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Experimental investigation of premixed flame propagation in silicon channels

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Abstract
Experiments are described for premixed flames in a mesoscale Silicon channel combustor (characteristic length scale ≤2mm) in which the flame is freely propagating in the laboratory frame. The objective of the work is to observe how the combustion process (flame speed, quenching of the chemical reactions due to heat loss, radical quenching and flame stretching) is influenced by varying channel dimensions, flow rates, equivalence ratio and material choice. Presented here are the results of tests for ethylene-air and propane-air mixtures, varying opposing flow velocity and equivalence ratio, as well as channel dimensions from 400um to 2mm. The results are consistent with published quenching distance limits and flame speeds. Larger channel test results indicate that the burning velocity for single propagating flames is relatively independent of heat loss, i.e. conditions are quasi-adiabatic, substantiating the projections of Fernandez-Pello, 2002 [1]. Near limit behaviour is accompanied by observations of instability, most likely due to enhanced thermal interactions between the wall, reaction zone and preheat zone.

1. Introduction

Combustion based Power MEMS devices have been the focus of several research facilities over the past 7-9 years and are receiving considerable more attention today as the needs for stand-alone small scale power units for microtechnology devices increase [1]. Thermochemical approaches can be divided into static and dynamic designs. Static designs include space heating and the thermoelectric/thermovoltaic conversion of heat of combustion to electrical energy and dynamic solutions include all manners of heat engines.

2. Experimental set up

The Silicon Channel Combustor (SCC) design was developed to collect data for PowerMEMS applications regarding on the physical aspects of combustion in microchannels with the main focus on burning velocity/ flame speed aspects, quenching conditions and heat loss mechanisms.

The housing is machined in Aluminum and the channel is constructed from 4” silicon wafers (p-type, double-sided, (100) orientation, from OKMETIC). The wafers are cut in two semicircles and

Figure 1. Schematic of the Silicon Channel Combustor (SCC)

stacked on top of each other, Figure 1.

Each wafer is 400 μm thick, which sets the lower limit for the channel height. The back plate is Silicon but can be replaced with copper and 304 Stainless Steel. The front plate is a Borosilicate glass plate for visibility and video monitoring. Neoprene® rubber, thickness 1/16" flange gaskets are used to seal the wafer stack and reduce leakage from the SCC. The gap between the stack of wafers/glass plate and the aluminum housing is sealed with high temperature RTV type sealant.

Channel dimensions are a rectangular cross-section with dimensions of 400um deep and 2mm wide. The 5:1 aspect ratio increases the heat transfer from the top and bottom plates. According to Wilcox however, the width should be at least 10h to avoid three - dimensional effects caused by the bounding walls [2]. Channel length, L, is the diameter of the Silicon wafers, 100mm. The entry length was not observed to significantly affect the flame characteristics of these relatively simple experiments, however there are several configurations in which they should be considered. A typical entry length is given by: $\ell_e = 0.06h\,\mathrm{Re}_h$ where the channel Reynolds number, Re_h, is defined with respect to the maximum velocity u_m [3]. The typical Reynolds number of a 2mm channel in these experiments lies between 10 and 100, and is thus a laminar flow. When applying this to equation 1, the length required to achieve fully developed flow is 12mm.

The gas supply system utilizes Aalborg® Mass Flow Controllers (MFC) for air and fuel gases to ensure high accuracy and stability in both flow rates and mixture composition. A LabView® data acquisition system is used to set flow rates of fuel and air, as well as monitoring the flow rates. Figure 2 shows the experimental set up. Flame propagation data are collected by a digital videocamera, at 50 frames/sec and photodiodes. The flame position in any point of time was related to a grid with a 1mm resolution. The discrepancies in position accuracy are about 5 mm, representing an uncertainty of 5-8%. The velocity of the flame, U [cm/s], with reference to a stationary observer is then used to find the burning velocity , S [cm/s], with respect to the opposing flow velocity, v_u [cm/s]. No corrections to the average flow velocity were made.

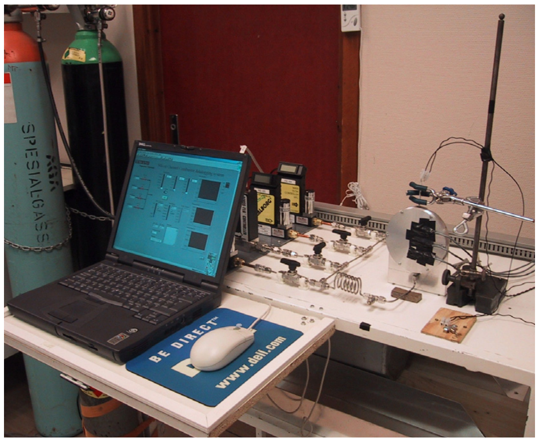

Figure 2. Experimental set-up showing MFC's, SCC and photodiodes for flame detection

3. Results and discussion

In contrast to many microscale combustion experiments, in which the flame is anchored in the laboratory frame, this work examines the behavior of periodic flames within small scale channels with dimensions near the quenching distance. These results can therefore be used to examine the transient effects of heat transfer on a propagating flame. Figure 3 shows a sequence of infrared images as a premixed hydrogen flame propagates downward through a 500um x 2 mm silicon channel. As the sequence of images clearly demonstrates, the flame is propagating into a channel

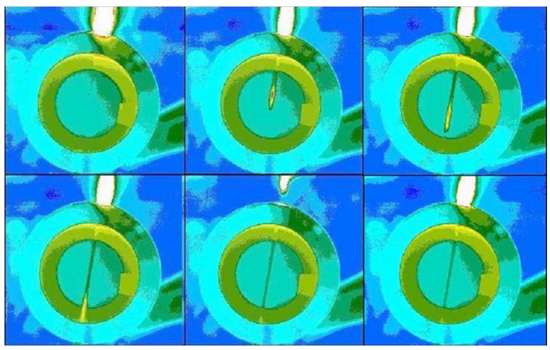

Figure 3. Premixed rich hydrogen-air flame propagating in a 500um by 2mm silicon channel.

with cold walls which are heated by the flame. The results of this series of experiments, in addition to providing data for Power MEMS applications, also can provide critical information for fire safety applications. As an example, a deflagration in a premixed fuel stream proceeding upstream in a flashback may encounter flow straighteners. These data can be used to quantify the distance which this deflagration may proceed through the straighteners and continue upstream.

Figure 4 shows the measured burning velocity for both propane and ethylene-air as a function of equivalence ratio. The dependence of stoichiometry is clearly seen for both fuels and the results are in agreement with published values [4]. Results for propane and ethylene are also shown for burning velocity vs. inlet gas flowrate for opposing flow rates of 50 – 300 ml/min. The propane data were consistent with the expected results. The ethylene-air data, on the other hand, show

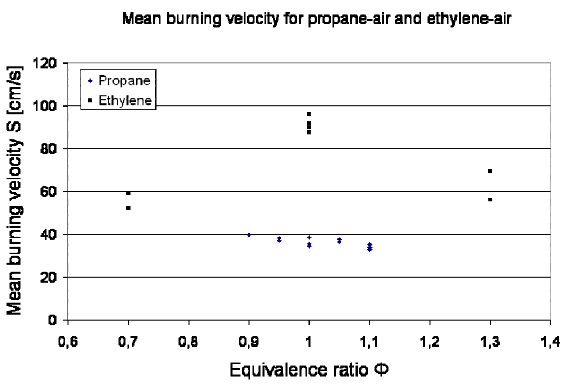

Figure 4. Burning velocity S for propane-air and ethylene-air mixtures in a 2mm x 10mm wide Si channel

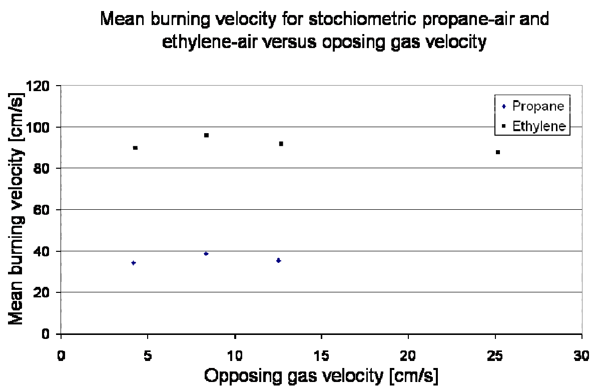

Figure 5. Mean burning velocity S for propane-air and ethylene air mixtures versus opposing gas flow velocity

higher flame speeds than published values. However, observations indicate that the flame does not propagate at a constant speed through the channel for the rich mixures, but retards and almost comes to a halt, then accelerates and exits the channel at a maximum velocity. These findings are similar to the effect of pressure waves/ rarefaction waves on propagating flames in larger diameter tubes. Further investigation with a high speed camera has confirmed the deceleration and reaccelerating in the channel, which indicates that either pressure effects or some instabilities caused by the opposing flow leads to flame stretching that in some situations quenches the flame, whereas for other conditions leads to an increased velocity. Further work is required.

Experiments were carried out (data not shown) for a variety of back plate materials of differing thermal conductivity. The results indicate that the flame speeds are relatively independent of heat loss, i.e. conditions are quasi-adiabatic, as described by an examination of the Fourier number [1]. The effect of buoyancy is expected to be of negligible importance by a Froude analysis, was also experimentally observed to be negligible (data not shown).

There is an increasing body of modeling and experimental work on small scale combustion systems including models by Maruta et al.[5], Ronney [6] and Norton and Vlachos [7,8]. Another model by Daou and Matalon [9] addresses a freely propagating premixed flame in the presence of a gas flow. This asymptotic model assumes Poisueille flow, fuel is assumed to be the deficient species, Ahrrenius chemistry is assumed and a constant density approximation is invoked. This assumption cannot account for the lateral expansion of the burned gases which in reality distorts the parabolic flow profile. The model indicates that the flame is most sensitive to heat loss in the opposing flow configuration (gas flow vector opposes flame velocity vector in lab frame). Under the conditions of these experiments, Daou and Matalon predict a slight reduction in burning rate (~90%) as compared to a truly planar flame in the microchannel, consistent with the current results. This reduction can be attributed to the quenching effects of the flame closest to the wall, occupying approximately $6*l_f$ nearest the wall. The experimental observation of this quenching was originally reported by Ferguson and Keck [[10]].

The difference between the stationary (in the laboratory frame) and traveling flame is in the heat transfer to the wall. There are two distinct changes to the heat loss term. In addition to the larger thermal flux driving gradient due to the lower wall temperatures, (T_f-T_w), the internal flow heat transfer coefficient, h is variable along the tube length (in this experimental configuration).

It is interesting to note that for the conditions of these experiments, the Biot number, Bi = hL/k, ranges from 10^{-3} to 10^{-4}. This implicitly states that the primary heat transfer thermal resistance is in the gas boundary layer, which as we have seen is variable along the region of flame passage in the channel. This is an important finding, indicating that for channels of this dimension, the results here can be extrapolated to all materials with thermal conductivities up to two orders of magnitude less than that of Silicon. As the quantity for the Biot number begins to approach 0.1, the thermal resistance in the solid wall begins to become important [[11]]. If we further compute the Fourier number, $Fo=\alpha t/L^2$, for the conditions of flame passage in the silicon microchannels, we find Fo~40. These values define the transient conduction problem. Heisler charts for these values indicate that the ratio of energy transferred to the wall in a given time, say 1 second, to the maximum possible amount of energy transfer ($t=\infty$) is about 10% [[12]]. In other words, Q/Q_o where $Q_o = \rho\ c\ V\ (T_i - T_\infty) = 0.1$. Clearly, however, heat transfer from the flame to the wall is reducing the temperature of the flame, leading to extinction, indicating that flame propagation under these conditions is clearly weak.

References

[1] Fernandez-Pello, C.A., "*Micro-Power Generation Using Combustion: issues and Approaches*", 29th Int. Comb. Symp., Japan, 2002
[2] Wilcox, D.C., "*Basic Fluid Mechanics*", DCW Industries, USA, 2000
[3] Schlichting, H., "*Boundary Layer Theory*", 7th ed., McGraw-Hill Science/Eng./ Math., (1979)
[4] Glassman, I., "*Combustion*", 3rd edition, Academic Press, USA, 1996
[5] K. Maruta, J. K. Parc, K. C. Oh, T. Fujimori, S. S. Minaev, and R. V. Fursenko, "Characteristics of Microscale Combustion in a Narrow Heated Channel", *Combustion, Explosion, and Shock Waves*, Vol. 40, No. 5, pp. 516–523, 2004
[6] Ronney, P. D., "Analysis of non-adiabatic heat-recirculating combustors," *Combustion and Flame*, Vol 135, pp. 421-439 (2003)
[7] D. G. Norton and D. G. Vlachos, "A CFD study for propane/air microflame stability", *Combust. Flame*, 138, 97-107 (2004)
[8] D.G. Norton and D. G. Vlachos, "Hydrogen assisted self-ignition of propane/air mixtures in catalytic microburners", *Proc. Combust. Inst.*, 30, 2473-2480 (2005)
[9] J. Daou and M. Matalon, "Influence of Conductive Heat-Losses on the Propagation of Premixed Flames in Channels" COMBUSTION AND FLAME 128:321–339 (2002)
[10] Ferguson, C. R., and Keck, J. C. *Combust. Flame* 28:197 (1977).
[11] Incropera and DeWitt
[12] Heisler, M.P., "Temperature Charts for Induction and Constant Temperature Heating", Trans. ASME, 69, 227-236, 1947.