flame dynamics. In addition to the flame–wall thermal coupling there is a coupling between flame and acoustics in the case of confined flames. Flame–wall thermal interactions lead to low frequency flame fluctuations (~100 Hz) depending upon the thermal response of the wall. However, the flame–acoustic interactions can result in a wide range of flame fluctuations ranging from few hundred Hz to few kHz. Wall temperature distribution is one of the factors that control the amount of reactant preheating which in turn effects the location of flame stabilization. Acoustic emission signals and high-speed flame imaging confirmed that for the present case flame–acoustic interactions have more significant effect on flame dynamics. Based on the acoustic emissions, five different flame regimes have been identified; whistling/harmonic mode, rich instability mode, lean instability mode, silent mode and pulsating flame mode.

1. Introduction

Over the past decade there has been great interest within the research community in the field of combustion and power generation in small-scales. The main motivation for combustion in small-scales is the high energy density of liquid hydrocarbons, much higher than that offered by the current batteries. If the chemical energy from the liquid hydrocarbons can be extracted at small-scales, then it can be used to replace the existing batteries. Micro-scale combustion also offers potential application in miniature propulsion devices and micro-satellites (divert and attitude control). Researchers have investigated various energy conversion schemes from hydrocarbon fuels in small-scale devices [1]. However, there are several challenges related to manufacturing, material failure and flame stability involved in the development of a miniature scale combustion system. As the size decreases the surface area to volume ratio of the combustion device increases which subsequently increases the heat loss to heat generation ratio. These higher losses in the smaller dimensions induce flame quenching. In order to extract power from small-scale devices using hydrocarbon fuel, this issue of flame quenching must be addressed.

Regenerative preheating of the reactants effectively eliminates the quenching limits associated with fuel air mixtures at standard conditions. In regenerative heating the thermal energy is recirculated from the outgoing combustion products to preheat the fresh incoming reactants without recirculating the combustion products themselves. Swiss-roll design is commonly employed [2–10] for heat recirculation. Other designs, such as counter-flow annular combustor design [11], counter-flow annular combustor design with porous media [12], multi-concentric tube design [13] are also possible.

The present paper discusses the flame dynamics of a meso-scale combustor which utilizes regenerative preheating of propane–air combustion prior to the introduction of fuel–air mixture into the combustion chamber. For heat recirculation, a rectangular shaped Swiss-roll design was employed, see Fig. 1. Gas phase self-sustained combustion of propane–air mixture was achieved in a volume of 32.6 mm^3. The combustor is fabricated from a low thermal conductivity ceramic (zirconium phosphate 0.8 W/m-K) material which was chosen because of its superior heat transfer properties as reported in the previous studies by the authors [8–10].

Combustion in small-scales is qualitatively different from conventional macro-scale combustion. The flame characteristics differ mainly due to the thermal coupling between the walls of the combustor and the associated flame. Wall effects are insignificant in conventional large-scale flames. However, the reaction zone is observed to expand due to the wall thermal coupling [14] in small-scale flames. Also due to the smaller length scales, hydrodynamic flame instabilities are generally absent [15].

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Nomenclature

c	sonic velocity (m/s)
L	length of the pipe (m)
L_{pre}	length of the preheating channel (m)
L_{chamb}	length of the combustion chamber (m)
L_{out}	length of the exhaust channel (m)
T_{in}	reactant inlet temperature (K)
T_{pre}	reactant preheating temperature (K)
T_{chamb}	combustion chamber temperature (K)
T_{out}	exhaust temperature (K)
T_{avg}	length-weighted average temperature (K)
v_b	first harmonic frequency of the pipe (Hz)
Φ	equivalence ratio

However, new kinds of flame oscillations in which flame with repetitive ignition and extinction (FRIE) occurs, are present. Several researchers [15–17] who examined combustion inside meso-scale channels have observed this phenomenon. FREI are non-stationary flame phenomena, namely, regular cyclic ignition in the downstream region and extinction in the upstream region. They generally occur for low or moderate flow velocities. However, for the present case FREI instabilities were completely absent. Since the combustion occurs in a confined space the flame is accompanied by significant acoustic emissions. The flame was observed to excite the harmonics of the hot gases inside the combustor. For some conditions, the flame is affected by the acoustics and oscillates at high frequencies. Though it has some effect on flame stability, the acoustics associated with the flame did not lead to flame extinction. This is evident from the significant acoustic emissions observed over a wide region within the flammability regime. The high intensity acoustical oscillations can lead to mechanical failure of the combustor through self excited and sustained resonance. The natural frequency of combustor is related to the mass and stiffness of the material. Combustors machined from Macor ceramic were the only ones which failed due to this effect. Fig. 2 shows a Macor combustor that was fractured due to acoustical interactions between the flame and the combustion chamber. For the particular combustor shown in Fig. 2 the crack propagated at a specific equivalence ratio, and the wall temperature was far below the maximum working temperature of the material.

For examining the flame regimes present, complete flame extinction limit map of the combustor was obtained experimentally. The regimes were distinguished based on the preheat temperature, flame oscillation and acoustic emission. Investigation of preheat temperature was performed with the aid of a K-type thermocouple installed at an upstream location of the combustion chamber. Fourier transforms applied to both the audio signal and high-speed images provide the sound level distribution (with respect to frequency) and flame oscillation frequencies, respectively. Experiments revealed the presence of five distinct flame modes. They included whistling flame, rich instability mode, lean instability mode, silent flame and pulsating flame. Even though the acoustic emissions showed significant variations with flow conditions, no corresponding changes in the flame structure could be visually observed because of the highly luminous nature of the flames, see Fig. 3. Hence, chemiluminescence imaging was employed to mark the region of reaction zone in the combustor [18]. The chemiluminescence signatures of excited OH, CH radicals were acquired at narrow band wavelengths centered at 307 nm and 430 nm, respectively. The chemiluminescence signatures at the above two wavelengths provide information on reaction zone location and heat release rate, respectively. In addition C_2^* radical emissions generated from within the flames at 470 nm and 515 nm were also determined. The results showed that only the, chemiluminescence signal from the excited OH^* radicals were able locate the flame zone correctly. There is a significant amount of thermal radiation originating from the walls due to high combustion temperatures and the closeness of the walls to the flame. Hence images of CH^* and C_2^* are somewhat skewed with the interference from background thermal radiation. There was no interference from background thermal radiation on OH^* images due to negligible wall thermal radiation at lower wavelengths (~307 nm).

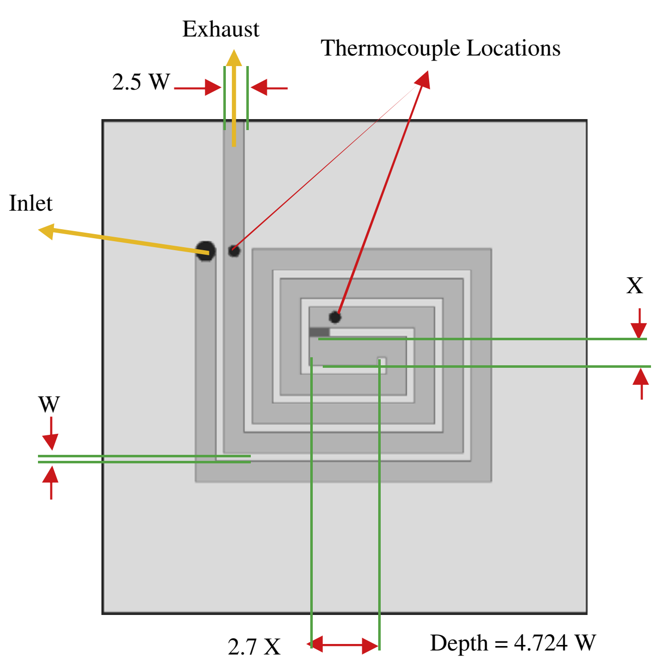

Fig. 1. A schematic diagram of the combustor geometry.

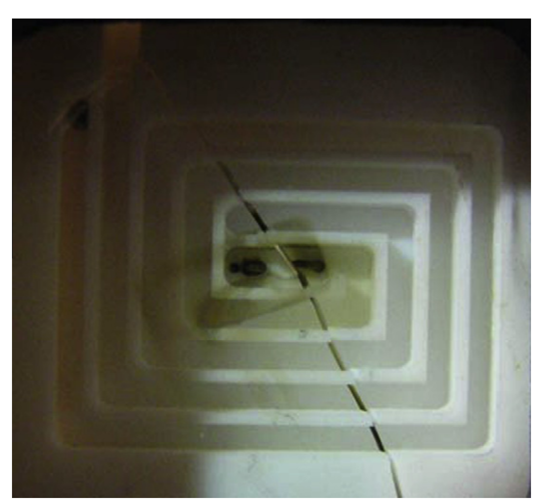

Fig. 2. Macor combustor that has fractured due to acoustic interactions between the flame and the combustor.