# Behavior of Non-Premixed Flames as Electrically Active Components in a High-Voltage Circuit

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## 1 Introduction

Active control of combustion is challenging because there are few actuators with sufficient power to overcome the effects associated with the significant energy release associated with flames. The control leverage afforded by adjusting the fuel stream has so far been the most effective for this purpose. Naturally occurring flame ions allow a control option via external electric fields, and we have studied electric flame control using this mechanism. During the course of these control studies, we have identified the voltage-current characteristics of small non-premixed flames and have used these characteristics directly in a circuit analysis of a flame acted on by a high-voltage grid. In particular, this paper describes how electric fields acting on flame ions affect the local convective environment and produce a very characteristic electrical behavior that can be analyzed as part of an electrical circuit for control in order to produce a desired flame response in terms of its ion production.

## 2 Combustion Control

Active feedback control is an interesting technique in order to obtain optimal performance from combustion systems. Combustion has always represented a substantial challenge for control because, along with complicated physical and chemical coupling, flames themselves can be considered nonlinear dynamic interfaces. From the discovery of fire, people have attempted to control and regulate it, according to their needs. In more recent days the desire for combustion control has not changed, though it has been pursued with different approaches. Control has been applied to reduce thermodynamics instabilities (Candel and Poinsot, 1992), to adjust flame luminosity (Strayer, et al., 1998), to control combustion efficiency and emissions (St. John and Samuelsen, 1994) and in many other applications (Neumeier and Zinn, 1995). All the studies above have used similar approaches to the problem of control, acting on the combustion system in response to a measured output. What differs among them is the choice of the output, as well as the actuator chosen to affect the flame (e.g., loudspeakers, fuel/air mixing, etc.). The intrinsic complexity of the combustion process, combined with the dynamics of the actuators discussed above, implied that using classical control techniques would be inappropriate. Moreover the methods used to control the flame presented a common negative peculiarity, namely a time-delay between the actuator action and its effect on the flame. For

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example changes in fuel flow will not produce variations in flame characteristics until the flow change reaches the flame, which can take a considerable length of time relative, for example, to the characteristic time for the growth of combustion instabilities. The presence of this delay is another source of nonlinearity in the combustion system that further complicates the control system design. As previously analyzed by Strayer and Dunn-Rankin (2001), an innovative mechanism to control the flame could be an imposed electric field. Because the electric field acts on the flame ions directly, there is virtually no associated time-delay between the field change and the start of ion motion. This earlier study showed, however, that there is a delay between the actuation of the electric field and when the ion motion creates a demonstrable effect on the flame's convective environment. Such an electric actuator could also be easily driven by an electric signal and is perfectly suited to the needs of a computer implemented control system. Consequently, we have chosen to use an electric field as the actuator for our combustion system that is a small diffusion methane/air flame. Prior studies have examined the flame behavior and the reaction intensity has been characterized by the overall ion current collection (Papac, 2005, and Papac et al., 2005). In this paper we consider the flame as an electrical element in a circuit, which we can then control using classical approaches. Despite the experimental setup and the peculiarities of this combustion system, the actuation and control techniques presented and developed can be useful in a much broader array of combusting environments.

## 3 Apparatus description

The flame and the equipment used to manipulate it are shown in Figure 1. The actuator is composed of two copper meshes above and below the flame, and an electric field occurs between them. The upper mesh is supplied by a High-Voltage Amplifier, whereas the lower one is connected to the ground. The actuator can be easily driven by an electrical signal generated from a computer, once the controller has been implemented. The electric field can be considered, to a reasonable approximation, a unidimensional vertical field, included between two parallel electrodes (the upper mesh being the positive pole and the other one the negative one), with an ion source in between (the 1 cm diameter flame).

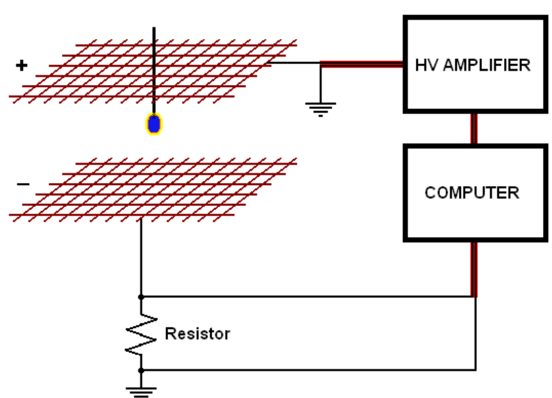


Figure 1. Schematic of experimental apparatus.

The diffusion flame under analysis uses methane gas as the fuel burning with atmospheric air. The small flame is fed through a vertical capillary (1.6 mm diameter) disposed between the two meshes. The overall ion current sensor is simply made up of a resistance (1 M) placed between the lower mesh and the ground. The voltage sensed at the ends of the resistor is proportional to the ion current, according to the relationship V = RI. This resistance raises the lower electrode voltage insignificantly above true ground relative to the high voltages used. For typical microamp ion currents at several thousand volts between the mesh electrodes, the lower plane is one the order of one volt above ground. In order to operate in a controlled environment, the actuator/flame system is placed in a closed acrylic box, with an air inlet at the bottom.

## 4 Results

The combustion of hydrocarbon fuels generates intermediate species which include charged ions. A body force can be applied to them through electric fields. The ions do not accelerate but transfer their additional momentum to the neutral gas during the collision that follows each mean free path transit. According to previous works (Papac, 2005), the prevalent ion species measured in all hydrocarbon flames are $CH_3^+$ , $H_3O^+$, $CHO^+$ and $C_3H_3^+$. In the case of methane burning, there is a large concentration of $CH_3^+$. The flame is not directly responding to the movement of flame ions, but to the ion wind that these ions produce, in the surroundings of the flame, as they try to accelerate through the neutral gas on their way to their terminating electrode (Lawton and Weinberg, 1969). Therefore, a properly aligned electric field can influence the net body force in the combusting region, so contrasting the natural convection and affecting the flame behavior. In our experiment the electric field that produces the actuation is downward oriented, with positive ions driven toward negative electrode (the lower mesh). An interesting preliminary examination

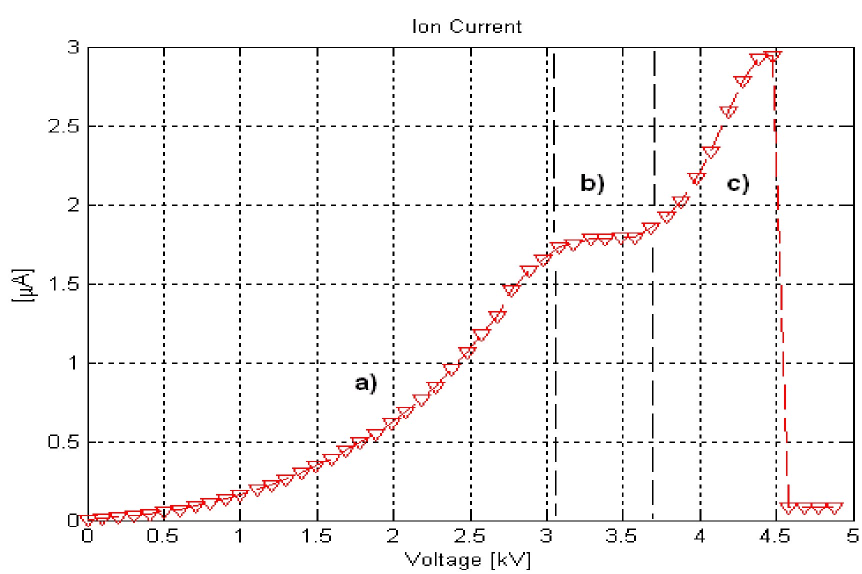


Figure 2. Voltage-current characteristics of a small non-premixed methane flame showing three primary regions of electrical behavior. The final drop in current occurs at blowoff.

would be the collection of flame current, for different applied voltages, as a view of flame response to actuation. In agreement with previous works, the relationship between voltage and ion current shows three distinct regions (see Figure 2). For low field strengths the current increases monotonically with applied voltage (subsaturation region), until it reaches a plateau, where no rise in ion current is observed for increasing potential (saturation region); finally a further voltage increase produces a new current rise (supersaturation region) until the flame blows off. More specifically: a) Subsaturation: an increasing ion current flux from the flame is observed. This region is characterized by a quadratic increase in ion current; b) Saturation: the rate of ion generation is the same of ion removal due to the electric field, so any increasing voltage does not produce a further rise in ion current. Hence, a plateau region is observed; c) Supersaturation: the increasing ion wind changes the local convective environment sufficiently to increase the local reaction rate and temperature. The ion production increases concomitantly. By considering these regions as providing a voltage-specific resistance (i.e., by taking V/I), it is possible to describe the flame as an active electrical element.

## 6 Acknowledgments

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## 7 References

Candel, S.M., Poinsot, T.J. 1992. “Combustion Instabilities Coupled by Pressure Waves and their Active Control”. Pages 1277—1296 of: 24th International Symposium on Combustion. The Combustion Institute.

Lawton, J., Weinberg, F.J. 1969. “Electrical Aspects of Combustion”. Clarendon Press. Oxford.

Neumeier, Y., Zinn, B.T. 1995. “Active control of combustion instabilities using real time identification of unstable combustion modes”. Pages 691-698 of: Proceedings of the 4th IEEE Conference on Control Application. Albany, NY, ( September).

Papac, M.J. 2005. “Electrical aspects of gaseous fuel flames for microgravity combustion and combustion control”. Ph.D. Dissertation., Mechanical and Aerospace Engineering Department, University of California, Irvine.

Papac, M.J. and Dunn-Rankin, D. 2005. “Canceling buoyancy of gaseous fuel flames in a graviational environment using an ion driven wind”. Proceedings of the 4th Interdiscplinary Transport Phenomena in Microgravity and Space Sciences Conference. Tomar, Portugal, August.

St. John, D., Samuelsen, G.S. 1994. “Active, optimal control of a model, industrial, natural gas-fired burner”. 25th Symposium (International) on Combustion. The Combustion Institute.

Strayer, B.A., Dunn-Rankin, D., Jabbari, F.J. 1998. “A comparison between frequency and amplitude modulated adaptive control of a non premixed flame. 27$^{th}$ Symposium (International) on Combustion, pages 1247-1254.

Strayer, B.A. and Dunn-Rankin, D. 2001, “Response of a Non-Premixed Flame to Electric Field Forcing,” 18th International Colloquium on the Dynamics of Explosions and Reactive Systems, Seattle, Washington, July 29--August 3.