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Oscillating flames in micro-combustion

Annalisa Di Stazio^a, Christian Chauveau^{a,1}, Guillaume Dayma^{a,b} and Philippe Dagaut^a

^a*CNRS – INSIS, ICARE, 1C avenue. de la Recherche Scientifique, 45071 Orléans cedex 2, France*

^b*Université d'Orléans, Collegium Sciences et Techniques, 1 rue de Chartres, 45067 Orléans cedex 2, France*

Abstract :

New experimental results that demonstrate the existence of oscillating flames in micro-combustion are reported here. The results showed the presence of oscillating regimes with different behaviors in the transition between the stable flames, FREI (Flame with Repetitive Extinction and Ignition), and weak flames. They are based on the CH^{*} signal at 430 nm recorded during the combustion of methane in a micro reactor with a controlled temperature profile. These results have never been observed experimentally before and further investigations are still required to better understand these oscillating regimes.

Keywords: micro-combustion; pulsating instability; methane; MEMS

1. Introduction

The recent interest in high-specific-energy miniaturized systems has driven the combustion studies toward small-scale technologies [1-3]. Despite the remarkable progress achieved during the last decade [4], huge efforts are still necessary to understand the flame behavior at micro-scale. As reported recently [5], a new experimental device has been designed to study combustion in micro-channels, and our measurements confirmed the existence of three flame regimes, namely stable flames, FREI (Flame with Repetitive Extinction and Ignition), and weak flames. The aim of this brief communication is to present newly observed oscillating flame behaviors at the transition of these different flame regimes. Even if oscillating FREI have already been reported by Tsuboi et al. [6], no detailed analysis has ever been carried out at the transition from stable flames to FREI. Furthermore, the existence of different oscillatory dynamics has never been observed experimentally. Moreover, the existence of oscillating weak flames in the transition from FREI to weak flames, already announced [5] is confirmed experimentally here for the first time and a frequency analysis is presented.

¹ Corresponding author: Tel.: +33 (0) 2 38 25 54 86 E-mail: christian.chauveau@cnrs-orleans.fr

2. Experimental set-up

The device employed here has been thoroughly described earlier [5]. It consists of a micro reactor heated by three blowtorches to ensure a homogeneous temperature profile. As shown in our previous study (Figs. 4, 5 and 6 in [5]), a decrease of the inlet velocity resulted in the transition between either stable flames and FREI or between FREI and weak flames. These transitions were characterized by the presence of oscillating flames. In order to further confirm the existence of these transitional regimes, new experiments were performed with stoichiometric CH₄/Air mixtures in a narrower tube with an internal diameter of 1.85 mm against 2.15 mm previously used [5].

3. Results and discussion

The results obtained for a 1.85 mm ID are shown in Figure 1. Three main flame regimes were observed as the inlet velocity decreases: stable, unstable (including the flames with repetitive extinction and ignition, FREI) and weak stable flames.

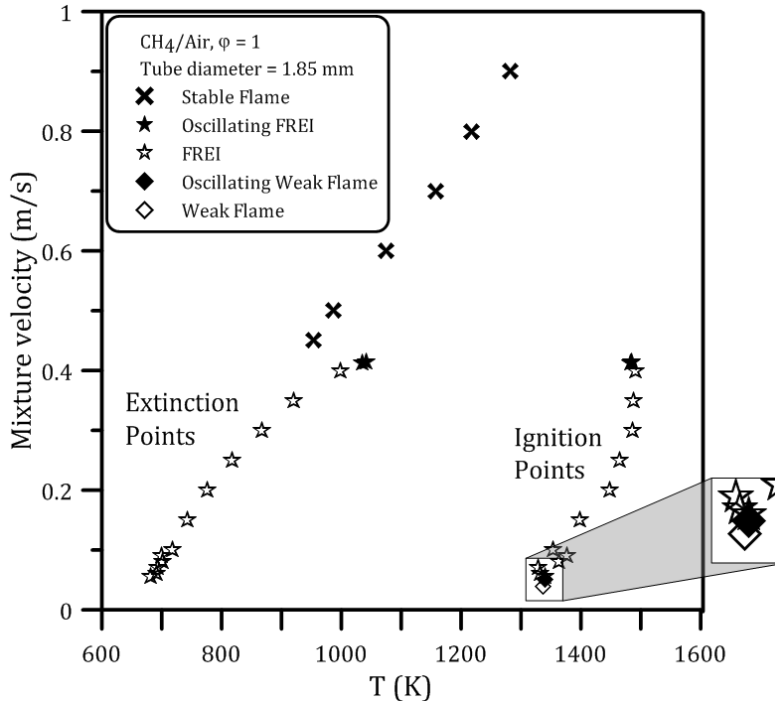


Figure 1: Experimental flame response as a function of wall temperature and mixture flow velocity.

A Princeton Instrument spectroscopy EMCCD camera, equipped with a band-pass filter was used to detect the CH* signal at 430 nm. The spatial resolution was 62 pixels/mm and for unstable flames the maximum recording frequency of 4260 Hz was used.

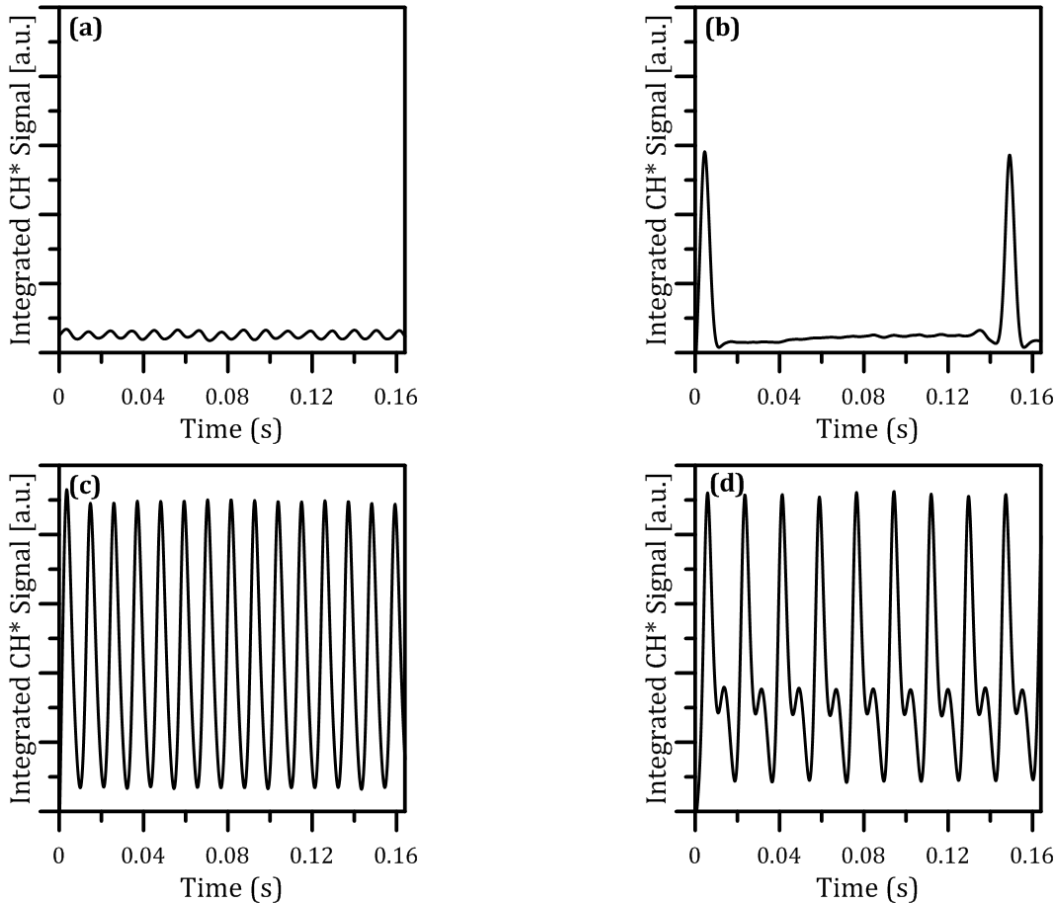


Figure 2: Temporal evolution of CH* signal with inlet velocity: a) $v = 0.05$ m/s (oscillating weak flame) $f = 94.7$ Hz, b) $v = 0.055$ m/s $f = 9$ Hz, c) $v = 0.4$ m/s $f = 96.8$ Hz, d) $v = 0.413$ m/s (oscillating FREI) $f = 57.2$ Hz.

Figure 2 shows the time evolution of the spatially integrated CH* signal for unstable flames: this signal was recorded on eight centerlines and vertical binning was operated. Significantly different flame evolutions were observed according to the inlet velocity. At $v = 0.050$ m/s (Fig. 2a) an oscillating weak flame is present. It switches to a FREI at higher inlet velocities. At 0.055 (Fig. 2b) there is a peculiar progression of the CH* signal, with small fluctuations before a sharp and fast increase of the signal: a pulsating weak flame oscillates slowly before evolving to the main flame that quickly propagates upstream. This behavior, mentioned in [7] as ‘combination’ flames, is similar to that predicted by Minaev et al. [8] who used a 1D thermo-diffusive model and by Jackson et al. [9]. Due to the small flow rate, the conductive time scale becomes longer compared

to the convective one, leading to nearly isothermal conditions along the radius [5]. Furthermore, despite fused silica is considered as an inert surface, high temperature and small channel width favor radical depletion [10] and for $T > 873\text{K}$ wall chemical effects are enhanced [11, 12]. The initial presence of a weak flame, which is characterized by exothermic radical recombination [13, 14], can provide the energy required to initiate the main flame which then propagates quickly thanks to the high gases temperature.

At $v = 0.4\text{ m/s}$ (Fig. 2c) a typical FREI was observed. Increasing further the inlet velocity leads to oscillating flames with regular oscillation pattern at $v = 0.413\text{ m/s}$ (Fig. 2d), the flame oscillates near the extinction point within a distance of 0.6 mm . Before reaching the stable flame region, irregular oscillations were observed (see Supplementary material, Fig. S1). In this case each oscillation has different amplitude and the total number of second order peaks for each cycle is variable. This periodic oscillatory behavior near extinction has been studied by Norton and Vlachos [15] who explained it as the consequence of pressure waves associated with the fluid density variation. Likewise, Miroschnichenko et al. [16] predicted this transitional regime using the thermal-diffusive model for rich hydrogen-air mixtures. They claimed that during the pulsations, the radical concentration fluctuates, while for the FREI regime it goes to zero before re-ignition. The presence of unburned gases behind the main flame, in a region where the temperature is high and the exothermic reactions at the wall are enhanced, can justify the existence of these multiple peaks.

Since both the flame amplitude and the CH^* intensity change with the inlet velocity, this figure plotted on an adapted scale is provided as Supplementary material (Fig. S2).

Figure 3 depicts the flame frequencies, obtained through a Fourier Transform analysis of the spectral cross-section of the CH^* signal. The oscillating FREI flames, observed during the transition from stable to FREI regime, have moderate frequency that increases once the FREI regime is fully established. As the mixture velocity is reduced, the frequency of the flames in the FREI regime decreases. At the lowest velocities, another flame regime, termed oscillating weak flame (at $v = 0.05\text{ m/s}$), with a high oscillation frequency was observed. According to Fig.1, this oscillating weak flame pulses with very small amplitude in a high temperature zone. It is possible that, unlike the case at $v = 0.055\text{ m/s}$, the radical recombination cannot provide the energy required for the flame propagation.

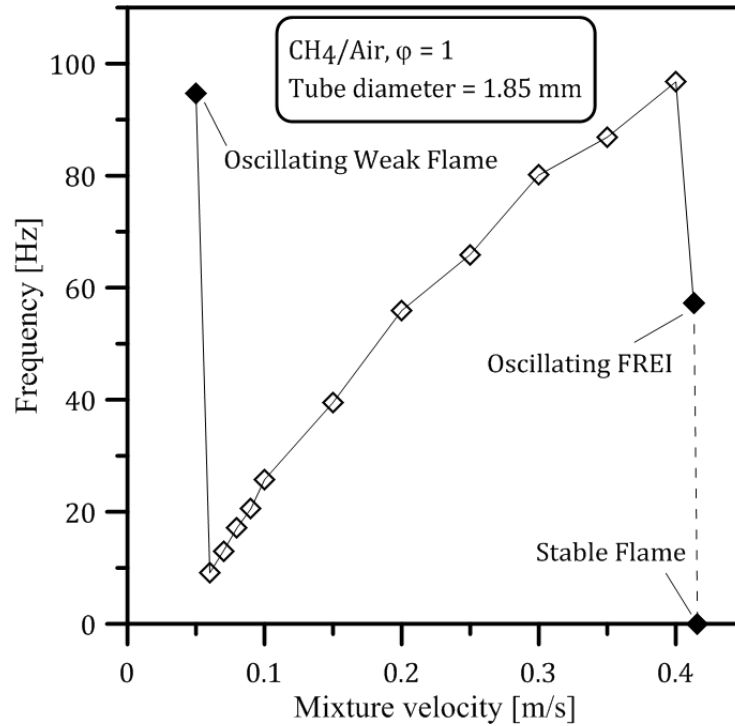


Figure 3: Frequency variation as a function of inlet velocity.

The existence of these oscillating flames supports the work of Jackson et al. [9]. Their mathematical model predicts oscillating weak flames as well as some instabilities observed at higher inlet velocity. For the first time, measurements at high frequency and a detailed analysis of the flame dynamics have been carried out. Our new experimental set-up allows the observation of a new oscillating behavior, namely the oscillating weak flame regime, which has never been observed before.

These results indicate that micro-combustion phenomena require further investigations before being used in micro-systems. The effects of nature of the fuel, dilution, and channel size on such an oscillating behavior are under investigation to better understand the flame behavior at micro-scale.

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Supplementary Material

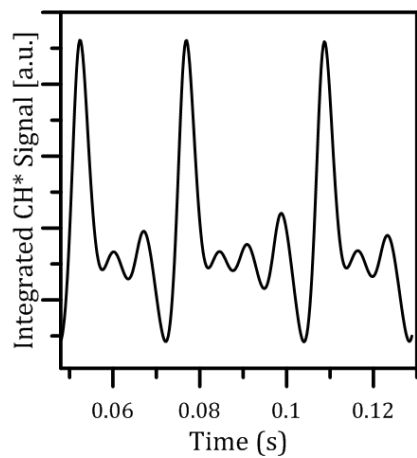


Figure S1: Oscillating FREI with irregular oscillations observed at $v = 0.415$ m/s.

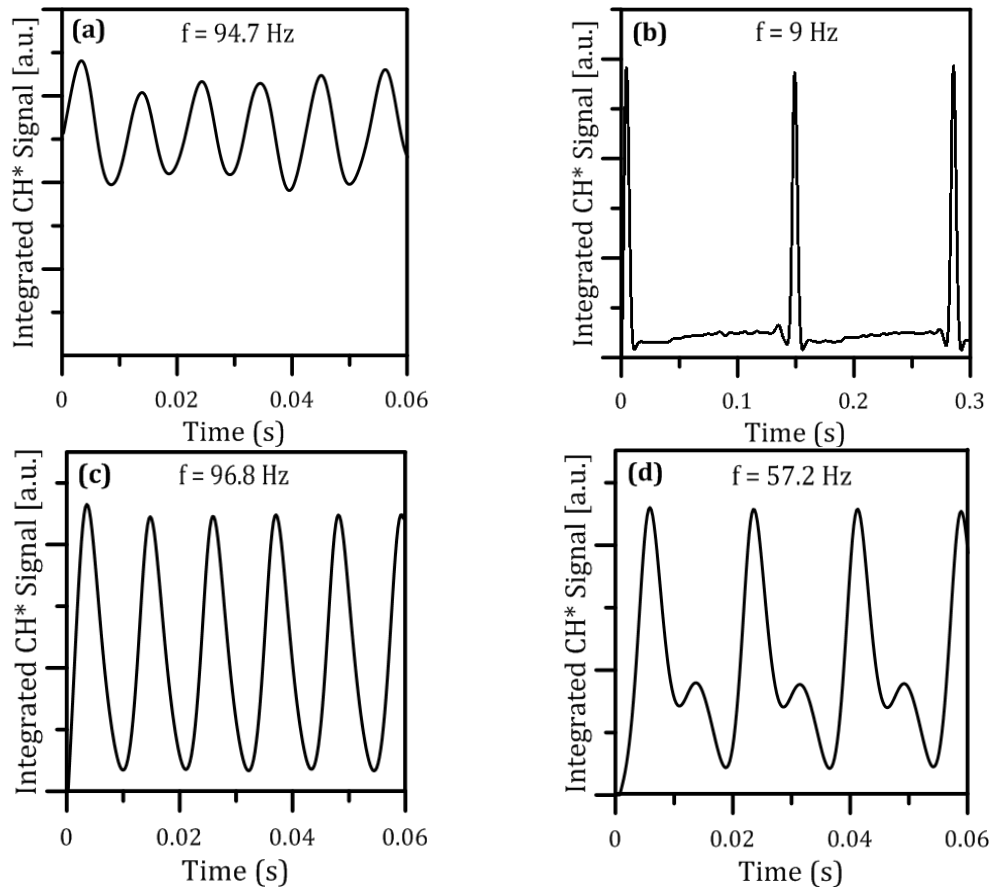


Figure S2: Temporal evolution of CH* signal with inlet velocity, with adapted scales: a) $v = 0.05$ m/s, b) $v = 0.055$ m/s, c) $v = 0.4$ m/s, d) $v = 0.413$ m/s.