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Experimental investigation of flame pattern transitions in a heated radial micro-channel

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ABSTRACT

Flame pattern transitions of CH_4/air mixture were experimentally investigated in a radial micro-channel. These transitions were triggered by a variation in the mixture equivalence ratio or inlet mixture velocity. The transition processes were recorded with a high-speed digital video camera. From the movies, it is shown that the mechanisms responsible for these transitions could be classified into two: (1) transitions from a stable circular flame to a traveling flame, and from a traveling flame to single or double Pelton-like flames were due to local extinction in the flame front, and (2) transition from an unstable circular flame to a spiral-like flame was due to local splitting of the flame front. Numerical simulation of the isothermal flow demonstrated that flow field is symmetric and steady when the inlet velocity is small, but it grows asymmetric and unstable at large inlet velocities. The asymmetric and unstable flow field is expected to be the possible reason for the local splitting of flame front. On the other hand, flame is noted to be quenched near the top wall surface. These two reasons are expected to induce the transition from an unstable flame to a rotating spiral-like flame.

1. Introduction

With the rapid development of MEMS technology, there is an urgent demand for micro-power generation devices and systems. As the electrochemical batteries have disadvantages of a short life span, long recharging periods and low energy densities, combustion-based power sources are considered to be potential alternatives to conventional batteries due to the much higher energy densities of hydrocarbon fuels [1,2]. Therefore, micro- and meso-scale combustions have received great attention in the past decade [3–33]. However, the increased heat losses due to large surface area-to-volume ratio and the wall radical quenching make it difficult to sustain a stable flame under small scales [1–5]. Numerical analyses demonstrated that heat conduction in the solid walls has a great effect on flame stability in micro-channels [6,7]. Heat recirculation is frequently adopted in the design of micro-combustors. The “Swill roll” combustor is a well-known example and it has already been implemented to stabilize flames in micro- and meso-scales burners [8–12]. Other researchers also developed different approaches to stabilize flame in micro-combustors [13–16].

Many contributions have been made to understand fundamentals of combustion at reduced scales with heat recirculation. To facilitate direct observation of the flame dynamics in micro-channels, Maruta et al. [17,18] used a micro-tube made of transparent quartz. The combustion chamber is optical accessible and thus the detailed flame structures and dynamics can be identified with an image-intensified high-speed video camera. In their experiments, in order to simulate the heat-recirculating effect like the “Swiss roll” combustor, a wall temperature profile in the flow direction was generated with an external heat source before the introduction of fuel. They found that stable flames occurred at high and low inlet mixture velocities. When the inlet mixture velocity was decreased or increased to a moderate value, transition from stable flame to unstable flame propagation modes occurred. Those combustion waves include the flame with repetitive extinction and ignition (FREI). It was also demonstrated that the flame location versus inlet mixture velocity exhibited an S-shaped curve [18,19]. This phenomenon stimulated the passions of many other researchers [20–27].

Following the idea of Maruta et al. [17,18], Kumar et al. [28–30] discovered a variety of non-stationary flame patterns of CH_4/air mixtures in a heated radial micro-channel, such as the traveling flame, rotating Pelton-like flame, spiral-like flame, and so on. Later, Fan et al. [31] carried out a 2D numerical simulation of combustion in this configuration using a global one-step Arrhenius reaction

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