

A Unique High Speed Camera System for Studying Pulsating Dynamics of Premixed Flames

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Abstract—A unique camera system, capable of high speeds (1KHz), is described for the study of pre-mixed flame dynamics and other low light level, high-speed phenomena that emit visible electromagnetic radiation.

WHEN A SMALL PLANE reaches cruising altitude, the pilot adjusts the throttle, reducing the fuel until the engine makes a “putt-putt-putt” sound, indicating that the combustion of the fuel-air mixture is oscillating. The pilot then reduces the fuel until the sound becomes uniform. In making this adjustment, the pilot is setting the operating point just inside the lean-burn limit, where the combustion is most complete and where the engine operates most efficiently.



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These pulsations are characteristic of most technologically interesting and important combustion systems, such as gas turbine combustors or jet engines. It is a general property that a combustion system does not abruptly extinguish; rather, it makes transitions from steady regimes to first, periodic, and, then, chaotic dynamics.

Over the past 15 years, we have conducted experiments on instabilities in premixed flames stabilized on a circular porous plug burner in a glass combustion chamber at low pressure. Almost all of our studies have concentrated on the dynamics of cellular flames¹ in which the uniform flame front forms a circular pattern of rings of brighter, hotter cells that are separated by darker, cooler cusps and folds. The rings undergo transitions to states in which (1) entire rings² uniformly rotate, (2) entire rings undergo modulated rotation, (3) individual cells abruptly and sequentially change their angular position in a ring,³ and (4) entire rings⁴ rotate very slowly (~ 1 deg/sec), speeding up and slowing down with their own distinctive dynamics. The dynamics are relatively slow (< 7 Hz), and they can be analyzed using standard video techniques. The domain of cellular flames is heavy hydrocarbon/air mixtures. Although this system is scientifically fascinating, it is not technologically interesting.



Figure 1. The camera body containing a 480 x 420 CCD array, made by Redlake Imaging.

When air is replaced by oxygen, the cells no longer appear. Instead, the entire flame front pulsates in modes with their own distinctive spatial and temporal characteristics, much like those of a vibrating drumhead. The modes are analogous to oscillations in engines and combustors. Typical frequencies are 35 Hz, which is above both the flicker frequency of the eye (~ 13 Hz) and the Nyquist frequency of videotape (15 Hz). The central problem in studying such dynamics in experiments on real engines and combustors, which are technologically interesting, is the difficulty in obtaining optical access to the combustion region.

The intensity of the flame front is reduced at low pressure in direct proportion to the number of molecules. It is further reduced near the extinction limits because the number of combustion reactions diminishes. The intensity per frame is also reduced as the operating speed of the camera is increased. A frame rate of 250 Hz produces approximately seven frames per cycle, which is usually sufficient to identify the spatial characteristics of the dynamics.

We have constructed a unique camera system at a cost of \$70,000 to study the dynamics of these pulsating modes. The

camera body, shown in Fig. 1, contains a standard CCD array capable of speeds of 1,000 Hz.

A micro-channel plate, shown in Fig. 2, is coupled to the CCD through double-lens optics (partially visible on the right). The array absorbs the incoming light from the collection lens which images the flame front on the array. A number of electrons proportional to the intensity are emitted, and they are amplified and impinge on a phosphor. The chemiluminescence of a premixed flame front is primarily in the infrared, due to vibrational excitations, and the blue/violet, due to electronic excitations. The emission spectrum of the phosphor is concentrated in the visible part of the spectrum where the CCD array has a greater efficiency. This system can produce images of varying intensity by continuously adjusting the variable amplifier voltage of the micro-channel plate. The optical system has a maximum gain of 100K, with a typical loss of 40 percent in the coupling optics, resulting in a net gain of 60K.

There are some, but relatively few, camera systems with image intensifiers attached. Our system obtains its uniqueness because it supports simultaneous, synchronized data collection from (up to) 16 differential or 32 single-ended electronic sensors, shown in Fig. 3, from National Instruments breakout boxes BNC 2110 and BNC 2115. These sensors can be attached to flow meters, photo-detector outputs, electric field perturbations, and other features in need of measurement. This difficulty with synchronization is the principal reason that there have been only a handful of experiments in which video data are correlated with electronic data.

Research support from ISSO enabled us to repair the micro-channel plate, which experienced a freak accident of unknown origin that shorted out the sensor and made the images unintelligible. Our entire research project would have collapsed had not ISSO provided a substantial fraction of the \$11,000 needed to make the appropriate repairs. We are now studying the dynamics of two-armed spirals on circular burners and counter-propagating hot spots on annular burners.

References

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Publications

Gorman, M. and R. Brockman. "Counter-Propagating Fronts, Hot Spots, and Other Dynamic Structures of Hydrocarbon-Oxygen Premixed Flames on an Annular Burner," *Chaos.* (Submitted Feb. 2006.)

Gorman, M. and R. Brockman. "Two-Armed Spiral States of



Figure 2. A micro-channel plate image intensifier with part of the coupling optics visible on the right. A cable (not shown) connects the intensifier to a power supply.



Figure 3. National Instruments breakout boxes for synchronized electronic data collection.

"Methane-Oxygen Flames on a Circular Burner," *Chaos.* (Submitted Feb. 2006.)

Gorman, M. and S. Perrollier. "Unusual Pulsating States of Hydrocarbon-Oxygen Premixed Flames on a Circular Porous Plug Burner," *Chaos.* (Submitted Feb. 2006.)

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