

Dynamic Response of a Non-Premixed Flame to Electric Field Forcing

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This paper describes the dynamic response of a small flame, as measured by its temporally varying heat release (CH chemiluminescence), to the forcing induced by an electric field. We find that the chemiluminescence behaves very much as a simple second order system (e.g., as a damped spring-mass) under these conditions. The electric field acts on the flame ions, creating an ion wind that produces a body force on the gas. It takes time for this ion wind to set up and affect flame behavior, and it is this time delay that accounts for the relatively slow system response. Nevertheless, with a linear second order model of the system, it is possible to design a fast controller.

Introduction

Active feedback combustion control is a relatively new and promising concept for achieving and maintaining optimal performance of combustion systems. Control has been applied to reduce thermoacoustic instabilities (e.g., Candel and Poinso, 1992), to manipulate oscillating combustion systems (e.g., Neumeier and Zinn, 1995), to adjust flame luminosity (e.g., Strayer, et al., 1998), and to control combustion efficiency and emissions (e.g., St. John and Samuelsen, 1994). Acoustic actuators (i.e., loudspeakers), pulsed fuel jets, pulsed air jets, and fuel/air mixing have all been used to modify the combustion process in response to some measured output. In virtually all of the above cases, the control operates on the combustion system, which includes both the flame and the enclosure in which it burns. Often, for example, the sensed quantity is acoustic emission, which, while excited by periodic heat release from the flame, depends strongly on the enclosure geometry. In addition, the actuation in these systems is

decoupled from the flame by a substantial convective time delay. For example, changes in fuel flow rate will not produce a change in the heat release until the fuel pulse reaches the reaction zone, which is a location relatively distant from the valve or actuator modulating the fuel. The complication of the convective time delay in combination with the fundamentally nonlinear nature of the combustion process has,

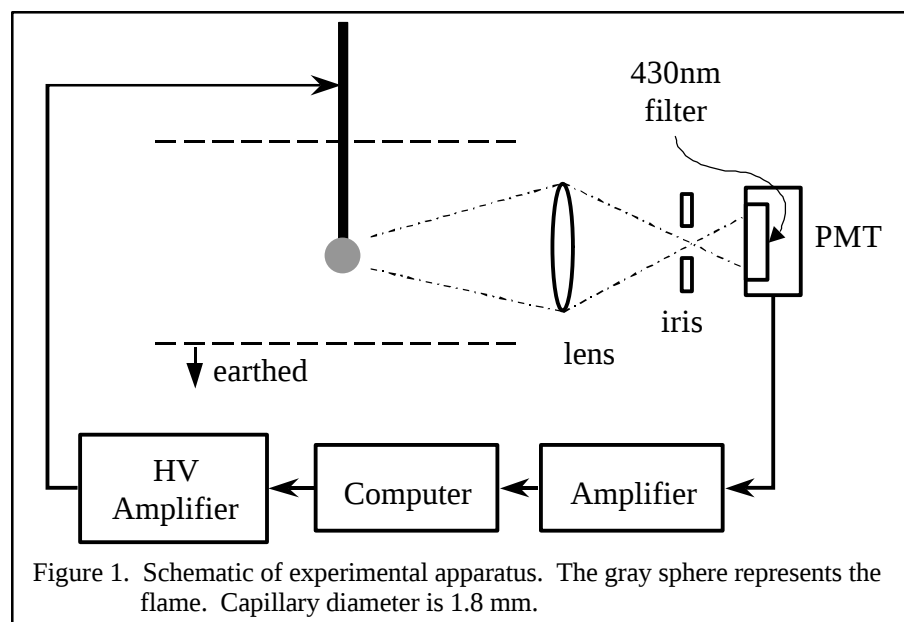


Figure 1. Schematic of experimental apparatus. The gray sphere represents the flame. Capillary diameter is 1.8 mm.

to date, confounded attempts to manipulate flames using classical control methods. When implemented, therefore, combustion control more often relies on adaptive techniques. One exception to the adaptive rule is the theoretical work of Annaswamy, Ghoneim and co-workers (e.g., 1995a; 1995b), but this approach has not yet been verified experimentally. The work described in the current paper is intended to illustrate the view of the flame as a dynamical system (essentially independent of an enclosure, but not independent of the surroundings), and to demonstrate the control of that dynamical system using a classical control approach. One novel feature of the work is that it uses an electric field as the actuator. Because the electric field acts on the flame ions directly, there is no convective time delay in the system (though there is a delay between the actuation and the response while the ions are set in motion).

Experimental Apparatus

The experimental apparatus is shown in Figure 1. The system consists of a small (1 cm diameter) non-premixed flame fed by methane through a narrow (1.8 mm diameter) capillary. Two wire mesh electrodes sandwich the flame. A PMT and lens combination collects CH chemiluminescence at 430 nm (± 5 nm), and an amplifier feeds this signal to the computer. Besides monitoring CH emission, the computer also runs the control law analysis, and outputs the control signal to the high voltage power supply. The electric field between the mesh electrodes acts on the ions in the flame and induces them to accelerate briefly before they collide with their neutral gas neighbors. The net result of these collisions is a steady ion wind that produces a body force counter to buoyancy. With proper care, the ion wind force can precisely cancel buoyancy, producing a local condition very similar to that found in a zero-g environment (Carleton and Weinberg, 1987, Strayer, et al., 2000). This point of balance condition is accompanied by a decrease in gradients and a reduction in the intensity and luminosity of the flame.

Open Loop Results

Figure 2 shows how the small capillary flame responds to an increasing electric field strength between the mesh electrodes. The upper trace is the ion current and the lower trace is the CH chemiluminescence signal. The ion current increases with potential to a plateau, at which point the system is saturated so the flame cannot increase its ion production rate. The increase in ion current beyond the plateau comes from the onset of secondary ionization, where fast moving primary ions

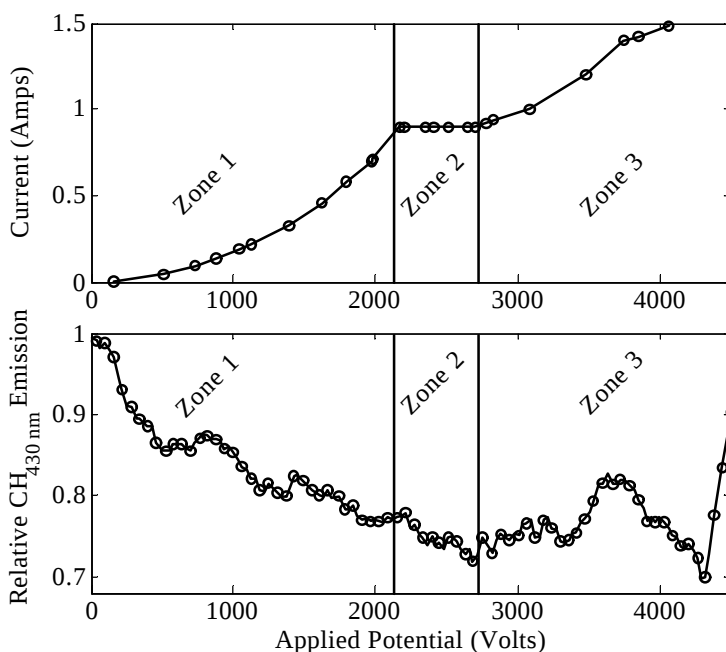


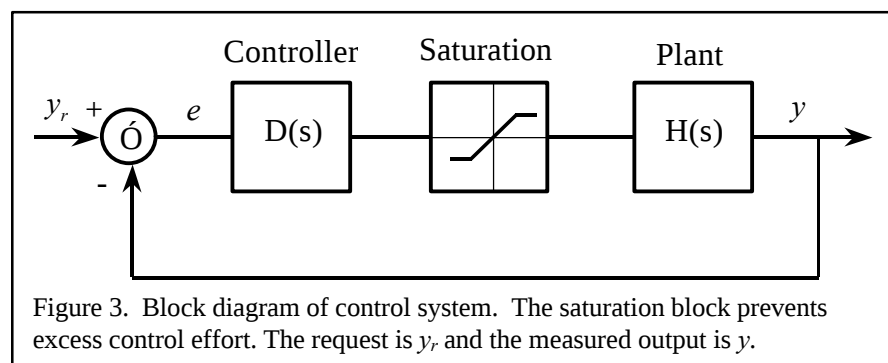
Figure 2. Response of the flame's chemiluminescence to applied potential. Operation in Zone 3 is forbidden to prevent instability in the control system.

produce additional charged particles through collision. The CH chemiluminescence signal decreases with increasing potential to the ion current plateau where it then begins to increase again with increasing potential. This minimum CH signal corresponds closely to the point of balance described above. Unfortunately, this minimum feature is a control complication since it means that in some cases increasing the potential will decrease CH while in others a decrease in potential is what is needed. Initially, we avoid the difficulty by restricting our control to electric fields less than those needed to cross the minimum CH point.

Figure 2 shows essentially steady-state results, but to implement a dynamic control, we are interested in the flame's dynamic response to electric field actuation. For these tests, the small capillary flame is subjected to a sequence of impulses (i.e., instantaneous changes in electric potential) and the CH response is recorded. We find that the CH signal follows very closely the behavior of a standard second order system. That is, the flame acts like a damped spring-mass oscillator, except that there is a time lag from the time of electric field application to the start of the flame response. Since there is no convective delay, this lag must be related to the onset of the ion wind needed to influence the flame. Incidentally, the existence of this lag indicates that the primary action of the electric field on the flame is fluid dynamic, not chemical, since changes in flame chemistry would occur at a much shorter timescale.

Control Law

The control law is implemented in the Matlab environment using Simulink. Since in this experiment the open loop studies show that the flame acts as a simple second order system, an array of control models are possible. After exploring a range of sophisticated strategies, a basic PID control was found to produce the best performance. More complex, but theoretically more



accurate, methods (e.g., Kalman filters) could not accept the noise levels of the actual experimental data. Figure 3 is a block diagram of the control system. The elements are described in their Laplace transform formulation, with the dynamic flame model being the plant.

All of the elements in the control system are standard blocks in the Simulink environment, making the construction and modification of the controller and model relatively straightforward. The controller is designed to minimize the error signal e between the desired level of CH signal y_r and the measured level y . While the structure of the controller can be predicted to some extent theoretically, the gains within the controller are adjusted manually to achieve best behavior. The saturation block is needed to prevent unstable behavior, particularly near the minimum CH signal location. Recall from Figure 2 that the CH signal decreases with increasing voltage to the left of the minimum and the reverse to the right. Without knowing where this minimum is, the controller can easily be confused to try and increase voltage in an attempt to decrease luminosity when the opposite is actually occurring. Additional model elements can be added to the system

to improve this behavior, but for the current study, we restrict operation to the low voltage side of the minimum.

Closed Loop Results

Figure 4 shows the theoretical performance of the control law when the model flame is asked to track a parabolic intensity profile. This figure demonstrates the ideal control performance and would be accurate so long as the flame behaves precisely as the second-order behavior predicts. Naturally, the flame behavior is not captured perfectly with the low-order representation, and Figure 5 shows the actual performance when the controller is applied to the real flame. Despite the fluctuations in the signal, this figure shows that a non-adaptive control can be effective under the conditions presented. The eventual goal is to further refine the model and controller so that the system can simulate various g-loadings on a flame in order to simulate and study transient buoyancy-induced behavior.

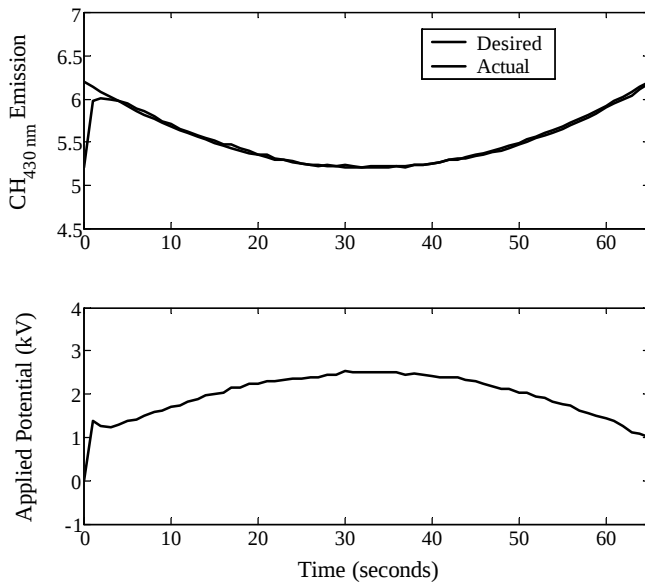


Figure 4. Comparison between desired trajectory and controlled trajectory using a second order system model with a time lag.

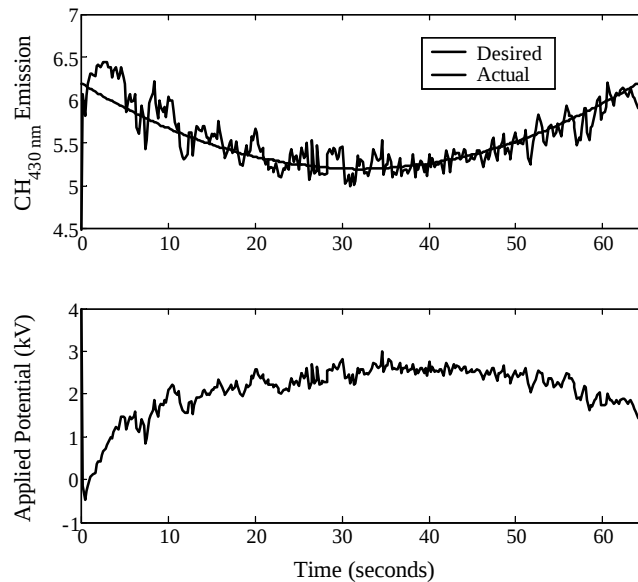


Figure 5. Comparison between desired trajectory and measured trajectory with the flame under active control.

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