Acoustic Pulsation for Luminosity Control in a Wolfhard-Parker Slot Burner

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Abstract

Acoustic forcing of a diffusion flame issuing from a Wolfhard-Parker slot burner affects soot production in the flame and thus its luminosity. This effect has been used to demonstrate closed-loop control of the slot burner system. The current work begins to detail the relationship between the fluid flow changes produced by the acoustic forcing and the flame’s luminous response. The study includes both square wave and sinusoidal wave input forcing, as well as symmetric and asymmetric forcing modes. The study includes configurations where both the fuel and air flows are acoustically perturbed. The relationship between the forcing flows and the flame’s temporal soot production is used to analyze mixing and soot reduction in an open-loop configuration. The results from these experiments will improve the models being developed for adaptive flame control, as well as for non-adaptive control approaches to combustion.

1 Introduction

The majority of energy utilization in the industrial world involves the combustion of fossil fuels. Modern control theory has the potential to improve the efficiency of, and minimize harmful emissions from, these combustion processes. In order to further develop the appropriate strategies for combustion control, the research described in this paper examines adaptive control techniques that can manipulate a generic flame through acoustic pulsation. More specifically, this research focuses on the luminosity response of a two-dimensional laminar flame sheet to both sinusoidal and square wave acoustic pulsation. Previous work in sinusoidal acoustic pulsation provides both the foundation and motivation for this research [2, 11]. Through the control formulation we will (1) refine the relationships between measurable flame behavior and controllable parameters; (2) demonstrate fixed point flame control using fast control updates despite moderate to large perturbations of fuel/air flow rates; and (3) demonstrate wide-range luminosity control. The research in this area has shown that these control techniques may eventually allow combustors to maximize efficiency and minimize pollutant emissions over a wide range of operating conditions despite fluctuations in fuel composition, external flow fluctuations, and system degradation through aging.

To date the four areas of research in active combustion control that appear frequently in the literature include: (1) control of waste incineration; (2) optimization of power boilers; (3) control of reciprocating engines for vehicles; and (4) control of instabilities in combustors and rocket motors. In spite of the vast array of research in these areas, few investigations demonstrate fundamental feedback control. Gutmark and co-workers have an impressive array of papers detailing the control of flames through acoustic forcing for application to hazardous waste destruction [5, 6, 7]. McManus et al. [9], Kemal and Bowman [8], Fung and Yang [3], and Annaswamy and Ghoniem [1] have made substantial progress in describ-
ing control of combustion instabilities.

The use of acoustic forcing for the control of combustion in enclosures has provided some evidence that classical and adaptive techniques can be effective. However, the response in such systems depends, and often relies, on the character of the resonant acoustic modes in the enclosure as much as on the response of the combustion process itself. To examine the potential for acoustic pulsation flame control, independent of enclosure effects, the current work examines adaptive closed-loop control of a diffusion flame in an unconfined configuration.

2 Experimental Setup

2.1 Wolfhard-Parker Slot Burner

The Wolfhard-Parker slot burner, shown in Figure 1, is similar to the burner used by Smyth et al. to produce a two-dimensional diffusion flame sheet [10]. The burner consists of two rectangular air ports sandwiching a central fuel port slot. The two air ports are 16 mm wide by 41 mm long and the central fuel port is 8 mm wide by 41 mm long. Glass beads with 3 mm diameters fill each of the three ports to produce uniform fuel and air flow. Three four-inch sub-woofer speakers inside hemispherical metal housings, connected to the burner as shown in the figure, provide the acoustic forcing in the system.

2.2 Control Apparatus

Figure 2 shows a schematic of the burner control apparatus. The system contains a single 486DX-33 computer which serves as both the controller and recorder. It performs all computations for driving the speakers, in addition to collecting the inputs to the system and outputs from the system sensor. The output function of the computer uses two CIO-DAS08-A0 digital to analog boards. Each board provides 12 bit output analog channels which can be addressed at a combined rate of 20 kHz. The computer program generates up to three different square waveforms for output through each channel to the system actuators (fuel and air speakers). In addition to independent frequency control for each channel, the program also allows independent phase and amplitude control. The analog outputs pass through a Denon power amplifier where they are amplified 40 times and then connected to the speakers attached to the Wolfhard-Parker slot burner. The outputs are also routed back to the computer for storage as system inputs. The system sensor (in these experiments a photodiode) measures the response of the flame to the system inputs. The photodiode signal is amplified 10 times by a Pacific Instruments amplifier and recorded by a CIOSSH-16 sample and hold board connected to the computer. The benefit of using this sample and hold board is that it allows all channels to be collected simultaneously and recorded within 200μs thus yielding a channel to channel droop rate of less than 20μV. The computer uses this recorded data to complete the control loop required for active control.

Figure 1: Rear view of the Wolfhard-Parker slot burner showing the location of the speaker housings for both the air and fuel lines. The general placement of the photodiode allows it to capture the total luminosity normal to the plane of the flame.
Figure 2: Schematic of the experimental apparatus for acoustic control of a Wolfhard-Parker slot burner

3 Control Theory

Classical control theory requires that the system designer either determine by analytical or empirical results an appropriate model for the system under consideration. Initially, however, due to the complexity of combustion processes, the aim of this research is to utilize a control law which requires very little information about the dynamic response of the system. Therefore, this research focuses on the implementation of an adaptive active controller. The general control formulation and approach are similar to the techniques described by Goodwin and Sin [4] and details can be found in our previous work [11].

4 Experiments and Results

4.1 Open-loop Studies

Figure 3 presents the effect of square wave air forcing for two different air flow rates on the nondimensionalized average flame luminosity (mean based upon 10,000 samples at each frequency), where we nondimensionalize the luminosity against the full-scale reading of our data collection apparatus. The driving frequency range tested is from 0 Hz to 90 Hz. This graph is for the case when the acoustic forcing on the left and right air ports are in phase and have an amplitude of 10 $V_{p-p}$. In one case the fuel flow rate is 7.23 cm$^3$/s and the combined air flow rate is 34.5 cm$^3$/s. In the other case, there is no mean air flow. The general observed trend for both experimental conditions is an 85% decrease in average luminosity as the driving speakers are pulsed through a range from 0 Hz to 90 Hz. Furthermore, we observe local extrema in the neighborhood of 10 Hz, 20 Hz, and 40 Hz suggesting dominant buoyant frequency modes of the laminar flame structure.

Figure 4 details the effect of sinusoidal wave air forcing for two different air flow rates on the nondimensionalized average flame luminosity. The frequency range progresses from 0 Hz to 100 Hz. Again, the acoustic air forcing is in phase and has a 10 $V_{p-p}$ amplitude. The fuel and air flow rates are the same as in the previous case. The trend shows approximately the same locations for local extrema. However, we notice only a 60% decrease in luminosity through a narrow region of 0 Hz to 20 Hz. Subsequent to this region of decreased luminosity the luminosity increases until it is within 20% of the unforced value.

Figure 5 reveals the luminous response of the
Figure 4: Results from earlier experiments showing the change in nondimensionalized average flame luminosity as a function of sinusoidal air forcing frequency.

Figure 5: Natural temporal flame response to acoustic air input. Also, note that the fluctuation in luminosity is much more dramatic at the higher forcing frequency.

Figure 8 shows the effect of forcing the fuel and air with square waves for different relative phases on the nondimensionalized average flame luminosity. The frequency range tested is from 0 Hz to 55 Hz. This graph is for the case when the acoustic forcing on the left and right air ports have an $8 \, V_{p-p}$ amplitude. The fuel flow rate is $7.2 \, cm^3/s$ and the combined air flow rate is $34.5 \, cm^3/s$. These results differ substantially from the results obtained when only the air was acoustically forced. Here, the luminosity decreases 90% in the range from 0 Hz to 40 Hz. Furthermore, changing the relative phase of the fuel and air does not change the shape of the luminous response but only the magnitude in the frequency range tested.

Figures 9 and 10 show the temporal response of the diffusion flame to acoustic square wave forcing of the fuel and air at 5 Hz and 22 Hz, respectively. We observe that the flame responds in a regular manner and that the luminosity varies in phase with the 5 Hz pulse plotted beneath the flame response. However, when the input acoustic frequency increases to 22 Hz, the luminosity no longer tracks the acoustic pulse, but rather experiences irregular periods of high and low luminosity. If we take the average lu-
Figure 6: Temporal flame response to 5 Hz square wave input to air port only

Figure 7: Temporal flame response to 20 Hz square wave input to air port only

Figure 8: Change in nondimensionalized average flame luminosity as a function of both air and fuel square wave forcing and relative phase of forcing between fuel and air.

For each of the inputs over 10,000 samples, we find that at 5 Hz it is 17% below the unforced scenario and that the 22 Hz response is 86% below the unforced scenario.

4.2 Closed-loop Studies

A one-step-ahead adaptive control formulation was used for closed-loop control.

4.2.1 Fixed Output Control

Figure 11 shows the temporal luminosity response of the system using a first order control with an initial nondimensionalized average unforced luminosity of 0.65 and a desired luminosity of 0.22. The fuel flow rate is 7.23 cm$^3$/s and the combined air flow rate is 34.5 cm$^3$/s. Both the air and fuel ports acoustically force the system with the same frequency square wave. The control algorithm has an update frequency of 2 Hz thus allowing for a 1/2 second average luminosity (250 samples) as the output from the system. The controller is off during the first 20 seconds in order to show the luminosity response before and after the control initiation. We observe that during the first 20 seconds of control the output frequency (plotted beneath
the temporal flame response) oscillates between 5 Hz and 16 Hz until it decays to a range of 8 Hz to 10 Hz. During this same period of time, the luminosity of the flame quickly decreases until it tracks the desired output of 0.22.

Figure 12 reveals the system response under the same conditions except that the fuel is no longer acoustically forced, the desired output is now 0.41, and the control frequency update is now 8 Hz (within 20% of the natural buoyant plume frequency of the diffusion flame.) Again, we find that the actual average luminosity tracks the desired output luminosity very well.

Figure 13 shows the temporal luminosity response of the system under the same initial conditions as before. During this test, the desired output is 0.12. As before the controller quickly locks on to the frequency range that will produce the desired average output. During this trial, however, the fuel flow rate is increased from the initial flow rate by 50% at 1 minute into operation to simulate a disturbance on the system. Without control the fuel flow increase would increase the average luminosity. If we look at the temporal flame response, however, we note no net change in average luminosity because the control produces a sudden compensating increase in the acoustic square wave input
4.2.2 Ramp Output Control

Figure 14 details the temporal luminosity response of the system under the same initial conditions noted previously. For this trial, the control update frequency is 4 Hz (i.e., control uses 0.25 second average luminosity for updates). This test simulates tracking a desired average luminosity ramp. The desired output ranges from 0.42 to 0.12. We observe that the average luminosity tracks the desired ramp and that the input frequency increases steadily (as expected from Figure 8.)

4.2.3 Square Wave Output Control

Figure 15 shows the response of the system to acoustic forcing of the air ports with a control update frequency of 8 Hz. The desired output for this system is a square wave of amplitude 0.44 and period of 8 seconds. The control is initiated after 8 seconds. We find that the luminosity follows the desired output very well. Under these conditions, the luminosity of the flame varies between a sooty bright yellow flame when the desired output is in the high portion of the square wave and a blue flame when the desired output is in the low portion of the square wave.
5 Discussion

Figures 3 and 4 show that there is a noticeable difference in the response of the system to sinusoidal and square wave acoustic inputs. We found that the system response to sinusoidal inputs beyond 20 Hz resulted in an increase in luminosity, suggesting decreased mixing. Forcing the system with square waves, however, resulted in a continuous decrease in luminosity through the entire testing bandwidth. Furthermore, the square wave inputs enabled the reduction of the luminosity by 90% compared to a 60% reduction possible with sinusoidal inputs. This phenomenon might be explained by the fact that square waves contain an infinite number of higher harmonics while the sinusoid contains only a single frequency. Since the luminosity of the flame is a function of the fuel and air mixing at the flame front, the higher harmonics present within the square wave excite modes in this region that would not be excited by single frequencies.

Using these findings as the motivation for implementing an on-line active control scheme we find that we can increase the control update frequencies to well under one second, whereas previous experiments with sinusoidal excitation required a several second average for successful performance of the low order models tested. The square wave allows control on a time scale that is 32 times smaller than the time scale possible with sine wave control. At the same time, we find that the responsiveness of the flame to this decreased time scale control results in better step, disturbance, and ramp responses.

6 Conclusion

While previous efforts to control the luminosity of the diffusion flame issuing from the Wolfhard-Parker slot burner proved effective [11], the results of this experiment show a dramatic improvement in the control capability of the diffusion flame sheet issuing from the Wolfhard-Parker slot burner. The improvement occurs when a single frequency sinusoidal acoustic excitation is replaced by a square wave acoustic input. This increased control allows the flame to transition from a bright yellow flame, characteristic of a sooty diffusion flame, to a completely blue flame, characteristic of a premixed flame, without adjusting the fuel or air flow rates, but by simply adjusting the forcing frequency on the fuel or air feeding the burner.

Using this improved control capability, we employed the adaptive control algorithm used previously with increased sampling rates, and we found increased system responsiveness. These results provide encouragement that we can achieve our ultimate goal of non-adaptive combustion control through a better understanding of the dynamic response of the flame to different inputs.

These results suggest that the next step in our combustion control research should focus on the effect of the acoustic forcing on the fluid mechanics of the system. After appropriate models are developed for this interaction we can proceed to non-adaptive control approaches. Furthermore, since we are now very close to controlling the flame at the rate of its natural flicker frequency, we must refine the relationship be-
between frequency input and luminosity output. In essence, the control input will transition to a series of high and low pulses (similar to a digital pulse train) and have the effect of sucking and blowing the fuel and air flows asynchronously, rather than oscillating the flows at fixed frequencies.

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References


