Film Combustion in Small Cylinders

Trinh K. Pham, Derek Dunn-Rankin, William A. Sirignano
University of California, Irvine, CA, USA

Corresponding author, T. K. Pham: tkpham@uci.edu

Introduction

Small-scale devices that require one to ten watts of power to operate, such as cell phones and portable music players, can be effectively powered by batteries or other electrochemical energy sources that rely on surface reaction mechanisms (e.g. fuel cells). In contrast, devices such as miniature unmanned air vehicles and distributed heaters that need on the order of tens to thousands of watts of power call for energy sources that possess much higher specific power. Such a demand can be met by developing portable combustion systems that run on liquid hydrocarbon fuels. Liquid fuels inherently contain high energy per mass and combustion can release this energy at very high rates. Furthermore, at the millimeter to centimeter scale, large surface areas relative to volume suggest that liquid films are a feasible and perhaps more effective alternative for optimum fuel vaporization than are more traditional forms of fuel injection[1].

Concept

Figure 1 illustrates the concept of a miniature liquid film combustion chamber. Swirling air entering a cylindrical chamber serves dual purposes: generating and stabilizing a liquid film that begins as point sources of fuel entry, and providing a mechanism whereby the flame can be stabilized. The resulting film also has two functions: supplying a surface area large enough to produce necessary fuel vaporization rates, and buffering the chamber walls from excessive heat flux. The combination of swirl and film effects results in a combustion chamber within which a stable flame can burn, relying on fluid dynamics to furnish desired mixing rates while maintaining relatively cool walls.

Experiments: Discussion and Conclusions

Although preliminary experiments employed a Pyrex glass chamber, cost and ease of manufacturing quickly led to the construction of several metal chambers. In particular, the majority of experiments up to this point were performed in the metal combustion chamber displayed in Figure 2[4-7]. Constructed from a steel tube 9.5 mm in diameter and 70 mm long, air from a calibrated ball rotameter is injected tangentially near the base of the chamber at two points at average bulk airflow rates between 1.5 and 2.4 m/s with corresponding cold Reynolds numbers of 1070 to 1500. Heptane fuel is injected into the chamber at two points downstream of and parallel to the air via two stainless steel capillary tubes. Each capillary is connected to a syringe pump that provides fuel at a rate of 9.7 mg/s. Resulting equivalence ratios vary between 1.4 and 2.2. In Figure 2, the air and fuel injection tubes are shown staggered for illustrative purposes only. Additionally, the figure displays planar sapphire windows through which the flame can be partially observed.

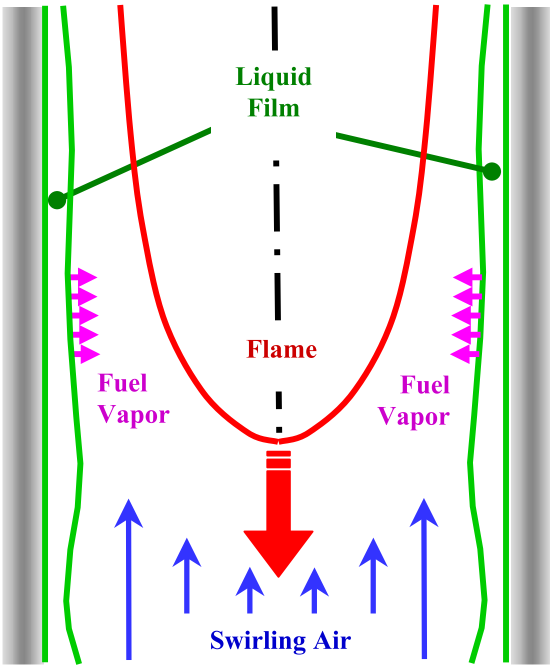


Figure 1: Sketch of film combustion concept.

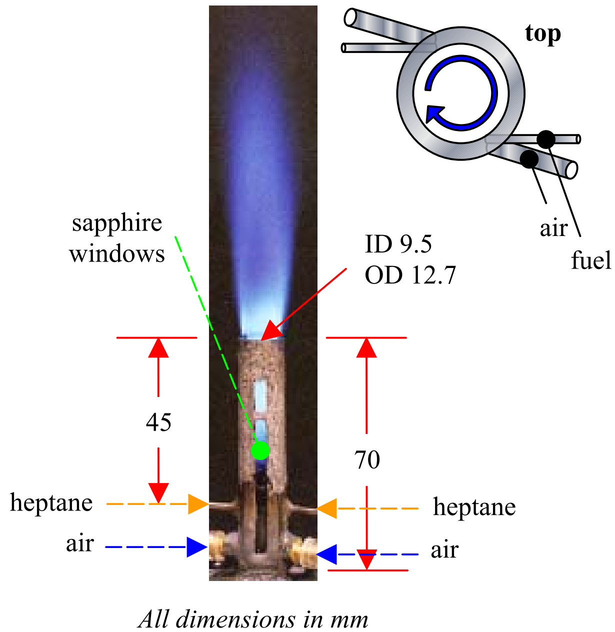


Figure 2: Schematic of combustor geometry and experimental setup.

Figure 3 depicts stable heptane flames at various flow rates in the steel chamber. Study of these and similar flames have illustrated several flame features of interest:

1. Airflow rates need to be fast enough to generate necessary swirl for film and flame stabilization, but must be slow enough to provide a stable anchor point for the flame where the highly strained transitional inlet flow competes with flame propagation into the chamber. Excessively high airflow rates result in flame extinguishment both by pushing the flame too far away from the fuel source and by increasing stress on the flame anchor. Exceedingly low airflow rates produce a pool at the bottom of the chamber where the flame burns with a long plume, heating up the chamber walls to a higher temperature than do swirling internal flames. Transition from stable internal flames to both unstable external and pool flames is evident by the oscillating nature of the flames, as illustrated by Figure 4.
2. Within the range of stable airflow rates, steady injection of fuel is necessary to impede oscillations in the flame and any resulting instabilities. Also, the amount of fuel must be large enough to keep the walls cool, but cannot exceed the flame's vaporization capabilities. In all experiments, the combustor must be operated in rich conditions since the flame does not burn stably under stoichiometric or lean conditions.
3. Long flame plumes indicate insufficient mixing. Implementation of swirl vanes is possible, but previous work demonstrated that the flame is very sensitive to swirler geometry[2]. The swirler's role as a flameholder and whether it will provide higher swirl and better mixing is uncertain. In the tangentially swirling case, jet interaction from transitional flows may be generating high local turbulent mixing. Increasing the number of jets may further improve mixing by amplifying jet interaction and turbulence. Adding a bluff body can enhance mixing by introducing recirculation, which does not currently appear to exist.

Figure 3: SLR camera photos of heptane flames at, from left to right, 1.8 m/s ($\phi = 1.9$, Re = 470), 2.0 m/s ($\phi = 1.7$, Re = 540), 2.2 m/s ($\phi = 1.5$, Re = 600), and 2.4 m/s ($\phi = 1.4$, Re = 660).

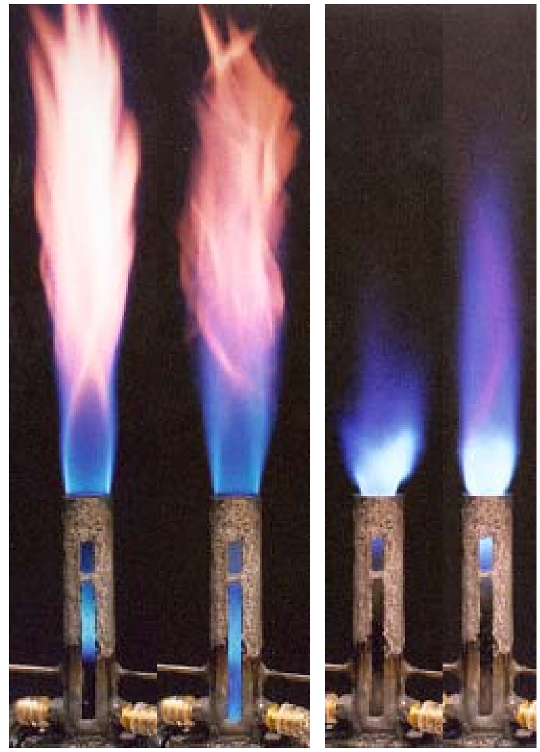
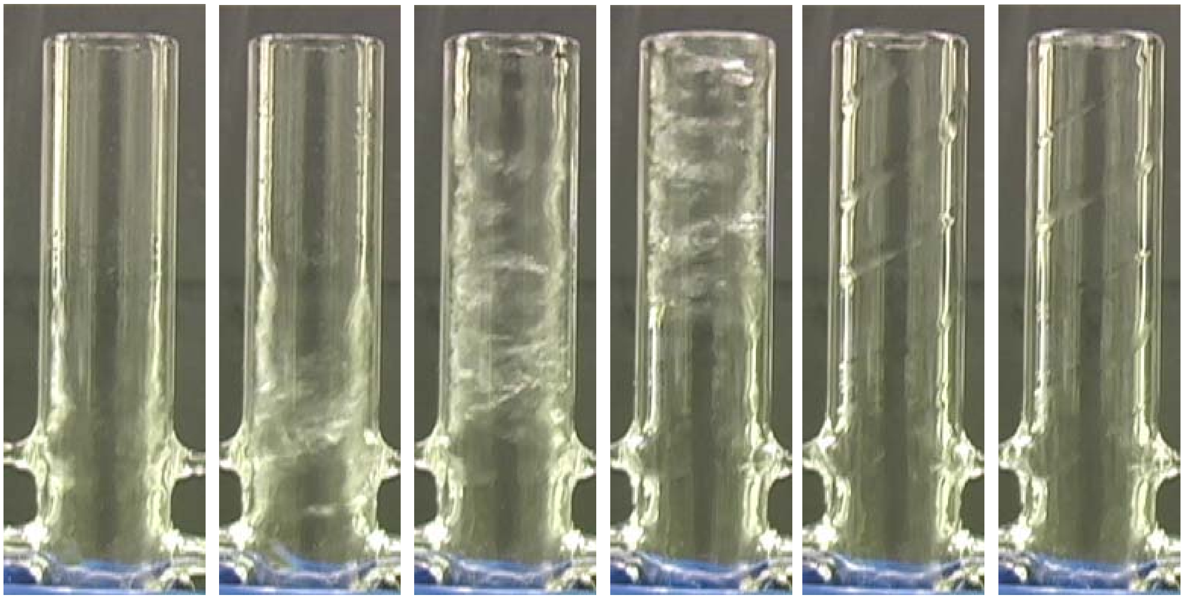


Figure 4: Oscillations in heptane flame anchor location and plume length for airflow rates of 1.5 m/s (left) and 2.7 m/s (right).

4. For airflow rates that permit stable burning within the metal chamber, either very thin or no films are present in the upper portion of the chamber. As is evident from Figure 5, which shows liquid films in a quartz chamber that has the same dimensions as the metal chamber, airflow velocities 2.5 m/s and above generate thicker films in the chamber exit region. These flows correspond to conditions where either unstable flames exist or flows are too fast to sustain a flame at all. This means that films must be thin enough to vaporize easily in the presence of a flame. Otherwise, excessive heat losses lead to flame quench.
5. Conduction effects play an important role in flame stability. Figure 6 demonstrates that chamber wall temperatures are highest at the exit where fuel films cannot reach and that when the flame is in close proximity to the wall, heat appears to conduct down towards the base of the chamber. This transfer of heat from the chamber exit towards the preignition regions significantly influences film vaporization rates where the chamber walls are relatively cool and films are thick. Conduction therefore affects flame stabilization since the absence of upstream heat transfer leads to the presence of excess fuel and eventual flame extinguishment, as is apparent from Figure 7, which shows that for the same conditions where a stable flame exists in the metal chamber, flames are unstable or non-existent in the quartz chamber. This same phenomenon was observed in previous studies of flames burning from liquid pools in cylinders[8-9]. For stable burner operation within insulating materials, introduction of a bluff body or temporary heat source may be required, as in prior experiments with a Pyrex chamber. Alternatively, a chamber material that is transparent but more thermally conductive than quartz (i.e. sapphire) would allow for stable flames over a broader operating range as well as permit visual observation of the entire flame.



1.5 2.0 2.5 2.9 3.4 5.3

air flow rate (m/s)

Figure 5: Heptane films for a liquid flow rate of 9.7 mg/s and increasing airflow rates from left to right.

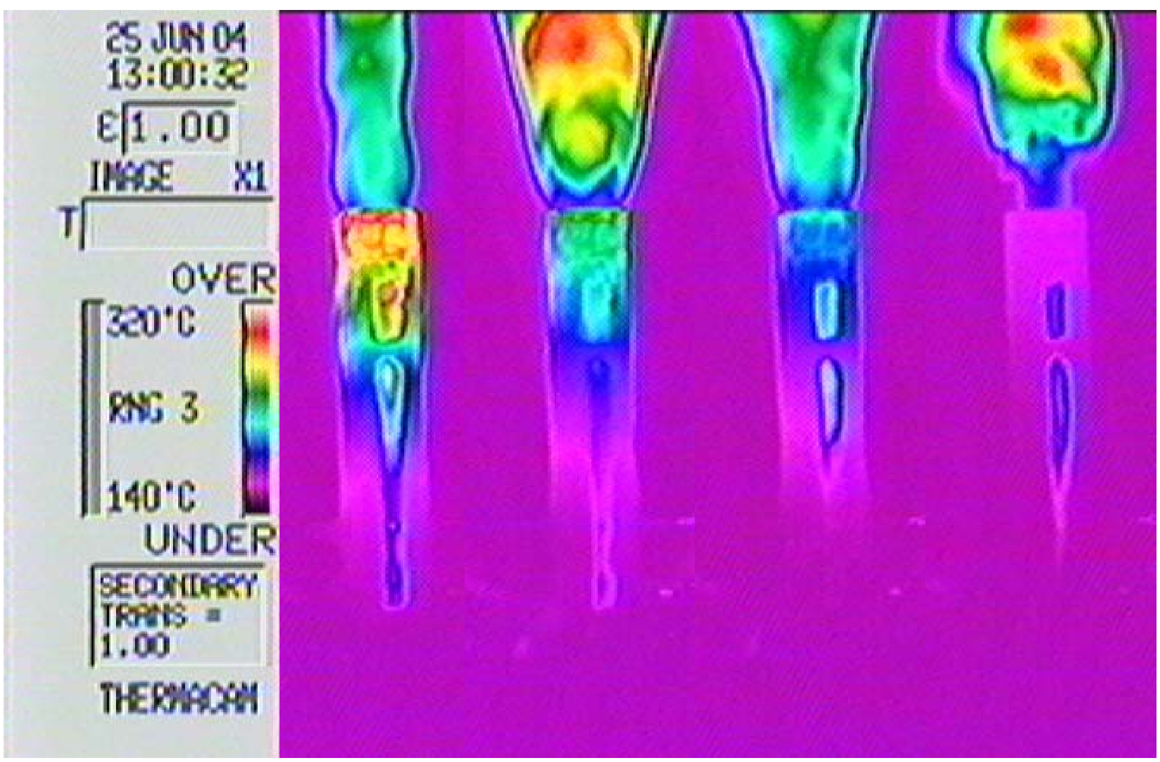


Figure 6: Infrared images of heptane flame in metal chamber for increasing airflow rates from left to right.

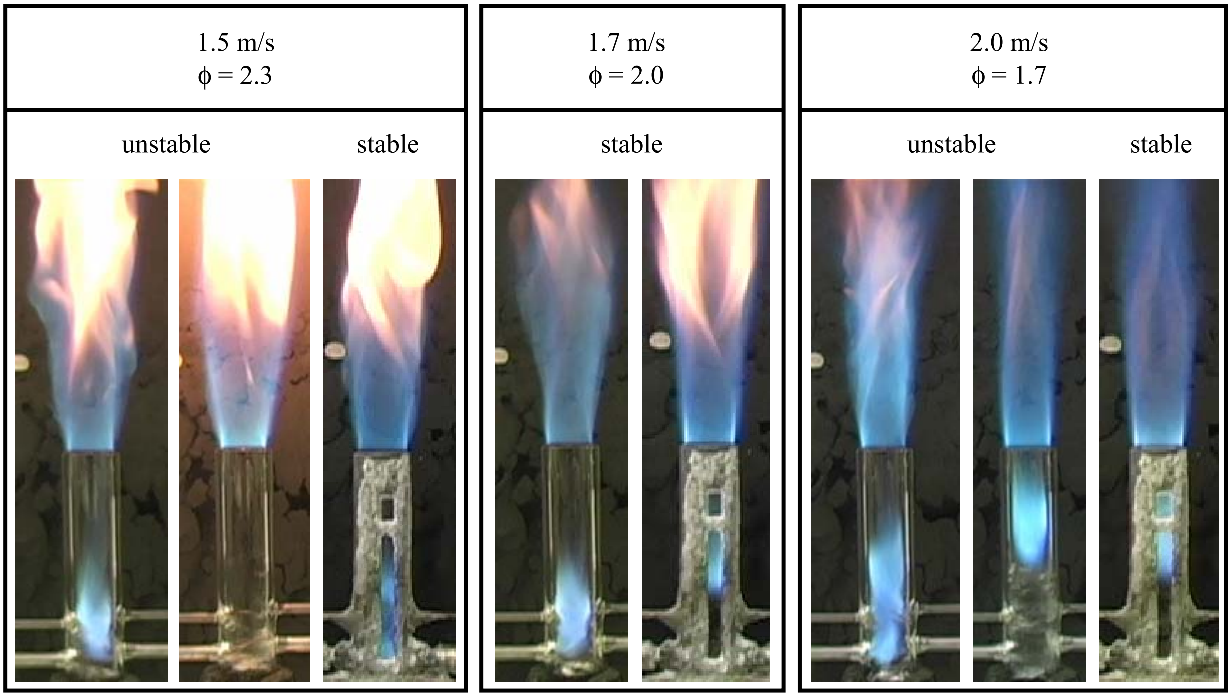


Figure 7: Flame comparison between quartz and metal chambers.

Acknowledgments

The authors would like to thank the National Science Foundation (NSF) and Program Director Linda Blevens for their support under grant CTS-02121663 as well as Dr. Carlos Fernandez-Pello, Dr. David Walther, and their lab group at UC Berkeley for their help and for the use of their equipment and facilities during the filming of the infrared videos.

References

1. Sirignano, WA; Dunn-Rankin, D; Strayer, B; Pham, T. "Miniature Combustor with Liquid-Fuel Film," *Proceedings of the Western States Section/Combustion Institute Fall Meeting*, October 2001, Salt Lake City, UT, USA.
2. Pham, TK; Dunn-Rankin, D; Sirignano, WA. "Further Developments on Miniature Scale Liquid-Fuel Film Combustion," *Proceedings of the Western States Section/Combustion Institute Spring Technical Meeting*, March 25-26, 2002, San Diego, CA, USA
3. Sirignano, WA; Pham, TK; Dunn-Rankin, D. "Miniature Scale Liquid-Fuel Film Combustor," *Proceedings of the 29th International Combustion Symposium*, July 21-25, 2002, Sapporo, Japan.
4. Pham, TK; Dunn-Rankin, D; Sirignano, WA. "Combustion Efficiency of a Miniature Fuel Film Combustor," *Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute*, March 16-19, 2003, Chicago, IL, USA.
5. Mehring, C; Pham, TK; Dunn-Rankin, D; Sirignano, WA. "Computational Investigation of a Miniature Liquid-Fuel-Film Combustor," *Proceedings of the Western States Section/Combustion Institute Fall Meeting*, October 20-21, 2003, Los Angeles, CA, USA.

6. Pham, TK; Mehring, C; Dunn-Rankin, D; Sirignano, WA. “Numerical Study of a Miniature Liquid-Fuel-Film Combustor,” *Proceedings of the Western States Section/Combustion Institute Spring Technical Meeting*, March 29-30, 2004, Davis, CA, USA.
7. Pham, TK; Amade, NS; Dunn-Rankin, D; Sirignano, WA. “Liquid film combustion in small cylindrical chambers,” *Proceedings of the Fourth Joint Meeting of the U.S. Sections of the Combustion Institute*, March 20-23, 2005, Philadelphia, PA, USA.
8. Nakakuki, A. “Liquid fuel fires in laminar flame region,” *Combustion and Flame*, 23(3): 337–346, 1974.
9. Nakakuki, A. “Heat-Transfer in Small-Scale Pool Fires,” *Combustion and Flame*, 96(3): 311–324, February 1994.