Homogeneous Combustion Characteristics and Flame Stabilization in Small Channels

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ABSTRACT
The push toward the miniaturization of electromechanical devices and the resulting need for micro-power generation systems with low-weight, long-life devices has led to the recent development of the field of micro-combustion. The concept behind this new field is that since batteries have low specific energy and liquid hydrocarbon fuels have a very high specific energy, a miniaturized power-generating device, even with a relatively inefficient conversion of hydrocarbon fuels to power, would result in increased lifetime and/or reduced weight of an electronic or mechanical system that currently requires batteries for power. The high energy density of hydrocarbon fuels creates a great opportunity to develop combustion based micro-power generation systems to meet increasing demands for portable power devices, micro unmanned aerial vehicles, micro-satellite thrusters, and micro chemical reactors and sensors. In this paper, the recent technological development and progress in fundamental understanding of micro-scale combustion are reviewed. Furthermore, gas-phase combustion in small channels is reviewed. Flame stabilization is contrasted to propagation and the mechanisms for stability loss are discussed. The role of key wall materials’ parameters and operation variables in flame characteristics and stability is elucidated.

Keywords: Homogeneous combustion, Flame stability, Quenching mechanisms, Flame propagation, Heat recuperation

INTRODUCTION
Recently, with the development of fabrication technologies for Micro-Electro-Mechanical System (MEMS), efforts are moving toward the integration of microelectronic and micro-mechanical systems on a single chip. The accelerometer sensors developed for automobile air bags is an example of the commercialization of such integration. Unfortunately, today’s MEMS are still relying on an external power. Therefore, there is a great need to combine the micro-machined electronic and mechanical systems with an on chip micro-power (power MEMS). The availability of efficient micro-power generators will significantly enhance the functionality of MEMS for many portable devices [1].

Furthermore, the development of advanced communication systems such as the 4G cellular phones and multi-CPU notebook computers presents new challenges to portable power generators requiring increased energy density and reduced recharge time. In addition, biomedical devices for drug delivery and artificial heart also need efficient and compact power sources. Therefore, the development of new micro-power devices with a high energy density to replace existing batteries is critical to meet the demands of technological innovations [2].

In order to increase the operational lifetime of a power device, the energy densities of the fuels and the energy conversion systems need to be examined. The most advanced currently available lithium ion batteries have an energy density of 0.2 kWh/kg [3], which is almost one sixtieth of hydrocarbon fuels (e.g. methane and diesel). In addition, the energy density of lithium battery is also one twentieth of a diesel engine (200 kW with 450 kg engine weight), and one eighth of the space shuttle main engine (SSME, 1.8 MN thrust and 730,000 kg of propellants with an exhaust gas velocity of 4400 m/s for 540 s). This comparison clearly shows that by using liquid hydrocarbon fuels, even with 10% of energy conversion efficiency, the energy density of a micro-combustor is six times higher than that of a lithium battery. In addition, it is also noticed that a liquid hydrocarbon fuel based micro-thruster will have a higher energy density than hydrazine based monopropellant rockets for satellite station keeping. With the decrease of power device, the weight of combustor chamber significantly decreases at elevated pressures. Micro-engine may have much higher energy density than that of conventional engines. Chigier et al. [4] estimated that a micro-combustor can achieve energy density up to 10 kWh/kg. In addition, micro-engines do not need long time recharging and is cheap and chemically stable. As such, a hydrocarbon fuel based micro-combustor can replace lithium ion batteries to deliver much higher specific energy density and specific power for the development of micro-electro-mechanical devices for biomedical applications, chemical sensing, telecommunication, and micro-propulsion.

In this paper, gas-phase combustion in small channels is reviewed. Flame stabilization is contrasted to propagation and the mechanisms for stability loss are discussed. The role of key wall materials’ parameters and operation variables in flame characteristics and stability is elucidated.

Flame Propagation and Stabilization
When flames (e.g., a torch) are put in narrow channels, they do not propagate through, when the gap size is below what is known as the quenching distance. As a result, confined spaces can serve as effective flame traps for safety. This earlier work was
confirmed with continuum theory that predicts that below a critical distance (in the millimeter length scale) flame propagation is infeasible. These theories, based on the competition between heat loss from the flame to the cold wall and heat generation by the chemical reaction, compare fairly well with experimental data. Quenching distances vary with fuel, pressure (as ∼1/P), and temperature (as ∼1/T^0.9).

Fig. 1. Schematic of various processes within a catalytic micro-burner. The mass and thermal processes are shown on left and right ends, respectively, for clarity; these processes indeed take place at the same location in a micro-burner.

The problem of flame stabilization (rather than of propagation) of an unignited, fuel/air mixture within a confined space was studied experimentally by Masel, Shannon, and co-workers who showed that contrary to the general belief, it is possible to stabilize flames in sub-millimeter, ceramic burners [5]. Their work focused mainly on methane/oxygen (premixed and diffusion) flames typically in 0.5-0.75 mm gaps but other fuels (propane and hydrogen) were also considered. They found a quenching distance in the range of ~2.5 mm for cold walls (500 K), i.e., when the burners were not insulated. The quenching distances were independent of the wall material. Loss of flame stability was attributed to thermal quenching. The quenching distance varied considerably with wall material when the burners were insulated (hot walls, ~1000 °C). Under these conditions, loss of flame stability was mainly attributed to radical quenching. The quenching distance decreases from ~1.5 mm for stainless steel to a very low ~0.1 mm for annealed cordierite [5], as shown in Fig. 9. Unfortunately, some of these earlier burners exhibited high temperatures leading to materials failure. The effect of wall temperature on the importance of radical recombination was independently verified in [6]. Given the effect of wall temperature and material on quenching and the fact of flame stabilization below the quenching distance, the concept of quenching diameter for flame traps may need reconsideration.

While these results demonstrated feasibility of flame stabilization within confined spaces, they, at the same time, underscored some of the challenges for sub-millimeter gaseous micro-burners. Burner insulation and thermal management are important in minimizing heat loss and mitigating thermal quenching. The choice of burner material is crucial to minimize radical quenching that dominates when walls are hot, e.g., upon ignition after the burner reaches steady state. The high temperature and proximity of flames to walls can easily cause material’s failure. Finally, instabilities have been observed over a wide range of conditions (discussed below), and under those conditions, low hydrocarbon conversion was observed.

**Homogeneous Combustion Characteristics**

There are two mechanisms for loss of flame stability: thermal and radical quenching. The thermal mechanism is the most popular and refers to heat loss from the burner walls and gases (e.g., by radiation and convection). The radical mechanism refers to diffusion of radicals from the flame to the walls followed by their recombination on walls to produce stable molecules. Radical recombination leads to loss of active combustion carriers and thus to flame retardation. The latter mechanism has been known to affect the first explosion limit of H2/air mixtures and has not been traditionally considered in the stability of large scale flames at moderate and high pressures, since flames usually lift off walls and the burner surface to volume ratio is rather small. Radical quenching has not been studied as much at the micro-scale.

Fig. 2. The role of thermal and chemical effects in micro-burner stability using a boundary layer model. (a) Stability map of premixed methane/air mixtures in terms of preheat temperature vs. coefficient of heat loss for flame propagation in a cylindrical tube. The tube radius R and the sticking coefficient, s, of key radicals are indicated in panel (a). The region under each curve indicates no propagation; conversely, the region above each curve indicates that the flame propagates. (b) Temperature contours of a typical simulation indicating a ‘cold figure’ emanating from the wall that eventually causes flame quenching (expanded in axial direction for easier viewing).

Initial experimental work in the early 2000s in micro-channels sparked a number of simulation studies that aimed at elucidating the mechanisms for flame stabilization. In a first attempt, the effect of heat and radical quenching on the stability of preheated premixed methane/air mixtures was modeled with detailed gas-phase chemistry and a simplified radical recombination mechanism in a cylindrical tube [7]. The boundary layer approximation of the governing equations was used, yielding computationally tractable parabolic equations with detailed chemistry. This approximation is reasonable for fast flows. The mixtures were preheated at various temperatures and the minimum inlet temperature for a stable flame was reported. Results are shown in Fig. 2a. The thermal and fluid slip was also studied to examine the effect of lack of thermal equilibrium and no-slip on flame stability. It was found that thermal accommodation and fluid slip are probably not as important at small scales, compared to their large scale counterparts, due to reduction of gradients (caused by fast diffusion over small length scales) in the direction transverse to the flow.

Fig. 2a shows that thermal quenching dominates at larger diameters. In fact, above a critical diameter (e.g., 1 cm), a flame is stabilized independently of the external (from the outside wall surface to the environment) heat loss coefficient due to the weak
thermal coupling of the flame with the solid. In other words, the flame is far away from the wall (located around the centerline; see Fig. 2b) that conduction of heat from the flame to the wall is too slow. Heat loss starts playing a role in flame stability when the radius is decreased below this critical value. For meso-scale and micro-scale burners, the flame can be stabilized by sufficient pre-heating of the incoming gases. In the meso-scopic range, i.e., for a radius of 1 mm and above, radical quenching plays only a secondary role. Interestingly, radical quenching plays an ever-increasing role as the diameter decreases below ~1 mm, as shown in Fig. 2a, and is the most significant mechanism for flame quenching in narrow tubes (e.g., radius of 0.1 mm). These results are in agreement with experimental observations described earlier about radical quenching being the dominant mechanism for flame quenching at critical dimensions of the order of 100 μm, whereas thermal quenching dominates at meso-scales (≥ 1 mm).

Given the importance of radical quenching at small scales, more detailed studies on this topic will be welcome. In addition, understanding the effect of wall temperature on radical quenching, suggested in experimental studies [7], will be valuable. These studies are particularly important to conduct with elliptic simulations given the profound role of wall conduction that render parabolic simulations without inclusion of heat transfer along the wall limited.

Scaling Analysis and Hierarchical Models

Given the above introductory background, a synopsis on model choice is herein given. Elliptic CFD simulations are computationally intensive. As a result, a limited number of them has addressed transients and incorporated detailed reaction mechanisms. Scaling analysis, zero-order asymptotics and hierarchical modeling provide simplified, computationally tractable models. Here an outline of simplified models is given in order to understand CFD results. Boundary layer models, applicable at high axial Peclet number [8], are an example of simpler models that capture the transverse transport phenomena in micro-burners. The diffusive terms are neglected in the axial direction in comparison to the convective term. However, without accounting for the wall energy balance, they miss important physics [9]. Gas-phase pseudo-steady state is another example of model reduction [10]. A suitable simplified micro-burner model is the pseudo-two-dimensional (2D) model, which accounts for species and energy conservation in the gas-phase (convection and chemical reaction), the continuity equation, and the energy equation in the wall. Transverse wall temperature gradients are ignored due to fast conduction in thin walls. Transverse heat transfer between the channel center and the wall is described with an effective heat transfer coefficient.

CFD simulations at select conditions can be used to develop heat transfer correlations for the pseudo-2D model. Developing these correlations is important because traditional correlations breakdown as the wall changes from being a heat source upstream to a heat sink downstream, and thus, the sign of Nusselt number is location dependent. By estimation of parameters (in this case, of correlations) of simpler models using more complex (CFD), one builds a hierarchy that can strike a balance between accuracy and computational cost. Despite the simplicity of the pseudo-2D model, very good qualitative agreement with elliptic 2D CFD simulations was found [11].

The pseudo-2D model treats the transverse heat and mass transport through lumped-parameter description (via Nusselt and Sherwood number correlations). Due to non-monotonic behavior of Nu and Sh numbers, the interaction between flame chemistry and the surface may not be reliably captured. An alternative is to solve the full elliptic model of the gas-phase flow-transport-reaction processes to derive correlations, and use these full model correlations in the pseudo-2D model with a 1D description for the solid energy balance. This results in significant savings in computational time compared to the full CFD simulations since solid thermal inertia is the slowest time scale (and hence governs the transient behavior) in the system. This may be termed as a 1D-plus-2D model; the 1D description of the solid energy balance is justified because of nearly uniform wall temperatures in the transverse direction even for low wall conductivity. For reasons not fully understood, the pseudo-2D model with even asymptotic values of the dimensionless groups (without the discontinuity related with the change in the direction of the heat flux) provides reasonable description of the full model.

Micro-burner Stability

Contrary to the general belief that more insulating walls stabilize micro-flames, the work of Norton and Vlachos clearly showed not to be the case [7]. Stability diagrams were constructed for the critical heat loss/transfer coefficient vs. material conductivity. In these and subsequent simulations by many groups, the energy balance is solved in the fluid phase within the burner and in the wall. Heat loss outside the burner is modeled using Newton’s law of cooling, with a heat loss or transfer coefficient that often lumps also radiation (this assumption is unnecessary; it simply reduces the number of heat transfer model parameters). An inverted, bell-like shape curve is found. Below such a curve, i.e., for heat losses below the critical value, a flame is stabilized upon ignition. Above such a curve, i.e., for sufficiently high heat losses, the flame cannot be stabilized. Interestingly, materials that give best stability are typical ceramics (e.g., alumina, cordierite), such as those used in the experiments of Masel, Shannon, and co-workers [5].

While low conductivity materials minimize heat losses in the transverse direction, they, at the same time, do not allow for fast heat transfer upstream needed for combustible ignition. As a result, the mixture has insufficient time to be preheated and blowout occurs. As the wall conductivity decreases, the flame temperatures become higher and the flame remains localized but drifts downstream due to insufficient pre-heating. Large transverse and axial gradients are observed even at these small scales for low conductivity wall materials. Highly conductive walls, on the other hand, dissipate heat to the environment and also longitudinally, causing the entire burner surfaces to be hot. Due to fast heat transfer in the transverse and longitudinal directions, the burner is nearly isothermal with small temperature gradients. As a result, the heat lost is substantial despite the wall temperature being moderate. The lower operating temperatures cause flame delocalization and widening of the combustion zone. As heat
losses increase, the flame temperature drops to the fuel extinction temperature and thermal quenching takes place. In summary, two modes of flame quenching occur: a spatially ‘distributed’ type for high wall thermal conductivities, thick walls, and/or low flow velocities (see below for the effect of velocity) and blowout at high velocities, low wall conductivity, or thin walls.

Fig. 3. Critical inlet velocity for self-sustained homogeneous combustion vs. wall thermal conductivity for single channel (SC, solid lines) and heat recirculating (HR, dashed lines) geometries though CFD simulations. Schematics of the SC and HR geometries are also shown. The dotted line indicates the laminar burning velocity of propane. HR expands the blowout limit significantly. SC: The parameters used are \( u_0 = 0.5 \text{ m/s}, d = 600 \mu \text{m}, b_w = 200 \mu \text{m}, \) and a stoichiometric feed; HR: the gap of the central channel is 600 μm, whereas that of both recirculating channels is 300 μm.

The inlet velocity is easily varied experimentally and controls the power input to a burner. We suggest that the shape of the temperature-velocity curve can be used to identify experimentally the dominant quenching mechanism. When increasing the inflow velocity, an increase in temperature would indicate extinction, as the dominant stability loss mechanism, and a decrease in temperature, blowout. Fig. 3 shows the critical velocity vs. wall thermal conductivity using the 2D CFD simulation (solid lines). There are two critical velocities: the lower one corresponds to extinction and the higher one to blowout. The region compounded by the two curves denotes stable combustion and the regions above the upper curve and below the lower one denote non-sustainable operation. The laminar flame velocity is also indicated with a horizontal dashed line. It is clear that flames can be stabilized for much higher flow velocities than the laminar flame speed. This enhanced flame stability stems from the heat recirculation along the burner walls. The range of flow velocities within which self-sustained combustion is feasible is fairly wide. The simple resistance model, discussed above, can rationalize these results.

**Excess Enthalpy Burners**

It is now well accepted that increasing the inlet feed temperature increases micro-burner stability. Given the large surface to volume ratio and thus the high heat loss of microsystems, heat recuperation strategies can further improve stability and energy efficiency of micro-burners. Weinberg and co-workers proposed the idea of recirculating the excess enthalpy of hot exhaust gases four decades ago [12]. This concept has since been applied in conventional-sized systems in High Temperature Air Combustion (HiTAC) and Mild combustion to reduce NOx emissions from boilers [13], often employing a porous, highly conductive solid matrix immediately upstream of the flame [14].

Single channel (SC) micro-burners are also excess enthalpy burners since the axial heat conduction through the micro-burner solid structure recirculates heat, resulting in super-adiabatic conditions and higher stability. However, micro-burner walls are also responsible for loss of heat from the combustion zone. An effective strategy for decoupling these two functions of a wall is to use insulating walls in the combustion zone and recycle the heat of exhaust gases to provide heat recirculation. Jones et al. considered various reactor designs to achieve this spatial thermal coupling for conventional-sized devices. The concept of excess enthalpy burners has been revived recently due to growing interest in stabilizing combustion at small scales and improving thermal efficiency. In this section, heat recuperation and heat recirculation strategies for homogeneous combustion are discussed.

Heat recuperation refers to temporal thermal coupling between the hot product and the cold reactant streams, achieved through periodic flow reversal in reverse-flow (RF) reactors [15]. The excess enthalpy of exit gases, stored downstream of the combustion zone in the burner solid structure, is released to the cold feed when the flow direction is reversed (since the heated region is now the inlet). This process is repeated periodically and heat recuperation is obtained through a “heat trap effect”[16]. The main requirements for heat recuperation are high gas-solid heat transfer rates and reasonably high heat capacity of the burner solid structure. Consequently, in conventional-sized burners, porous beds are required to increase the gas-solid heat transfer rates [17]. In micro-burners, the large area to volume ratio and small device sizes ensure that both conditions are met. Hence, heat recuperation is possible without any structural change to an existing micro-burner.

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number of turns. The diameter of the spiraling tubes can be kept small to enhance heat transfer, whereas the diameter of the central combustion zone can be designed independently of the heat exchange section. The depth of the SR micro-burner (inside the plane of paper) can also be varied independently.

Several groups [18] independently fabricated SR micro-burners. The diameter of the channels in the heat exchange section was sub-millimeter to promote heat transfer, whereas in the central combustion was a few millimeters to accommodate a flame. A catalyst may also be included in the combustion zone to improve burner stability and to reduce the ignition temperature. Vicen et al. tuned the equivalence ratio to manage the skin temperature of their device and were able to generate 60 mW electricity from a thermoelectric attached to their micro-burner [18].

![Fig. 4. Schematic of the Swiss-Roll micro-burner with three turns. The central section (indicated by a symbol) of the Swiss-Roll burner forms the combustion zone.](image)

Maruta et al. [19] studied the effect of micro-burner size on stability. They varied different geometric parameters and found that the stability of their SR micro-burners is most affected by the dimensions of the central combustion region. They fabricated three different planar SR micro-burners with different diameter and depth of the central combustion region. Their results are summarized in Fig. 5. The combustion zone in the S-geometry was 3.5 mm in diameter and 6 mm depth. Although the spiral channels isolate the combustion zone, significant heat losses occur through the top and bottom plates. Insulating the cover plate enhances micro-burner stability. The W-type geometry was similar to the S-type, except the diameter of the combustion section was 12.7 mm. Clearly, smaller combustion zones are preferable. In comparison, increasing the depth of the channels from 6 to 15 mm (D-type) improves stability significantly. In conclusion, the SR geometry improves stability, and insulation of the reaction zone from ambient enhances stability.

Some of the early modeling efforts used simplified models to qualitatively understand SR micro-burner performance. Weinberg et al. [20] used global energy balances to demonstrate feasibility of excess enthalpy concept, whereas Ronney [21] improved their model to predict stability limits by assuming the flame to be located between the inlet and the recirculation channels and solving the heat transfer problem. Ju and Choi [22] proposed a model with flames propagating in opposite directions. These models indicate SR burners to be more stable than straight channel burners, and that improvement in stability is greatest for lower wall conductivities.

Temperature and conversion profiles in SR burners have also been studied. At low inlet velocities, close to or lower than the laminar flame speed, the flames are located upstream of the combustion zone. The SR heat exchanger then acts as a net heat sink [4]. When the velocity is increased, the flame gets anchored in the central combustion zone. Further increase in the velocity pushes the flame downstream and into the recirculating section. Blowout is reached soon thereafter. Flame propagation into the inlet and the recirculating sections can be avoided by reducing the diameter of the heat exchange section or using a catalyst in the central combustion zone. In either case, thermally isolating the central combustion section and low conductivity wall materials ensure greater stability of the SR micro-burner.

**Micro-burner Geometry**

![Fig. 5. Effect of (a) gap size and (b) micro-burner length on the critical values of heat loss coefficient vs. solid thermal conductivity for stability of homogeneous micro-burners. Inlet velocity is 0.5 m/s and stoichiometric propane/air mixture is considered. (a) Larger channels can sustain combustion at higher heat losses for highly conductive materials, whereas smaller channels are more stable for very insulating materials. (b) Combustion is typically less stable for longer reactors due to higher total heat loss.](image)
self-sustained combustion. Size effects are more profound for methane than for propane combustion.

Increasing the reactor length shrinks the region of self-sustained combustion, due to increased heat losses through the reactor solid structure. Due to the localized nature of homogeneous combustion, the residence time effect caused by varying burner length does not appear to play any role [11].

The effect of inlet manifold has not been studied extensively. Unpublished results from our group show that the effect of inlet manifold can be rather weak at moderate velocities [23, 24]. Specifically, we compared a premixed feed condition for propane/air mixtures with “diffusion flames”, i.e., separate inlet manifolds for fuel (propane) and air. At moderate velocities, premixed and diffusion flames showed similar characteristics. Due to small transverse scales, diffusion flames attain a premixed character over short distances, giving similar behavior to premixed flames. On the other hand, flames were not sustainable at higher velocities for separate feeds (but were sustainable for a premixed feed). However, further work is required to quantify this effect.

CONCLUSION

In this paper, homogeneous micro-burners were reviewed. Three distinct zones were found, including a pre-heating zone, a combustion zone, and a post-combustion zone. Flames are fairly localized, especially when low conductivity walls are used, with high fuel utilization. An important challenge is stabilization of flames against heat loss and radical recombination at walls. Flames may extinguish or blowout depending on flow conditions, wall material conductivity, etc.

- Heat transfer along the wall is crucial for pre-heating of cold reactants to ignition and flame stabilization. The competition between pre-heating and heat loss renders materials with medium wall conductivity, such as common ceramics, to be the best in terms of stable operation. The wall thickness is another important design variable: thinner walls reduce the heat flux along the wall and behave like lower conductivity materials; conversely, thicker walls transfer heat upstream and behave like higher conductive materials. Heat recirculation along the wall may result in super-adiabatic temperatures and enables operation above the flame speed of a freely propagating flame. Simple models can explain this physics as long as the conduction along the wall is captured. In addition, wall conductivity and thickness affect temperature uniformity in the wall and thus the prospect of mechanical failure. Highly conductive walls and/or thick walls result in nearly isothermal systems, whereas low conductivity and/or thin walls cause large temperature gradients and hot-spots.

- Excess enthalpy burners have also been reviewed. Heat recirculation can happen either in a steady state mode or by periodic switching of the flow, giving qualitatively similar results.

- Aside from steady state operation, several dynamic features have been reported, including cellular structures, non-symmetric patterns, and repetitive ignitions and extinguitions. Dynamics is inherently complex to understand and will require further work. In addition, closer comparison of experimental data to modeling results is desirable.

- Micro-scale burners stabilize flames too close to walls and result in high wall temperatures, reducing the burners’ life time. This becomes progressively less of a problem as the gap size increases to the meso-scale regime. Aside from the gap size and wall thickness, the length of a burner is also important since it determines the area for heat loss. Understanding how the different phenomena vary, as one transitions from the meso-scale to the micro-scale, will require further study.

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