

Feedback Combustion Control Using Chemi-Ionization Probe in Supersonic Flow of Combustion Products

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DOI: 10.2514/1.43809

The results of the present work demonstrate feasibility of feedback combustion control using a chemi-ionization current sensor placed in a supersonic flow of combustion products. Operated in the saturation regime, the ionization sensor (Thomson probe) removes nearly all electrons from the flow and therefore acts as a global chemi-ionization detector. The results show that a relation between the equivalence ratio in the combustor and the chemi-ionization current in the $M = 3$ flow can be used to maintain the equivalence ratio at the desired value. The experiments have shown that using different target values of the chemi-ionization current in the feedback control program enforces transition from near-stoichiometric to fuel-lean and from fuel-lean to near-stoichiometric conditions in the combustor. The experiments have also demonstrated that the feedback control system can counter external perturbations, which either increase or decrease the equivalence ratio in the combustor and bring the fuel–oxidizer mixture composition back to the specified values. The combustion feedback control system based on a Thomson chemi-ionization probe is simple and straightforward and can be easily adapted for practical applications.

I. Introduction

MAINTAINING stable combustion at conditions minimizing major pollutant emissions, such as NO_x and CO, as well as overcoming various combustion instabilities are among the main objectives of combustion control. In particular, NO_x and CO emissions in hydrocarbon–air flames at fuel-lean conditions strongly depend on the equivalence ratio Φ and usually follow opposite trends, with NO_x concentration increasing and CO concentration dropping as Φ is increased [1]. Although lower flame temperature in fuel-lean mixtures results in lower NO_x emissions, it may also prevent complete oxidation of CO and hydrocarbon species, which would result in incomplete combustion [1]. Operating a combustor at fuel-lean conditions also considerably increases the risk of a flame blowout. Lean blowout is marked by a series of events in which the flame is repeatedly detached from the flameholder before blowing out completely, which may occur over several seconds [2,3]. Therefore, operation at lean conditions requires a flame-sensing/combustion-control system that would be able to maintain the combustion process at the desired equivalence ratio producing minimum pollutant emissions, detect the onset of flame blowout, and prevent it. The main objective of the present paper is to demonstrate feasibility of combustor operating-point control using a global chemi-ionization sensor placed in a high-speed flow of combustion products.

Previously, various types of lean-flame-blowoff sensors have been used for this purpose, including high-bandwidth pressure transducers, diode laser absorption sensors, optical emission sensors, and flame chemi-ionization sensors. An extensive review of these and other diagnostic techniques is given in [1]. The use of pressure transducers in a nonlaboratory environment is limited by their cost and fragility. Both diode laser absorption and optical emission measurements (mainly line-of-sight-integrated) require optical access to the combustor. Diode-laser-based absorption

sensors for in situ species concentrations and temperature measurements appear quite promising. However, their accuracy is limited by weak absorption strength in the visible and near infrared, which requires a long optical path, as well as by an adverse effect of flow turbulence and mechanical vibrations on optical alignment [1]. Note that optical access windows may need film cooling and purging to avoid solid particulate (soot) deposit, which may strongly affect window transmission [1,4]. This problem becomes especially critical for methods relying on absolute emission measurements. Self-absorption due to optical thickness may also become a significant issue for some emission bands. However, it has been previously shown that equivalence ratio in the combustor can be calibrated and controlled using chemiluminescence emission from $\text{CH}(A^2\Delta \rightarrow X^2\Pi)$ and $\text{OH}(A^2\Sigma \rightarrow X^2\Pi)$ bands [4–6]. Docquier et al. [4,5] developed a multiwavelength chemiluminescence (MWC) sensor based on CH/OH emission intensity ratio measurement in a premixed high-pressure methane–air flame. An MWC sensor maintains the equivalence ratio in the combustor by sending a control signal to a mass flow controller in the fuel delivery line. Thiruchengode et al. [2] used $\text{OH}(A^2\Sigma \rightarrow X^2\Pi)$ chemiluminescence to detect lean-blowout precursor events and to control the fuel injection pattern inside a premixed methane–air swirl-stabilized dump combustor.

Compared with chemiluminescence, chemi-ionization measurements are relatively simple and appear to have fewer limitations. Most of them involve current measurements between two biased electrodes placed in the combustor. In spark-ignition engines, spark plug electrodes can be used for this purpose and data can be collected through a spark plug cable. Chemi-ionization ignition sensing has been widely used in spark-ignition automotive engines to detect misfire, knocking, and flashback in a cycle-ignition process [1,7]. Feasibility of using chemi-ionization sensors, instead of pressure transducers, for engine performance analysis has also been studied in a homogeneous-charge compression-ignition engine [8]. The dependence of chemi-ionization current on the equivalence ratio in lean-hydrocarbon flames has been shown to be close to linear [1,9,10], which suggests that it can be used to control the equivalence ratio in a combustor. Finally, our recent results [10] show that chemiluminescence (CH and C_2 emission) in ethylene–air flames is closely correlated with the chemi-ionization current measured in the flow of combustion products at the same conditions. This suggests that both chemiluminescence and chemi-ionization measurements can be used for combustion control, with the latter approach being more attractive for practical applications due to its low cost and simplicity.

Presented as Paper 1056 at the 46th Aerospace Sciences Meeting and Exhibit, Reno, NV, 7–10 January 2008; received 13 February 2009; accepted for publication 6 October 2009. Copyright © 2009 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved. Copies of this paper may be made for personal or internal use, on condition that the copier pay the \$10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0748-4658/10 and \$10.00 in correspondence with the CCC.

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Operating-point control using flame chemi-ionization has been previously demonstrated in a propane burner where the chemi-ionization current feedback signal was used to maintain the burner at an equivalence ratio of $\Phi = 1$, using a microcomputer-driven step motor [9]. Recent work also suggests the feasibility of using chemi-ionization sensing and feedback control in high-pressure combustors of gas turbine engines [11,12]. The major difference of the present work from previous combustion control studies using chemi-ionization is that in the present approach the chemi-ionization sensor is placed in the high-speed combustion-product flow rather than in the combustor. This precludes the electric field in the sensor from affecting the flame stability as well as prevents exposure of the sensor electrodes to high temperatures in the combustor, thereby reducing the effect of thermionic emission. Finally, the chemi-ionization probe used in the present work (Thomson probe) can monitor the electron density in the entire flow rather than at a specific location in the combustor, thereby acting as a global ionization sensor.

II. Experimental

The experimental setup used in the present work is similar to our previous experiment [10] and is discussed there in greater detail. Briefly, the experimental apparatus, shown in Fig. 1, consists of a combustor followed by a converging-diverging nozzle designed for a $M = 3$ exit flow. Downstream of the nozzle is a supersonic test section through which combustion products exhaust into the vacuum system. The oxidizer, a 20%O₂–80%Ar mixture, enters the combustion chamber through a 1-in.-diam delivery line connected to the back plate of the combustor, as shown in Fig. 1. The oxidizer flow is choked using a sonic choke plate, with the orifice diameter of 4.5 mm, inserted into the delivery line. The fuel, ethylene, is delivered through a $\frac{1}{4}$ -in.-diam line and is injected into the combustor through a 1.0-mm-diam choked orifice, as shown in Fig. 1. The fuel-oxidizer mixing occurs in the 2-cm-diam and 4-cm-long circular channel in the combustor back plate, as shown in Fig. 1. Using choked flows allows independent variation of fuel and oxidizer flow rates as well as prevents flow rate oscillations at the conditions when the combustor pressure becomes unstable. The fuel and oxidizer mass flow rates are calculated from the known orifice areas and stagnation pressures upstream of the chokes using the compressible choked-flow equation. In the present experiments, the baseline mass flow rate of a stoichiometric fuel-oxidizer mixture is $\dot{m} = 9.6$ g/s.

The 6-cm-long combustor has a rectangular cross section (5 cm width, 1 cm height). The fuel-oxidizer mixture in the combustor is ignited by three spark plugs arranged in an isosceles triangle, as shown in Fig. 1. The spark plugs are connected to a high-voltage dc power supply (Glassman, 5 kV, 2 A) and are individually ballasted ($R_s = 10$ k Ω). The dc power supply voltage is $U_{PS} = 2$ kV. After dc arc discharges are initiated in the spark plugs, the voltage and current in each spark plug are $U_s = U_{PS} - IR_s = 1$ kV and $I_s = 100$ mA.

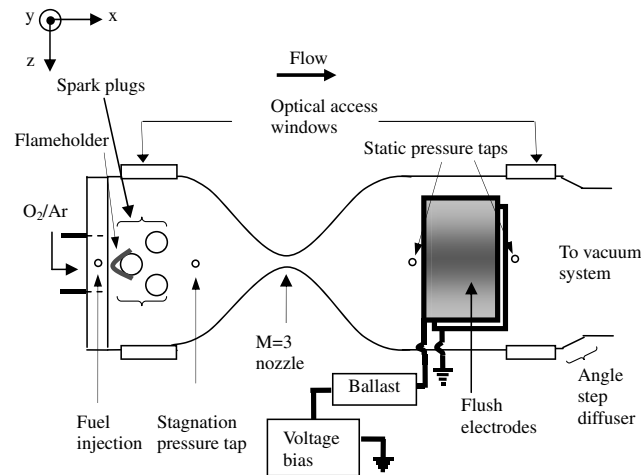


Fig. 1 Schematic of experimental setup (top view).

A V-shaped copper-plate flameholder is located upstream of the spark plugs, as shown in Fig. 1. The flameholder stabilizes the flame after the spark plugs are turned off. The combustion chamber also acts as a plenum of the aerodynamically contoured converging-diverging $M = 3$ nozzle. The side walls of the nozzle are the contoured walls. The nozzle height remains constant, $h = 1$ cm, in the subsonic part up to the throat. The nozzle throat cross section is $A^* = 1 \times 0.82$ cm. Downstream of the throat, the top and the bottom walls are diverging at a 1° angle each to provide boundary-layer relief. The combustor Mach number, estimated from the subsonic-area ratio of the nozzle, $A/A^* = 6.1$, using quasi-one-dimensional compressible-flow theory is $M \approx 0.1$ (flow velocity $u \sim 30$ m/s at $T = 300$ K and $u \sim 80$ m/s at $T = 2000$ K).

Downstream of the nozzle is a rectangular cross section of supersonic test section that is 4 cm wide and 6.8 cm long. The test section is equipped with two rectangular optical-access magnesium fluoride windows and a rectangular copper electrode, 4-cm-wide and 6.8-cm-long, flush-mounted in the top wall, as shown in Fig. 1. The electrode is insulated from the grounded test section using a mica ceramic housing and is used for chemi-ionization current and electron density measurements. In the present experiment, the electrode also acts as a chemi-ionization sensor for feedback control of the equivalence ratio in the combustor. The grounded test section acts as the second electrode. The electrode can be biased to moderate voltages (up to a few hundred volts) using a separate low-current dc power supply (Thorn EMI 3000R, 0–3 kV, 0–5 mA). The electrode is connected to the power supply through a ballast resistor $R_e = 0.747$ M Ω , as shown in Fig. 1. The current between the electrode and the test section is determined by measuring the voltage drop on the ballast resistor R_e using a Tektronix P6139A high-voltage probe. Typically, the voltage applied to the electrode is much lower than the breakdown voltage at the present conditions. Therefore, the applied voltage does not generate any charged species in addition to chemi-ionization of the flow in the combustor. Downstream of the supersonic test section is an angle step diffuser. The combustor/nozzle/test section/diffuser assembly is attached to a vacuum system connected to a 1200 ft³ dump tank pumped out by an Allis-Chalmers 1900 ft³/min rotary-vane vacuum pump. In the present

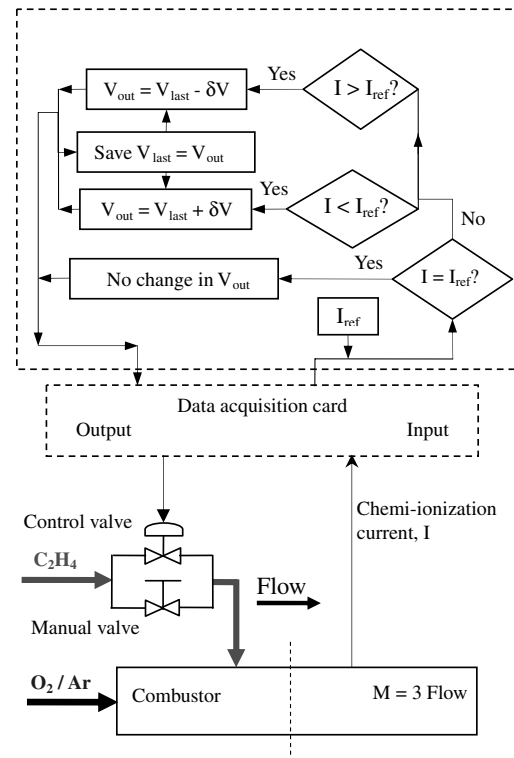


Fig. 2 Combustion feedback control schematic. Input signal is chemi-ionization current measured in the $M = 3$ flow. Output signal controls fuel mass flow rate through the control valve.

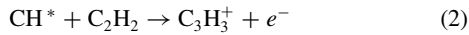
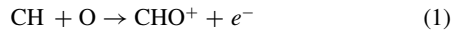
experiments, the combustor pressure after ignition is $P_0 \approx 1$ atm and the supersonic test section pressure is 12–15 torr. Assuming that complete combustion occurs in the nozzle plenum [10], this corresponds to a Mach number in the test section of $M = 3.1$ – 3.2 .

Figure 2 shows the schematic of the feedback combustion control system. The input signal from the high-voltage probe, proportional to the chemi-ionization current, is acquired by a National Instruments data acquisition card and is analyzed by LabVIEW software, as shown in Fig. 2. The sampling frequency of the data acquisition card is 2 kHz (i.e., the chemi-ionization current is acquired every 0.5 ms). The current signal is averaged using a running average over 250 data points (125 ms). If the averaged chemi-ionization current I is less than the target (reference) current I_{ref} , the output (control) voltage generated by the data acquisition card, V_{out} , is increased by a small increment δV , and if I is greater than the reference current, the control voltage is reduced by the same amount. The control voltage increment used is $\delta V = 12$ mV unless $|I - I_{\text{ref}}| < 5 \mu\text{A}$, in which case it is reduced to $\delta V = 5$ mV. This reduces control-signal oscillations at small deviations of chemi-ionization current from the target (reference) value. The control signal generated by the card, V_{out} , is used to operate an actuator valve in the fuel delivery line (see Fig. 2). The actuator valve (ETI Systems, VA-21 series) incorporates a microprocessor-controlled dc motor coupled with a metering valve. Since the valve turn angle is proportional to the control signal, $\alpha = 180^\circ \cdot V_{\text{out}}$ and $V_{\text{out}} = 0$ – 2 V, the fuel flow rate and the equivalence ratio in the combustor are varied proportionally to the reference current I_{ref} . The fuel delivery line is also equipped with a manual valve bypassing the actuator valve, as shown in Fig. 2.

III. Results and Discussion

The present experiments have been conducted using a 20%O₂/80%Ar mixture as oxidizer and C₂H₄ as fuel. In the stoichiometric C₂H₄/O₂/Ar mixture, steady flame was ignited and sustained in the combustor. At these conditions, $P_0 \approx 1$ atm and $\dot{m} = 9.6$ g/s, the flame temperature was inferred from CH(A²Δ → X²Π) emission spectra from the combustor, $T_0 = 2000 \pm 200$ K [10]. The run time did not exceed several seconds, to prevent overheating of the combustor, which was not actively cooled. As discussed in our previous work [10], Fourier transform infrared absorption spectra of combustion-product samples demonstrated nearly complete combustion at these conditions. In stoichiometric ethylene–air and propane–oxygen–argon mixtures at the same mass flow rate, the flame was unstable and was repeatedly blown off by the fast flow entering the combustor ($u \sim 30$ m/s) and reignited as long as the spark plugs were operating. At these conditions, turning the spark plugs off resulted in the flame extinguishing.

Ionization in the combustor is created by chemi-ionization reactions in the flame [13], such as



Because of a very low ionization fraction of the flow, $\sim 10^{-9}$ [10], electrons and ions generated in the combustor do not have time to recombine in the nozzle, and the flow of combustion products in the $M = 3$ section remains ionized. When no voltage bias is applied to the electrode placed in the supersonic test section (see Fig. 1), the weakly ionized flow of combustion products remains quasi-neutral. When dc voltage bias is applied to the electrode, both the electrons and the ions are removed from the flow by the applied field, although electrons are removed faster because of their higher mobility. This generates electrical current between the biased electrode and the grounded test section. As long as the applied voltage is lower than the breakdown voltage, the induced current is entirely due to the removal of charged species (electrons and ions) from the ionized flow. In other words, the applied field does not produce any ionization, and the current is sustained by chemi-ionization in the combustor (nozzle plenum). This type of a non-self-sustained electric discharge between two plane electrodes separated by an ionized gas is known

as Thomson discharge [10,14–16]. A Thomson probe has been previously used to measure the rate of ion generation in hydrocarbon flames [17].

When the applied voltage is sufficiently high (but still below the breakdown threshold), the electrons are removed from the supersonic ionized flow at the same rate they are brought to the test section by the flow, resulting in current saturation. Basically, the saturation current is equal to the flux of electrons through the test section. Note that unlike a Langmuir probe, a Thomson probe is designed to remove electrons from the entire ionized flow. Therefore, at saturation, the electron density in the flow can be inferred from the current [10]. Further voltage bias increase would result in electrical breakdown (i.e., additional ionization by the applied field), which dramatically increases the current [10]. In the present experiments, the voltage was kept below the breakdown threshold, and current voltage characteristic of the Thomson discharge was measured up to the breakdown point (see Fig. 3). A well-pronounced saturation plateau at the voltage bias of $U_e = 200$ – 300 V demonstrates that nearly all electrons are removed from the flow long before breakdown occurs at $U_e > 400$ V. This shows that up to $U_e \sim 300$ V, electron impact ionization does not contribute to the measured current. Detailed discussion and results of kinetic modeling of the Thomson-probe operation can be found in our previous work [10].

Figure 4 shows a typical time-resolved Thomson-probe current trace in a flow of C₂H₄/O₂/Ar combustion products, at the equivalence ratio of $\Phi = 1$ and electrode bias of $U_e = 300$ V. Two curves plotted in Fig. 4 correspond to the raw current signal, measured by an oscilloscope, and the current averaged by the data acquisition system using a running average over a 125 ms sampling

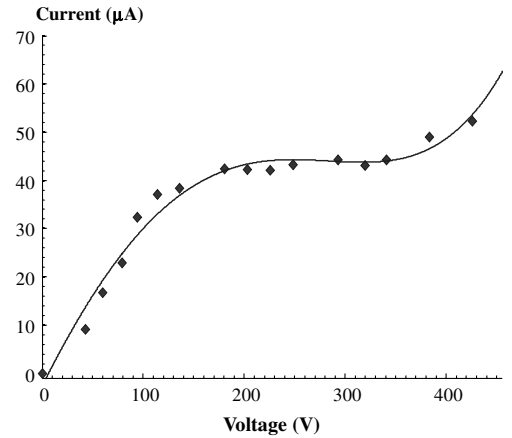


Fig. 3 Current voltage characteristic of Thomson discharge in the $M = 3$ test section. C₂H₄/O₂/Ar mixture, $\Phi = 1$, and $P_0 = 730$ torr.

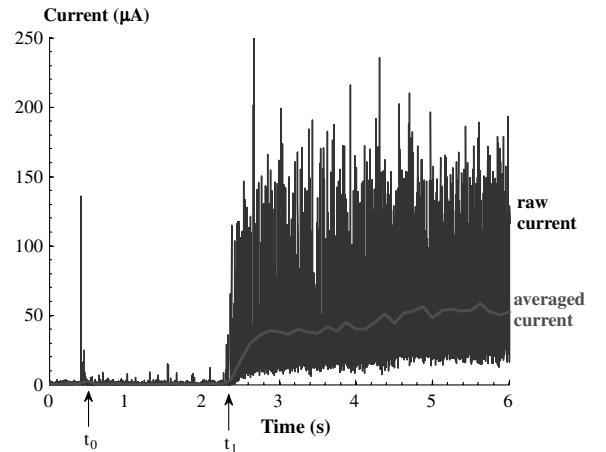


Fig. 4 Chemi-ionization current in the $M = 3$ flow at the conditions of Fig. 3. Electrode bias $U_e = 300$ V. Spark plugs are powered at $t_0 = 0.4$ s and turned off at $t_1 = 2.3$ s.

period. As discussed in Sec. II, the averaged current is used to generate the output signal of the feedback control system (see Fig. 2). In Fig. 4, the spark plugs were powered by a 2 kV dc power supply at $t_0 = 0.4$ s, producing a chemi-ionization current overshoot during ignition, and turned off at $t_1 = 2.3$ s. It can be seen that the Thomson probe in the $M = 3$ section starts measuring current only after the spark plugs are turned off. This occurs because while dc arc discharges are sustained in the spark plugs ($U_s = 1$ kV, $I_s = 100$ mA for each spark plug), electrons generated by chemi-ionization in the combustor are removed through the discharge circuit, and the electron density in the $M = 3$ test section is greatly reduced. This effect is further illustrated in Fig. 5, where a moderate voltage bias, $U_s = 300$ V, is applied to the spark plugs at $t_1 = 1.8$ s, after they have been disconnected from the main 2 kV dc power supply at $t_0 = 0.3$ s. It can be seen that applying a voltage bias to the spark plugs produces chemi-ionization current between the spark plug electrodes in the combustor, $I_s = 180$ μ A, and considerably reduces the Thomson-probe current in the $M = 3$ section (approximately by 40%).

This effect demonstrates that the spark plugs in the combustor cannot be used as quantitative Thomson chemi-ionization sensors that determine the electron density from saturation current. First, Fig. 5 shows that applying moderate bias ($U_s = 300$ V) to the spark plug electrodes does not remove all the electrons from the combustor since residual chemi-ionization current is still measured in the $M = 3$ flow (i.e., spark plug current is not saturated). Since the electron density in the high-pressure combustor is considerably higher than in the $M = 3$ flow, complete electron removal from the combustor would require significantly higher spark plug voltage bias, up to ~ 1 – 2 kV [10]. This may well result in electric breakdown and additional electron generation by self-sustained arc discharges in the spark plugs. Applying a strong electric field in the combustor may also result in flame-instability development [18,19] and possibly to blowout. Finally, unlike a localized spark plug probe, a Thomson probe in the $M = 3$ section acts as a global chemi-ionization sensor, since it samples and removes electrons from the entire flow of combustion products.

Our previous experiments [10] demonstrated that chemi-ionization current measured in the supersonic combustion-product flow can be used to monitor combustion instabilities. As an illustration, Fig. 6 [10] plots time-resolved flame emission and chemi-ionization current at the unstable combustion conditions, in a stoichiometric ethylene/air mixture. In this case, the spark plugs remained powered during the entire run, while the flame emission from the combustor (CH 4300 Å bands at 431 nm) and the chemi-ionization current in the $M = 3$ test section were monitored simultaneously. The results plotted in Fig. 6 show that chemi-ionization current spikes are in very good correlation with CH emission spikes, which occur due to repeated ignition and

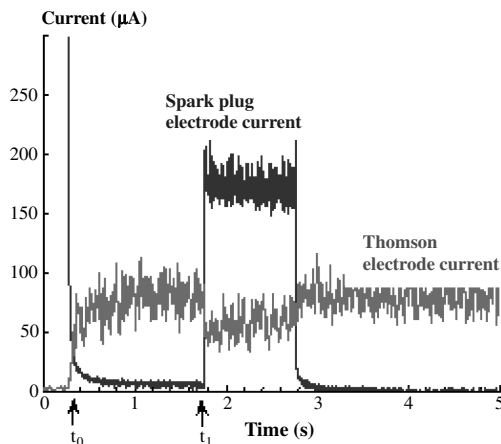


Fig. 5 Current measured in a spark plug (in the combustor) and Thomson probe (in $M = 3$ flow) after ignition. Spark plugs are turned off at $t_0 = 0.3$ s, 300 V voltage bias is applied to the spark plugs at $t_1 = 1.8$ s and removed at $t_2 = 2.8$ s, and 300 V bias is applied to the Thomson probe at all times.

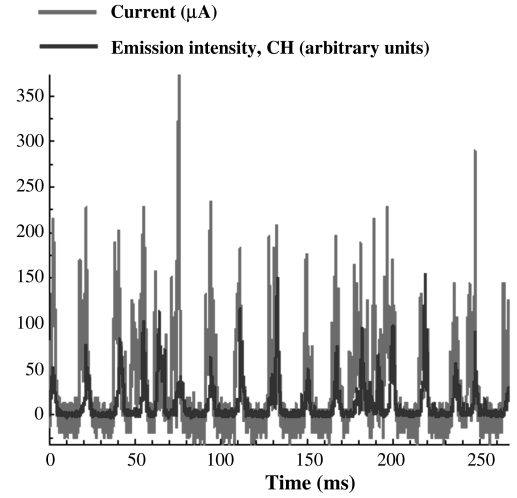


Fig. 6 Time-resolved flame emission from the combustor (CH, 431 nm) and chemi-ionization current in the $M = 3$ flow [10]; stoichiometric ethylene/air mixture and $P_0 = 1$ atm.

flame blowoff in the combustor. Very similar correlation was detected between the current and the $C_2(0 \rightarrow 0)$ Swan band at 516 nm emission. Note that chemi-ionization current spikes are not related to the spark plug current, which remains steady during the entire run. This result suggests that chemi-ionization current can be used both as a flame sensor and as a control parameter for feedback combustion control. Basically, current reduction would indicate approaching flame extinction, which can be countered by either adding more fuel to the combustor or by turning on an ignition source.

Figure 7 shows Thomson-probe saturation current measured in a $M = 3$ flow of combustion products of ethylene/oxygen/argon mixture as a function of the equivalence ratio. It can be seen that the chemi-ionization current in fuel-lean mixtures increases with the equivalence ratio, whereas the current in fuel-rich mixtures decreases with the equivalence ratio, peaking at near-stoichiometric conditions ($\Phi \approx 1.1$). A similar result (current maximum at near stoichiometric conditions and gradual reduction both in fuel-lean and fuel-rich mixtures) was obtained when 5% dry air was added to the flow. Such a relationship between equivalence ratio and chemi-ionization current has also been detected earlier [1,9]. This result suggests that measuring chemi-ionization current in combustion-product flows can be used to monitor and control the equivalence ratio in the combustor, especially at fuel-lean conditions or at low combustor pressures, when the flame may become unstable. In the present experiments, we used the relationship between the chemi-ionization current and the equivalence ratio for the fuel-lean mixtures, shown in Fig. 7, to control the fuel-oxidizer mixture composition in the combustor. These results are discussed below.

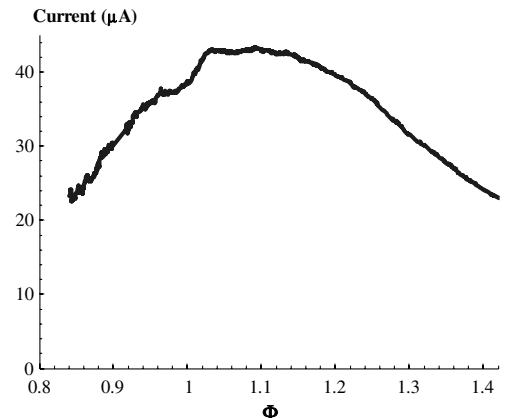


Fig. 7 Chemi-ionization current in a $M = 3$ flow of $C_2H_4/O_2/Ar$ combustion products vs the equivalence ratio in the combustor.

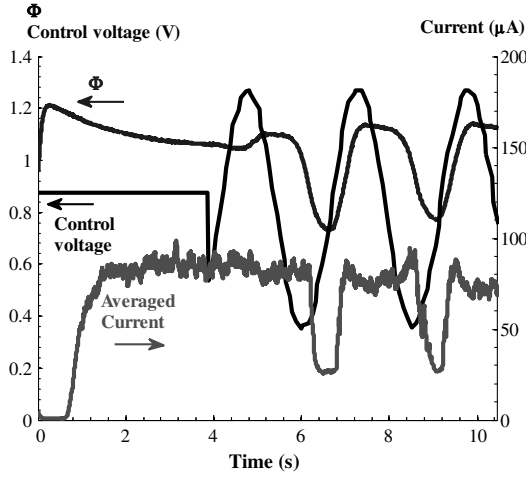


Fig. 8 Actuator control signal (V), equivalence ratio (Φ), and chemi-ionization current during open-loop control operation. Spark plugs are powered at $t = 0$ and turned off at $t = 0.5$ s. The sine-wave control signal is turned on at $t = 3.8$ s.

Figure 8 demonstrates an example of open-loop control of the equivalence ratio in the combustor. In this experiment, a constant-in-time control voltage of $V_0 = 0.875$ V is sent to the actuator valve (see Fig. 2), producing the fuel flow rate corresponding to the steady-state equivalence ratio of $\Phi \approx 1.0$. The initial overshoot of the equivalence ratio [(up to $\Phi = 1.2$ (see Fig. 8))] is due to a sudden opening of a solenoid shutoff valve in the fuel delivery line at $t = 0$. The flow is ignited at $t = 0$ and the spark plugs are turned off at $t = 0.5$ s. At $t = 3.8$ s, the control voltage is changed to a sine-wave signal, $V(t) = V_0 + V_1 \cdot \sin(2\pi\nu t)$, with the frequency of $\nu = 0.4$ Hz and the amplitude of $V_1 = 0.4$ V. As can be seen from Fig. 8, this produces a periodic increase and decrease of the equivalence ratio in the combustor and, as a result, of the chemi-ionization current in the $M = 3$ flow. Both the equivalence ratio and the current exhibit a time delay of approximately 0.7 s compared with the control signal (see Fig. 8). The time delay is built into the microprocessor controlling the actuator valve motor.

Chemi-ionization current plotted in Fig. 8 has been averaged by the data acquisition card using a running average over a period of 125 ms, as discussed in Sec. II. Figure 9 shows the raw current signal and the equivalence ratio for that same run. From Fig. 9, it can be seen that as the equivalence ratio is reduced to $\Phi = 0.73$ – 0.78 , not only the time-averaged current decreases, but the amplitude of current fluctuations (with a frequency of 160–180 Hz) is also greatly reduced. At these conditions, the flame in the combustor appears visibly unstable. This suggests that the onset of flame instability in lean mixtures can be detected by monitoring

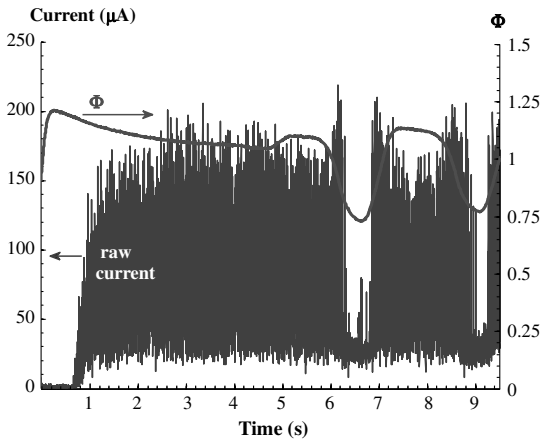


Fig. 9 Equivalence ratio and raw chemi-ionization current measured at the conditions of Fig. 8.

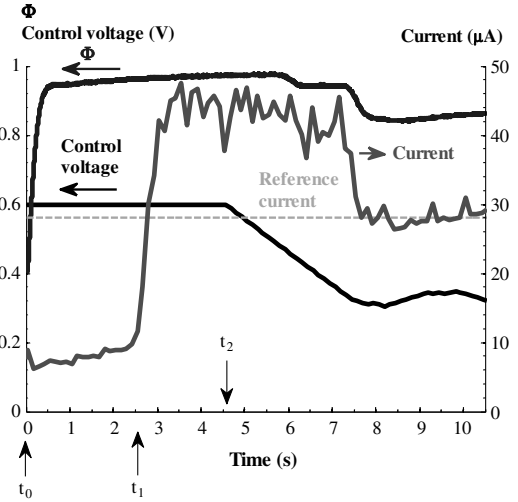


Fig. 10 Closed-loop control (equivalence ratio reduction) using the chemi-ionization sensor. Spark plugs are powered at $t_0 = 0$ and turned off at $t_1 = 2.5$ s. Feedback control starts at $t_2 = 4.6$ s. Current reference value $I_{ref} = 28$ μ A corresponds to fuel-lean conditions (see Fig. 7).

chemi-ionization current and can be prevented by keeping the current above a certain level.

Figures 10 and 11 demonstrate feasibility of closed-loop control. In Fig. 10, a $C_2H_4/O_2/Ar$ flow is ignited at $t_0 = 0$, the spark plugs are turned off at $t_1 = 2.5$ s, and a constant control signal maintains near-stoichiometric equivalence ratio, $\Phi \approx 0.96$ (at chemi-ionization current of $I = 40$ – 45 μ A), for $0 < t < 4.6$ s. The reference current is set to $I_{ref} = 28$ μ A, which corresponds to fuel-lean conditions [$\Phi \approx 0.88$ (see Fig. 7)]. After the feedback control is turned on at $t_2 = 4.6$ s, it can be seen that the control signal is reduced until the chemi-ionization current reaches the reference value and the equivalence ratio is stabilized at $\Phi \approx 0.86$. In Fig. 11, the mixture is ignited and steady combustion is achieved at the initial equivalence ratio of $\Phi \approx 0.80$ and chemi-ionization current of $I = 20$ μ A. In this case, the reference current is set to $I_{ref} = 40$ μ A, which corresponds to near-stoichiometric conditions [$\Phi \approx 1.01$ (see Fig. 7)]. After the feedback control is turned on at $t_2 = 7.8$ s, the control voltage increases until reference current is reached and the equivalence ratio is stabilized at $\Phi \approx 0.91$. In both of these cases, the reference current value is reached and the equivalence ratio is stabilized over a period of 3–4 s (see Figs. 10 and 11), primarily controlled by the response time of the actuator valve, approximately 1 s.

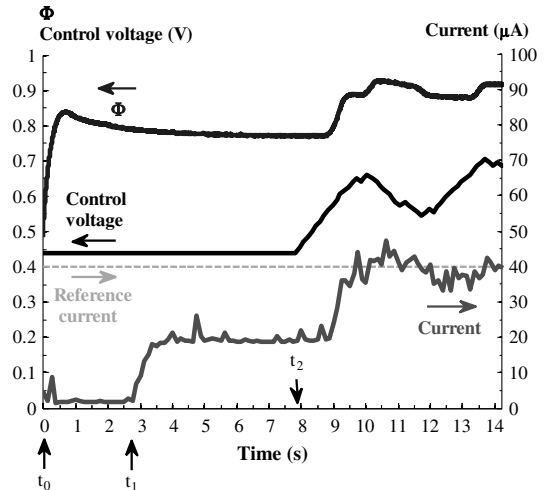


Fig. 11 Closed-loop control (equivalence ratio increase) using the chemi-ionization sensor. Spark plugs are powered at $t_0 = 0$ and turned off at $t_1 = 2.6$ s. Feedback control starts at $t_2 = 7.8$ s. Current reference value $I_{ref} = 40$ μ A corresponds to near-stoichiometric conditions (see Fig. 7).

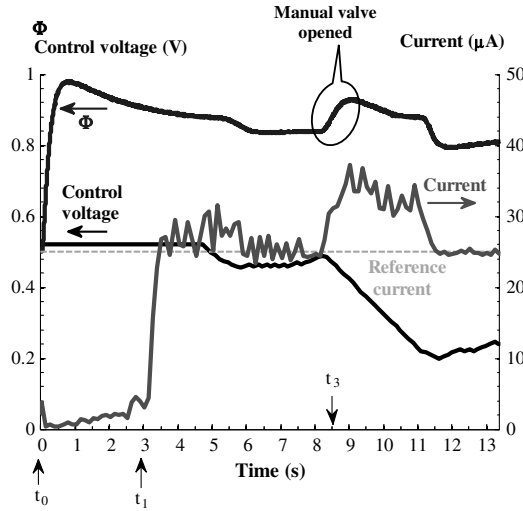


Fig. 12 Closed-loop control using chemi-ionization sensor. Spark plugs are powered at $t_0 = 0$ and turned off at $t_1 = 3.0$ s. Feedback control starts at $t_2 = 4.5$ s. The bypass valve is opened at $t_3 = 8.0$ s. Current reference value $I_{\text{ref}} = 25 \mu\text{A}$ corresponds to fuel-lean conditions (see Fig. 7).

Figures 12 and 13 demonstrate feasibility of closed-loop control, with an external perturbation changing the fuel–oxidizer mixture composition in the combustor. For this, a bypass metering valve in the fuel delivery line, shown in Fig. 2, was used. In these experiments, the bypass valve was opened or closed manually to change the equivalence ratio in the combustor. In Fig. 12, a lean $\text{C}_2\text{H}_4/\text{O}_2/\text{Ar}$ mixture is ignited at $t_0 = 0$, the spark plugs are turned off at $t_1 = 3.0$ s, and feedback control with the reference current of $I_{\text{ref}} = 25 \mu\text{A}$ starts at $t_2 = 4.5$ s. In this run, the bypass valve is initially closed. The control system brings the current to its reference value and stabilizes combustion at $\Phi \approx 0.84$. At $t_3 = 8.0$ s, the bypass valve is opened and the equivalence ratio is increased from $\Phi \approx 0.84$ to $\Phi \approx 0.93$, and the current increases from 25 to 37 μA (see Fig. 12). It can be seen that feedback control brings the current back to the reference value and the equivalence ratio to $\Phi \approx 0.81$ in approximately 3 s (see Fig. 12). In Fig. 13, a near-stoichiometric $\text{C}_2\text{H}_4/\text{O}_2/\text{Ar}$ mixture is ignited at $t_0 = 0$, the spark plugs are turned off at $t_1 = 1.5$ s, and feedback control with the reference current of

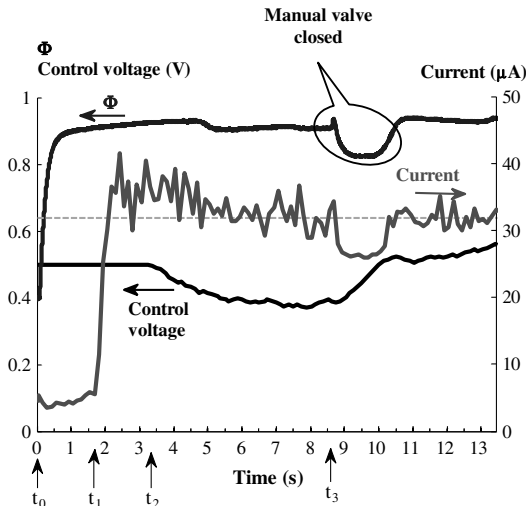


Fig. 13 Closed-loop control using chemi-ionization sensor. Spark plugs are powered at $t_0 = 0$ and turned off at $t_1 = 1.5$ s. Feedback control starts at $t_2 = 3.0$ s. The bypass valve is closed at $t_3 = 8.5$ s. Current reference value $I_{\text{ref}} = 32 \mu\text{A}$ corresponds to near-stoichiometric conditions (see Fig. 7).

$I_{\text{ref}} = 32 \mu\text{A}$ starts at $t_2 = 3.0$ s. In this run, the bypass valve is initially open. At $t_3 = 8.5$ s, the bypass valve is closed and the equivalence ratio is reduced from $\Phi \approx 0.92$ to 0.82 (see Fig. 13). In this case, feedback control brings the current back to the reference value and the equivalence ratio to $\Phi \approx 0.93$ in approximately 1.5 s (see Fig. 13).

The results shown in Figs. 10–13 demonstrate that a straightforward relationship between the saturation chemi-ionization current (i.e., the electron density) in the flow of combustion products and the equivalence ratio in the combustor, such as plotted in Fig. 7, makes it possible to maintain the desired equivalence ratio and to sustain a stable flame in lean fuel–oxidizer mixtures. The present approach requires calibration to measure saturation current for a particular fuel–oxidizer mixture at a given combustor geometry and pressure, in a wide range of equivalence ratios. The use of the Thomson probe in the flow of combustion products (downstream of the combustor) as a feedback combustion controller is applicable at sufficiently high flow velocities, $u > L/\tau_{\text{rec}}$, where $L \sim 0.1$ – 1.0 m is the characteristic length scale and τ_{rec} is the electron–ion recombination time.

At the present experimental conditions, the electron density in the combustor, inferred from the saturation current of the Thomson probe in our previous work [10], is $n_e \approx 2 \times 10^9 \text{ cm}^{-3}$, and an estimated recombination rate coefficient is $\beta \sim 10^{-7} \text{ cm}^3/\text{s}$ [13]. This gives the characteristic recombination time of $\tau_{\text{rec}} = 1/\beta n_e \sim 10^{-2}$ s and the minimum flow velocity of $u > 10$ – 100 m/s. This estimate shows that the present method is also applicable to subsonic flows of combustion products. Note that in this case, the combustion-product flow temperature would not decrease nearly as rapidly as during supersonic expansion ($T \approx 670$ K at $M = 3.16$ compared with the plenum temperature of $T_0 = 2000$ K [10]), although it may still be reduced significantly due to heat transfer to channel walls and/or ambient-air entrainment. Significant flow-temperature reduction may accelerate electron decay rate substantially, due to both electron attachment and formation of cluster ions with high electron–ion recombination rates. Three-body electron attachment to oxygen entrained with ambient air would be a significant factor below $T \sim 1000$ K, when the strongly-temperature-dependent electron-detachment frequency, $\tau_{\text{det}} \sim \exp(-5000/T)$ [20], becomes lower than the attachment frequency at $P \sim 1$ atm. Formation of molecular cluster ions, which also occurs at low temperatures due to their low binding energies, 1.06 eV for N_4^+ [21], may increase the electron–ion recombination rate by about an order of magnitude, up to $\beta \sim 10^{-6} \text{ cm}^3/\text{s}$ [22]. Therefore, Thomson-probe electrodes used for feedback combustion control need to be placed in a relatively-high-temperature region of a subsonic combustion-product flow.

IV. Conclusions

The results of the present work demonstrate feasibility of feedback combustion control using chemi-ionization current sensor placed in a supersonic flow of combustion products downstream of the combustor (nozzle plenum). Operated in the saturation regime, the ionization sensor (Thomson probe) removes nearly all electrons from the combustion-product flow and therefore acts as a global chemi-ionization detector. The results demonstrate that a simple relation between the equivalence ratio in the combustor and the chemi-ionization current in the $M = 3$ flow for $\Phi < 1.1$ can be used to maintain the equivalence ratio in the combustor at the desired value. The experiments have shown that using different target (reference) values of the chemi-ionization current in the feedback control program enforces transition from near-stoichiometric to fuel-lean and from fuel-lean to near-stoichiometric conditions in the combustor. The experiments have demonstrated that the feedback control system can also counter external perturbations, which either increase or decrease the equivalence ratio in the combustor and bring the fuel–oxidizer mixture composition back to the desired (reference) values. The combustion feedback control system based on Thomson chemi-ionization probe is simple and straightforward and can be easily adapted for practical applications.

Acknowledgment

The support of the Space Power and Propulsion Directorate of the U.S. Air Force Office of Scientific Research is gratefully acknowledged.

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