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Diffusion flames and diffusion flame-streets in three dimensional micro-channels

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ABSTRACT

Experiments of non-premixed combustion in micro-channels have exhibited different modes of burning. Typically, a diffusion flame is established along or near the axis of a channel spanning the entire mixing layer. It separates a region of fuel and no oxidiser from a region with only oxidiser. Often, however, a periodic sequence of extinction and reignition events, termed collectively as "diffusion flame-streets", are observed. They constitute a series of separate diffusion flames, each with a tribrachial edge flame structure that is stabilised along the channel. The current work focuses on understanding the underlying mechanism responsible for these unique observations. Numerical simulations were conducted in a thermo-diffusive limit to examine the effects of confinement and heat loss on flames in three dimensional micro-channels with low aspect ratios. An asymptotic analysis was used to reduce the mathematical equations into a two-dimensional problem which effectively captured the three dimensional nature of the combustion process. Two key burning regimes were identified: (i) stable continuous diffusion flames and (ii) stable diffusion flame-streets. The transition between regimes is demarcated primarily by the Damköhler number, defined as the ratio of a diffusion time to a chemical reaction time, but is also influenced by the extent of heat loss. Occasionally within the diffusion flame-street regime, the residual mixture would reignite but would fail to evolve into stationary auxiliary flames. This was generally observed at low flow-rates for Reynolds numbers below a critical value. The behaviour appeared to be periodic in time with a frequency that depended on the removal from criticality.

1. Introduction

Recent advances in the miniaturisation of energy storage and propulsion devices have piqued interest in small scale combustion. The primary difference between large and small scale combustion, and in particular non-premixed combustion, lies in (a) the dominant mode through which mixing is achieved and (b) the extent to which heat loss impacts the burning process. The miniaturisation of a combustion chamber affects the reacting mixture's residence time which decreases as the characteristic dimensions of the combustion chamber decrease. Unlike large scale systems where the fluid flows are mostly turbulent, the characteristic Reynolds and Péclet numbers are small in small scale systems and hence the flow is essentially laminar. At small scales, mixing is achieved primarily through molecular diffusion by increasing diffusion times. Combustion however necessitates chemical reaction times be comparable to, or preferably smaller than, diffusion times which offers insight into why low combustion efficiencies are attained in small scale devices. Additionally, large scale flames are relatively impervious to external heat losses. However, as the chamber is miniaturised, the surface area-to-volume ratio increases resulting in increased heat loss to channel walls and potential destruction of radical intermediates at the walls. At scales smaller than the quenching diameter, no combustion can be supported without the aid of external thermal management. The challenges posed by small scale combustion have warranted numerous experiments to be dedicated solely at enhancing the understanding of flames at small scales, the progress of which has been extensively reviewed amongst Fernandez-Pello [1], Maruta [2] and Ju and Maruta [3].

At small scales, the interaction between the combustion chamber walls and the gaseous reacting mixture often leads to peculiar behaviour in both premixed and non-premixed environments. In premixed combustion, aside from typical flames, repetitive extinction and ignition events were observed in straight [4–6] and curved ducts [7], with widths less than the flame's quenching diameter. Since the temperature in the walls was regulated, combustion was supported under these adverse conditions. In these ducts, flames were ignited periodically in the hot part of the channel

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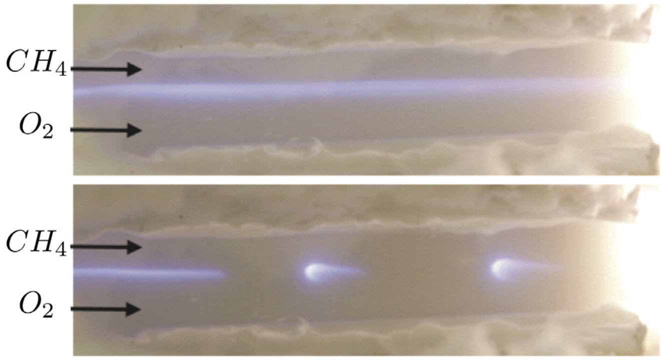

Fig. 1. Photographs of flame structures observed in a non-premixed microcombustor showing in one case a continuous diffusion flame (top) and in the other a diffusion flame-street consisting of separated flame segments (bottom), aligned in the stream-wise direction; taken from Prakash et al. [13].

before propagating upstream where the flames then extinguished due to heat loss to the cooler parts of the channel. Generally, these flames did not stabilise and the phenomenon was termed as *"frequent repetitive extinction and ignition"* or *"repetitive extinction and reignition instability"*. These simplified configurations were motivated in turn by the more complex excess enthalpy combustion devices like the Swiss roll microcombustor [8,9]. Understanding conditions which cause such behaviours are critical to improve on low combustion efficiencies associated with small scale combustors.

There are fewer studies examining non-premixed flames in small scale combustors. One of the first non-premixed microcombustors was fabricated at the University of Illinois to study the structure, properties and dynamics of spatially confined combustion at the micro-scale [10–13]. Fuel and oxidiser were supplied at the base of the burner where the inlet streams were separated by a wedge-shaped splitter. A continuous diffusion flame was not always observed and often the burning was irregular with the diffusion flame separating into discrete flame segments, referred to by the authors as "cells", aligned with the stream-wise direction; see Fig 1. Upon careful examination, it was revealed that these irregularities were not a result of imperfections in the burner surface's catalytic activity or temperature profile. The number of cells formed, for example, depended on the total flow rate and initial mixture strength. In some cases, the flame cells were observed to collapse into a continuous laminar diffusion flame that underwent an unsteady behaviour along the channel. At the time, it was speculated that the observation was an instability [11].

The repetitive extinction and reignition pattern was then reproduced in a larger (meso-scale) channel under a more controlled setting by Xu and Ju [14]. The patterned formations were termed colloquially as "*flame-streets*" owing to its periodic, repetitive nature, a resemblance that it shares with the von Kármán vortex street. Like the experiments conducted by Miesse et al., the reactants were initially segregated and introduced into the combustion chamber through a honeycomb such that a uniform inflow of fuel and oxidiser could be achieved. The reactants would merge and generate a mixing layer. The channel walls in previous experiments, which allowed for variations in temperatures, were instead maintained at prescribed uniform temperatures. Thus, in addition to studying the implication of using different fuels and a range of different flow rates, the effect of varying wall temperature was also examined. Like previous experiments, it was seen that flame-streets were observed at large flow rates whilst an unsteady behaviour was observed at low flow rates. A series of scaling arguments were then used to predict flame position (and thus separation between individual flames). The analysis excluded spatial variations in the velocity field, the structure of the trailing diffusion flame and hence interaction between successive flame segments, and also the effects thermal expansion. The predicted position at which each flame was stabilised was predicated on the assumption that each segment was held stationary solely by the incoming flow.

Many studies conducted previously have examined the nature of flame spread in laminar mixing layers generated by two co-flowing reactant streams. One of the many aspects investigated in these studies was the stabilisation mechanism of the associated diffusion flames. Liñán [15] argued that in the wake of a splitter plate there are two modes of stabilisation: a flame can be stabilised in the vicinity of the splitter plate due to the local momentum deficit and conductive upstream heat fluxes or further downstream by the flow. It is known that the edge of a diffusion flame plays an important part in its stabilisation. Studies conducted by Dold [16] and Hartley and Dold [17] based on a thermo-diffusive model, formally assuming low heat release, showed that the propagation speed of an edge flame is a function of the mixture fraction gradient near the edge. The diffusion flame thus stabilises at a point where the edge flame speed balances the incoming flow velocity. The structure of the edge flame is also contingent on the local mixture fraction gradient. For small mixture fraction gradients, one may observe either a three pronged or tribrachial structure comprising of two premixed branches in addition to a trailing diffusion flame. As this gradient is increased and if there are asymmetries present, such as unequal reactant Lewis numbers, the tribrachial flame degenerates into either a bibrachial or monobrachial flame. Edge flame studies have also been reviewed comprehensively by Buckmaster [18], Lyons [19], Chung [20] and Matalon [21].

Studies relevant to the present investigation were conducted by Kurdyumov and Matalon [22–24] focusing on diffusion flames in unconfined mixing layers stabilised by their edge. The parametric studies, conducted in a thermo-diffusive limit with a uniform prescribed flow field [22,23] and a full resolved flow field [24], generally investigated the effects of varying initial mixture strength, flow rates, Lewis number and external heat losses on the flame's stability and dynamics. More recently, Bieri and Matalon [25], investigated the effects of confinement in addition to the aforementioned parameters. In adiabatic channels, lateral confinement results in a diffusion flame of finite length. This is in contrast to unconfined channels where the diffusion flame extended infinitely far downstream due to an abundance of reactants. As the channel is made narrower, the diffusion branch was seen to vanish and the edge of the flame became flatter. In channels with heat loss, the flame's length is seen to further decrease and unburnt reactants were seen left behind the flame. The absence of a reignition mechanism prevented the observation of flame-streets. Parametric studies which included the effects of heat release and thus allowed for density variations were conducted in both unconfined [24] and confined mixing layers [26]. In addition to the increased speed of the edge flame caused by flow redirection, it was observed that thermal expansion allowed the flame to stabilise closer to the splitter plate.

The overall objective of this work is to identify the physical mechanism responsible for the emergence of diffusion flame-streets and to construct a mathematical model that simulates the development and stabilisation of flame-streets in micro-channels. Specifically, the goals are to (i) identify conditions conducive to the formation of flame-streets; (ii) describe the key stages in the evolution of diffusion flame-streets and (iii) perform a parametric study to understand the implication of varying flow-rates, channel widths, preferential diffusion and external heat losses on the structure and position of the flame segments that constitute a flame-street. To address these objectives, it is essential to focus on *three-dimensional* micro-channels to ensure adequate mixing of fuel and oxidiser whilst maintaining control of the temperature across the narrow gap and sensitivity to heat loss.