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Behavior of a small diffusion flame as an electrically active component in a high-voltage circuit

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ABSTRACT

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 an alternative control option via external electric fields, and this mechanism has been investigated, in experimental analysis of small non-premixed flame acted on by a high-voltage grid. During the course of these studies, the *voltage–current* characteristics of air–methane flames has been identified. This article 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, using the ion production as a sensor for overall reaction intensity and a fairly simple PID control algorithm to effect the desired flame response.

1. Introduction

Feedback control is an interesting and not completely exploited technique in order to obtain optimal performance from combustion systems. Combustion has always represented an interesting challenge for control because, along with complicated physical and chemical coupling, flames themselves can be considered nonlinear dynamic interfaces. Consequently, the potential for and thereby useful combustion has been an important research topic.

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 [1], to adjust flame luminosity [2], to control combustion efficiency and emissions [3] and in many other applications [4]. 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, many of the methods used to control the flame presented a common challenge, namely a time-delay between the actuator action and its effect on the flame. For 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 combustion systems that further complicates the control system design (even though solutions to this drawback were developed, see for example [5]).

The flame itself presents some electrical aspects [10,14]. Discovered at the end of the 16th century by W. Gilbert (1544–1603), physician to Queen Elizabeth I, these electrical peculiarities of flames have affected the studies of several physicists (e.g., Volta, Thomson and many other) but, despite this early beginning, it was only along the second half of the 20th century that the subject came into prominence, thanks to several potential applications.

Electrical behavior of flames depends on the presence of ions in the flame and in exhaust gases, notably when a hydrocarbon is the fuel. A body force can be applied to the neutral gas field through electric fields acting on the ions.

In this situation the prevalent ion species likely to be dominant in the electrode space are CH_3^+, H_3O^+, CHO^+, and $C_3H_3^+$, since they are common to all hydrocarbon flames and are among the first ions to form, and consequently the first ones to be affected and moved away by the electric field. Even though their relative concentration may vary with the fuel type, usually H_3O^+ is the predominant ion (due to its abundance, longer lifetime and lower mobility), even

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if in some circumstances, like methane being the fuel, CH_3^+ and CHO^+ may be present in concentrations larger than usual. On the other side, nearly all of the corresponding negative charge is carried by free electrons.

In accordance with Lawton and Weinberg, the flame ions are deeply related to flame properties. In fact, the concentration and rates of generation of ions closely follow the trend of the rate of heat release; the temperature reaches a maximum in the same region. In this way, the flame performance can be measured by collecting the overall ion current, thus representing the flow of electric charge carried by all the flame ions, which are moved by the electric field imposed.

As previously analyzed by Strayer and Dunn-Rankin [6,13] 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. The 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, in the current work an electric field has again been chosen as actuator for a small diffusion *methane/air* flame. The overall ion current is used as the sensor of the flame behavior, which, according to prior studies [7,9,8]), characterizes the reaction intensity. The flame itself has been considered as a dynamical system that has been identified through a classical control approach, analyzing the system response to different inputs. Then a PID regulator, based on a simple flame model, has been used to close the feedback loop in order to actively control the combustion process. Although demonstrated on a particular experimental setup, the actuation and control techniques presented and developed can be useful in a much broader array of combustion environments.

2. Experimental set-up

The flame and the equipment used to manipulate it are shown in Fig. 1. A vertical capillary (inner diameter 1.35 mm, outer diameter 1.5 mm) feeds downwards a small diffusion methane/air flame burning between two planar gauze electrodes. The fuel rate is in the range of 20–60 ml/min (see Fig. 5). The two horizontal electrodes are arranged above and below the flame (two square grids 20.4 cm wide, placed at a distance of 6.8 cm), so that an electric field occurs between them. The upper mesh is supplied by a High-Voltage Amplifier, driven by an electrical signal generated from a computer, whereas the lower one is connected to the ground. The voltage between the grids can climb up to several thousand volts. 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 the negative one. They represent the *actuator* affecting the flame. An ion source, which is the flame in this case, is placed in between. The presence of a conductive capillary does not compromise the unidimensional approximation, since non-linear modifications of the field only occur very close to the tip/flame [7,9].

With the electric field applied, positive ions in motion through the air gap neutralize at the cathode plane, where the current is measured. The overall ion current *sensor* is simply made up of a resistance (1 MΩ) 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 Ohm's law $V = RI$. 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 only of the order of few volts above ground. A capacitor (5 nF) in parallel with the resistor acts as a first-order low-pass filter to eliminate electrical noise from the system.

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.

The choice of actuator and sensor implies an intrinsic compatibility, since both of them are electrical devices which involve electrical quantities.

3. Flame behavior

Forced by the electric field, the ions try to accelerate through the neutral gas on their way to their terminating electrode. In this situation they transfer their additional momentum (induced by the electric field) to the neutral molecules during the collisions that follows each mean free path transit [10]. This produced the so called "*ion wind*".

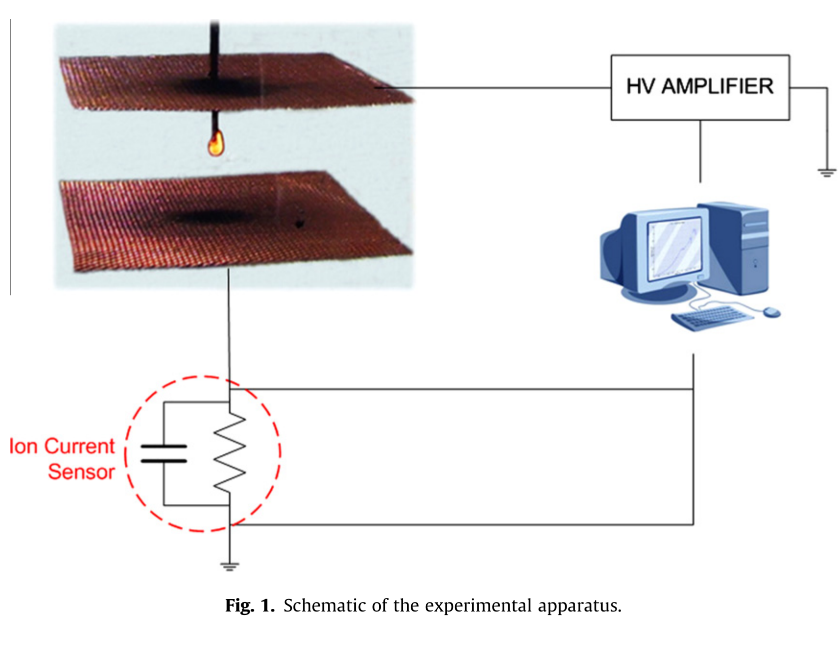

Fig. 1. Schematic of the experimental apparatus.