JOURNAL OF PROPULSION AND POWER
Vol. 18, No. 1, January–February 2002

Scale-Up Experiments on Liquid-Fueled Active Combustion Control

Ken H. Yu*
University of Maryland, College Park, Maryland 20742
and
Ken J. Wilson†
U.S. Naval Air Warfare Center, China Lake, California 93555

Liquid-fueled active instability suppression and the associated scaling issues were investigated in a model ramjet dump combustor that was operated between 70 kW and 1.3 MW output conditions. When the secondary fuel injection was pulsed and its timing was controlled, pressure oscillations were suppressed. The controller performance was adversely affected by reducing the flow residence time, but the correlation was modest. The amount of pulsed fuel, on the other hand, had a significant effect on the controller performance, which suggested the existence of a critical fuel flux. To maintain control authority for instability suppression, a fuel amount in excess of the critical fuel flux was required for the secondary injection. In the scale-up experiments, when the Sauter mean diameter of fuel droplets was decreased from 40 to 10 μm, the critical fuel flux was lowered from 8% of the total fuel flux to about 2%, which indicated that it was a strong function of fuel droplet size. Last, a novel control approach was demonstrated using pulsed fuel injection that was closed-loop controlled at the second harmonic of the instability. This showed that instabilities could be suppressed with closed-loop control even when the frequencies are outside the actuator's repetition capability.

I. Introduction

BECAUSE future propulsion systems will be subjected to rapidly evolving environmental regulations as well as increasingly demanding combustion performance requirements, an advanced combustion control system that can shorten the combustor development time and improve performance will be desirable. An active control approach that relies on proper timing of fuel injection is an attractive idea because timing adjustment using electronics is becoming increasingly convenient. In contrast, geometry modification, required in passive control approach, is often time consuming and can be expensive to develop. Some of the interest in active-combustion-control(ACC) approach stems from potential flexibility in performance, which ACC could provide without costly changes in hardware.

Past studies on ACC have been motivated by undesirable combustor behavior that includes combustion instabilities,[1−10] poor burning efficiency,[8−13] limited operational range,[8−10,14] and excessive production of pollutants.[8,12,13,15−17] These studies have contributed greatly to the present understanding of fast-response ACC, but several technological challenges still remain before the ACC technique can be implemented to practical propulsion systems. One such challenge is to use liquid fuel for control and to minimize the fuel amount by directly pulsing it into the combustion chamber. Such a control has been difficult to obtain, and the physical processes have not been well understood.[18,19]

Liquid fuel was seldom utilized in the previous ACC studies because it was not only difficult to actuate liquid-fuel injection at high frequencies, but the combustion delays associated with liquid-fuel atomization, droplet heating, vaporization, and burning processes made such control extremely slow for dynamically controlling the combustion processes. As a result, until recently,[18−22] the use of liquid fuel was confined to either steady injection processes[13] or upstream addition of prevaporized fuel,[4,7] which limited the ACC flexibility associated with temporal responsiveness. The goal of this project was to make ACC more practical for propulsion systems by using pulsed liquid-fuel injection directly into the combustor and demonstrate ACC scale-up at higher output levels.

Combustion instabilities in propulsion systems and the associated physical mechanisms were reviewed by Culick.[23] Extensive reviews on active instability suppression techniques were conducted by McManus et al.,[24] Candel,[25] Yang and Schadow,[26] and Schadow and Yang.[27] Also, Zinn and Neumeier[28] provide an overview of research and developmental needs for practical applications. To reduce the amplitude of undesirable oscillations, one may control the phase of fluctuating heat release so that the heat release oscillations interfere destructively with pressure oscillations. For instance, according to Rayleigh's criterion[29] (also see Ref. 30), acoustic energy density is reduced if pressure fluctuations p' and heat release fluctuations q' satisfy the proper phase relation such that

$$\iint_{\vartheta\, T} \frac{p'q'}{\bar{p}}\, \mathrm{d}t\, \mathrm{d}\vartheta < 0$$

where the double integral is taken over an instability period T and over the combustor volume ϑ. One simple way to achieve heat release oscillations with controllable phase is to pulse the fuel injection.

Recent advances in active control and liquid-fuel-actuator technology have provided an ideal background for extending ACC to liquid-fueled combustors. Because local fluctuations of heat release are affected by instantaneous distribution of fuel droplets in that area, one needs to control how the fuel droplets are dispersed inside the combustor as well as modulating the global fuel flux into the combustor. In this experiment, pulsing liquid fuel directly into the combustor effectively controlled temporal fuel flux. To control fuel dispersion, periodic interaction between fuel droplets and large-scale flow features was utilized. To ensure good interaction with flow structures, the droplet Stokes number must be sufficiently

Presented as Paper 98-3211 at the AIAA/ASME/SAE/ASEE 34th Joint Propulsion Conference and Exhibit, Cleveland, OH, 12–15 July 1998; received 5 January 2001; revision received 27 July 2001; accepted for publication 2 August 2001.

*Associate Professor, Department of Aerospace Engineering, Senior Member AIAA.

†Aerospace Engineer, Research Department, Member AIAA.

small.[18,31–35] The injection timing is an important control parameter because the severity of the interaction was sensitive to the initial slip velocity between droplets and flow. Needless to say, the fuel-droplet size must be very small to obtain fast combustion response as well.

II. Experimental Setup and System Components

Combustor

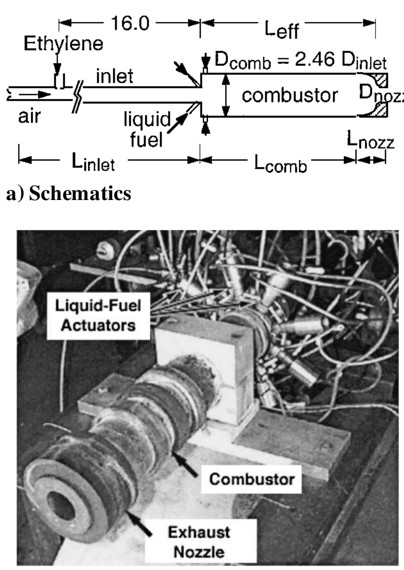
Experiments were performed in a model ramjet dump combustor (shown in Fig. 1). Air was provided to the combustor from high-pressure storage tanks through a long inlet pipe. A choked orifice was used to meter the airflow rate and to define the upstream acoustic boundary of the inlet. During a typical run, which lasted anywhere from several minutes to an hour, the airflow rate was held steady by manually maintaining the upstream regulated pressure within 2% of the intended value. Ethylene was injected into the inlet airflow at a location sufficiently upstream of the dump plane to guarantee complete premixing. The ethylene flow rate was also held constant using another choked orifice, and the flow rate was again maintained within 2%. The premixed ethylene–airflow entered the combustor by expanding over the dump plane. At the dump plane, liquid fuel was injected in a pulsating manner to control actively the combustion dynamics. In contrast to the upstream premixed flow, which was held constant, the controller fuel flux was rapidly modulated in time using on–off type actuators. At the downstream end of the combustor, a long-radius exhaust nozzle was utilized to control the combustor pressure.

Active instability suppression experiments were performed using three different controller fuels and at several operating conditions, which resulted in natural instabilities. Table 1 lists the dimensions of the dump combustor along with the type of liquid fuel used in the controller. Table 2 lists the specific flow conditions associated with each configuration in which instabilities occurred. Time-averaged values were used to report the controller fuel flux. Finally, Table 3 shows some of the pertinent parameters in the experiments. The role of these parameters will be discussed later in the paper. The case number in Tables 2 and 3 corresponds to the combustor configuration, and the ensuing letter indicates a particular flow condition that the configuration was tested at.

Table 1 Dump combustor configurations[a]

Configuration	Liquid fuel	L_{inlet}	L_{comb}	L_{eff}	D_{nozz}	L_{nozz}
1	Ethanol	58.5	10.2	11.7	1.29	1.85
2	Heptane	25.8	12.4	12.4	0.615	1.85
3	Heptane	25.8	12.9	12.9	0.862	1.32
4	Heptane	25.8	8.9	8.9	0.615	1.85
5	JP-10	20.2	15.4	16.8	1.36	1.81
6	JP-10	20.2	13.3	14.8	1.27	1.81

[a]All dimensions are in terms of $D_{\text{inlet}} = 42$ mm.



a) Schematics

b) Configuration 5

Fig. 1 Axisymmetric dump combustor setup.

Actuators

One of the most important components in ACC is the actuator used to affect instantaneous combustion heat release. After evaluating several types of high-frequency fuel injectors, we initially chose a set of off-the-shelf automotive fuel injectors that provided a good mechanical response at high frequencies as well as a high volume flow rate. A square wave with adjustable duty cycle was used to drive the injector electronic control unit (ECU) extending the frequency response beyond 1 kHz. However, these injectors produced relatively coarse droplets that were clearly not suitable for fast combustion response applications. To reduce droplet size, a swirl-based atomizer with 300-μm exit diameter[36] was fitted at the fuel jet exit. In this close-coupled configuration, the automotive fuel injectors were used as a high-frequency solenoid valve for fuel flux control while the atomizers improved the overall atomization characteristics even at high frequencies. In typical cases using actuators 1, the Sauter mean diameter D_{32} ranged between 40 and 50 μm on the basis of photographic droplet sizing under similar conditions[18] and empirical analysis for a similar class of atomizers.[37] The results in Secs. III and IV were obtained using these actuators.

Later, a different actuator (actuator 2) was utilized to reduce the fuel droplet size even further. A set of prototype fuel injectors that used air-assisted atomization was used to reduce D_{32} below 10 μm. The reduction in D_{32}, which resulted in faster combustion response, improved the combustion control. According to the manufacturer specification, these injectors required a very small amount of atomizing air, less than 1% of the air needed for stoichiometric reaction of the injector fuel flux. The results of the experiment using the new improved actuators will be presented in Sec. V along with the droplet size measurements.

Sensor

For closed-loop operation, Kistler pressure transducers with high-frequency response, on the order of 100 kHz, were utilized. One pressure transducer, which was mounted at one inlet diameter downstream of the dump plane, was used for feedback. Although the pressure signals taken from other locations along the combustor and inlet were also effective, no attempt was made to optimize the pressure transducer location. In most cases, pressure oscillations were observed at frequencies close to the quarter-wave mode of the inlet with varying phase of pressure oscillations along the inlet duct. In contrast, pressure oscillation phase along the combustor wall stayed nearly constant.

Controller

For open-loop control, the controller fuel was pulsed at frequencies other than the instability frequency. In some cases, this approach effectively shifted the dominant oscillation frequency to other frequencies with more benign levels of oscillations. In some other cases, particularly when the injection frequency was close to the instability frequency or its harmonics, the dominant frequency became less coherent or was affected by beats. However, in most other cases, an open-loop injection simply produced an independent peak, which was superposed on the frequency spectrum. For these cases, because an open-loop approach was not very effective, the secondary fuel injection had to be closed-loop controlled for suppressing the oscillation amplitude.

For closed-loop control, the approach we had taken was to pulse the liquid fuel at the instability frequency or at the harmonics of the instability frequency and adjust the timing using a simple closed-loop circuit. Because our emphasis was on extending active control to liquid-fueled combustors, a simple phase-delay approach was utilized instead of more sophisticated control methods such as an adaptive technique[38] or model-based designs.[39–41] Figure 2 shows the ACC system that was used to control the fuel injection scheduling in the dump combustor. Combustor pressure oscillations were detected by the pressure transducer. The pulsed injection timing

Table 2 Average flow conditions during naturally unstable operations

	Flow rate, g/s					Unstable conditions			
Case	Air	Ethylene	Ethanol	Heptane	JP-10	ϕ	$\bar{P}_{comb}/P_{exit}$	f, Hz	$p'_{rms}/\bar{P}_{comb}$
1A	45	1.0	0.75	——	——	0.47	1.02	34±1	0.008
1B	45	1.3	0.75	——	——	0.58	——	35±1	0.005
2	120	3.3	——	0.62	——	0.51	2.20	87±2	0.042
3A	150	5.1	——	0.73	——	0.59	1.59	98±2	0.092
3B	200	7.0	——	0.65	——	0.57	2.06	96±1	0.089
4	120	3.3	——	0.63	——	0.51	2.17	95±1	0.054
5A	270	11	——	——	2.2	0.72	1.39	120±3	0.076
5B	270	11	——	——	1.1	0.69	1.38	120±3	0.11
5C	270	11	——	——	0.55	0.66	1.33	122±3	0.095
5D	610	25	——	——	2.2	0.66	2.67	125±5	0.13
5E	610	25	——	——	1.1	0.63	2.72	125±5	0.21
5F	610	25	——	——	0.6	0.61	——	125±5	——
6	270	11	——	——	2.2	0.74	1.44	120±3	0.11

Table 3 Characteristic parameters for two-phase reacting flow

Case	Power output, kW	Reynolds number	Sauter mean diameter, μm	Stokes number	Flow residence time, ms	Pulsed power fraction	Relative amount of suppression $\left(\frac{p'_{natural} - p'_{control}}{p'_{natural}}\right)$
1A	66	7.7×10^4	50	0.21	16	0.30	0.78
1B	82	7.7×10^4	50	0.21	16	0.25	0.81
2	180	2.0×10^5	39	0.28	15	0.15	0.67
3A	270	2.5×10^5	36	0.27	8.8	0.12	0.66
3B	360	3.4×10^5	38	0.30	8.4	0.08	0.60
4	180	2.0×10^5	39	0.31	11	0.15	0.45
5A	630	4.4×10^5	10	0.034	5.6	0.15	0.71
5B	580	4.4×10^5	10	0.034	5.5	0.079	0.66
5C	560	4.4×10^5	10	0.034	5.3	0.041	0.61
5D	1280	1.0×10^6	10	0.035	4.7	0.072	0.52
5E	1230	1.0×10^6	10	0.035	4.8	0.037	0.49
5F	1210	1.0×10^6	10	0.035	4.8	0.019	0.11
6	630	4.4×10^5	10	0.034	5.1	0.15	0.82

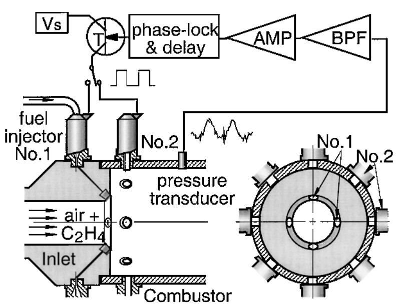
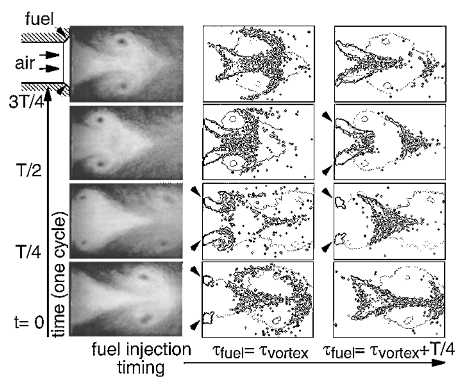


Fig. 2 Liquid-fuel actuation system and a simple phase-delay closed-loop control.

with respect to the combustor pressure signal was digitally adjusted using a Wavetek Variable Phase Synthesizer. The liquid fuel was supplied through a set of pulsed injectors that were evenly spaced along the circumference of the inlet at the dump plane. The initial injection angle was fixed at either 45 or 90 deg with respect to the airflow direction depending on the type of injectors used.

III. Active Control Operation (Case 1)

ACC using pulsed liquid-fuel injection is more complex than the corresponding approach using gaseous fuel. Whereas vortex dynamics in the shear flow is easily manipulated by gaseous fuel actuation that generates acoustic waves and controls turbulent mixing, liquid-fuel droplets are less affected by acoustic waves. Furthermore, because of nonuniform time delays associated with burning of polydisperse fuel sprays, modulating only the global fuel flux may or may not result in controlled oscillations of local heat release. Consequently, other mechanisms were needed in addition to periodic modulation of the total fuel flux into the combustor.



a) b) c)

Fig. 3 Fuel droplet dispersion as a result of interaction with vortex: a) planar Mie-scattering images of airflow without fuel injection, b) Mie-scattering intensity of fuel droplets with injection timing at τ_{fuel} = τ_{vortex}, and c) τ_{fuel} = τ_{vortex} + $T/4$.

In the present experiment, a new approach was utilized that relied on timing-dependent droplet dispersion behavior. As a result of pulsed sprays interacting with periodic flow structures,[42] the fuel droplet dispersion behavior was sensitive to the timing of fuel injection that determined the initial slip velocity between fuel and airflow. Figure 3 shows fuel droplet dispersion pattern as a function of the injection timing and vortex development phase in a simulated nonreacting combustor flow.[18] The images were obtained using phase-locked planar Mie-scattering technique (see Ref. 43) and were phase averaged to filter out random motion associated with turbulence. The fuel droplets injected ahead of the vortex shedding (Fig. 3b) were subjected to the accelerating flow associated with the

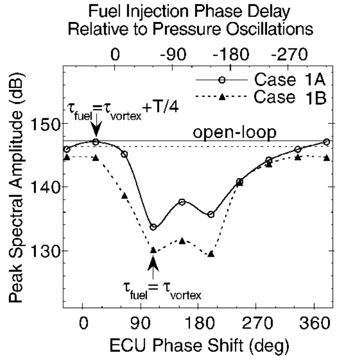


Fig. 4 Pressure oscillation spectral amplitude as a function of injection timing; two straight lines show the amplitude levels for uncontrolled cases.

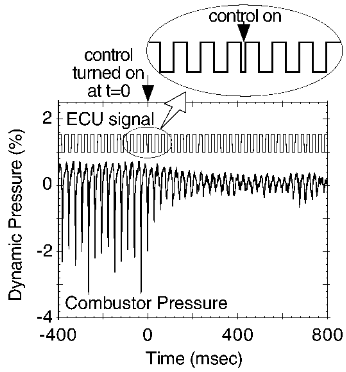


Fig. 5 Onset of active instability suppression by adjusting the timing of pulsed fuel injection (case 1A).

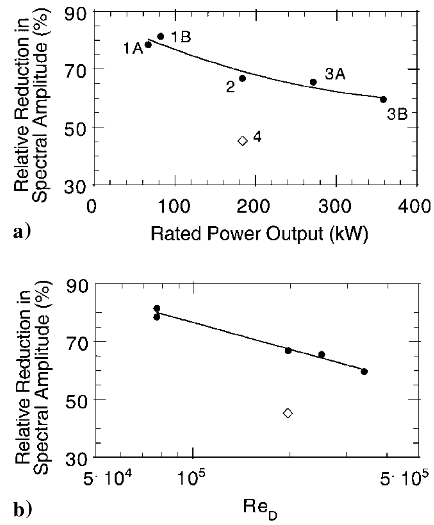


Fig. 6 Relative amount of instability suppression as a function of a) rated power output and b) inlet flow Reynolds number.

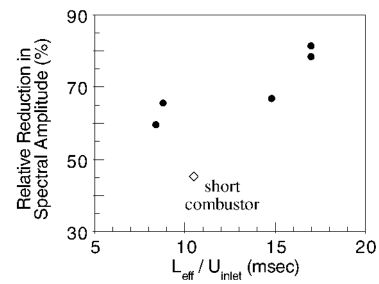


Fig. 7 Effect of flow residence time on the amount of relative amplitude reduction.

vortices, which resulted in rapid dispersion into the recirculation zone. On the other hand, when fuel was injected after the vortex shedding (Fig. 3c), the droplets clustered in the core of the jet flow.

Because this method provides some control over spatial distribution of fuel droplets, it may be possible to control the phase of local heat release oscillations. The method was first tested previously[44] under relatively low combustor output conditions (cases 1A and 1B) that produced strong pressure oscillations at 35 Hz in the vicinity of the lean-mixture flammability limit. To suppress these oscillations, the closed-loop controller of Fig. 2 with actuator 1 was applied. Figure 4 shows the average spectral amplitude of pressure oscillations as a function of the phase delay assigned to the ECU. To assist the phase lock, the pressure signal was filtered between 25 and 40 Hz using a Butterworth bandpass filter. The actual phase delay with respect to the pressure signal is also shown in the top abscissa. The oscillation amplitude was maximum when the pulsed injection started at phase $\pi/2$ after the vortex shedding, and it was minimum when the start of the injection was synchronized with the vortex shedding. The maximum amplitude in these cases was very close to the natural oscillation amplitude without the control. For cases 1A and 1B, the sound pressure level was reduced by 12 and 15 dB, respectively. The phase relation was not affected by small changes in operating conditions.

Figure 5 shows the transient behavior of the combustor pressure as the proper phase-delay was applied at time $t = 0$. When the start of the fuel injection cycle was timed with the vortex shedding process, oscillation amplitude was quickly brought under control. To apply the phase lock and the proper timing of fuel injection, a small amplitude of oscillations needs to be maintained. The rms pressure amplitude under active control was, however, well below 0.5% of the combustor pressure. The combustor pressure spectrum showed that all of the harmonics as well as the fundamental mode were effectively reduced in this case.[44]

IV. Scale-Up Tests (Cases 2–4)

Similar experiments were extended to higher output power levels by increasing the flow rates and changing the liquid fuel from ethanol to heptane (cases 2–4) Whereas the change in fuel type stemmed from the effort to use more energetic fuel, the combustor configurations were selected for their naturally developed instabilities. The same actuator system was utilized throughout the scale-up experiments in cases 1–4 because the fuel actuation characteristics is critical for liquid-fueled active control, and those used in configuration 1 were well proven. In a similar manner as before, pulsed-fuel-injection timing was adjusted with the closed-loop controller for each case. While holding the controller fuel flux constant, the overall combustor power output was raised by increasing the total mass flux. Although it was possible to suppress the oscillation amplitude by as much as 15 dB at lower output conditions, the present control system was no longer effective beyond 360-kW output. This appeared to be related to the reduction in secondary fuel flux amount relative to the total fuel flux. At the 360-kW condition, the relative amount of time-averaged fuel flux into the controller was about 8% of the total fuel flux.

Figure 6 shows the amount of relative reduction in peak spectral amplitude as a function of the rated power output and the inlet flow Reynolds number. With the exception of case 4, all other data followed a general trend that indicated the diminishing control effectiveness with flow scale. To elucidate the possible cause of this behavior, the effect of flow residence time was first examined. Because large fuel droplets in pulsed sprays would require a long induction time before releasing heat, they are especially susceptible to the decrease in flow residence time. Figure 7 shows that the relative amplitude reduction was generally lower with reduced residence time. However, the data were widely scattered in the plot, and it was difficult to draw a conclusion based only on the flow residence time consideration. Because large droplets tend to not follow the carrier fluid flow closely, the flow residence time would not be a good measure of the droplet residence time. This may explain the peculiar behavior associated with the short combustor in case 4. Clearly, reducing the combustor length, which proportionally decreased the droplet residence time, appeared to be more detrimental to the control effectiveness than increasing the inlet flow speed.

Another explanation was provided by considering the relative contribution of heat release from the pulsed fuel injection. The relative amount of instability amplitude suppression was plotted as a function of the relative amount of controller fuel, which is defined

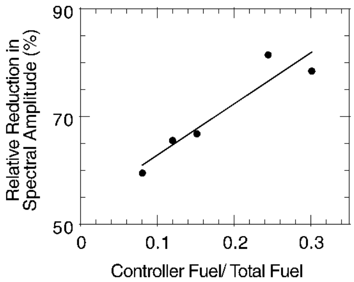


Fig. 8 Effect of pulsed fuel ratio on the amount of relative amplitude reduction.

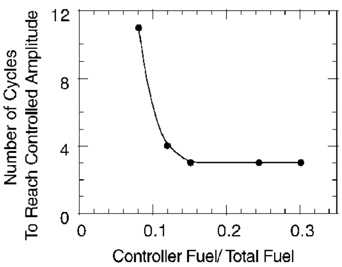


Fig. 9 Active control effectiveness as a function of pulsed fuel ratio.

as the ratio between the time-averaged potential heat release from the controller fuel flux and the overall heat release from the total fuel amount. Because the same actuator system was utilized in all of the experiments, this ratio was subject to change as the steady flux of the primary fuel was increased in the scale-up tests or as the type of the controller fuel was changed in the actuator system. Figure 8 shows the dependence of the controlled amplitude reduction on the relative controller fuel ratio. The data were compared for similar length combustors that included all but the case 4 condition. The resulting relationship was quite similar to the dependency on Reynolds number, indicating the importance of the relative controller fuel flux on the potential amplitude reduction.

Figure 9 shows another measure of the control effectiveness on the fuel ratio in terms of the total number of oscillation cycles required to bring the amplitude to the final controlled level. Because polydisperse characteristics of typical fuel sprays make it inefficient to convert pulsed fuel flux into corresponding pulsed heat release, a relatively large amount of pulsed fuel would be required to generate periodic heat release. As the fuel ratio was lowered to 0.08, the controller became only marginally effective requiring many cycles to bring down the oscillation amplitude. Again, the result correlated well with the fuel ratio, which suggested that about 8% or more of the total fuel flux had to be controlled to make ACC effective in this case. However, it is likely that the critical amount of pulsed fuel would be a function of the actuator characteristics including the fuel droplet size.

V. Effect of Droplet Size Reduction

Atomizing Actuator and Further Scale-Up

Fuel droplet size is an important factor in liquid-fueled ACC because it affects the degree of interaction with flow structures, which in turn determines the characteristic dispersion. Also, more important, the droplet size establishes the temporal response characteristics of heat release. For instance, it is well established that the characteristic heating time for small fuel droplets is proportional to the droplet diameter, whereas the vaporization rate follows the so-called D^2 law.[45,46] This implies that the characteristic delay time associated with heat release would be closely related to the droplet diameter. Therefore, it is reasonable to expect that the critical amount of fuel needed for the controller would be a function of the droplet size as well as the fuel type.

In an effort to reduce the relative amount of fuel needed for ACC, the characteristic droplet size was reduced using new actuators. The performance of the new actuators (injector 2) was investigated as a function of frequency and duty cycle. Figure 10 shows the results of the droplet sizing experiment using a Malvern Mastersizer. There was roughly a factor of four reduction in fuel droplet size from the earlier case, which made it possible to investigate the influence of

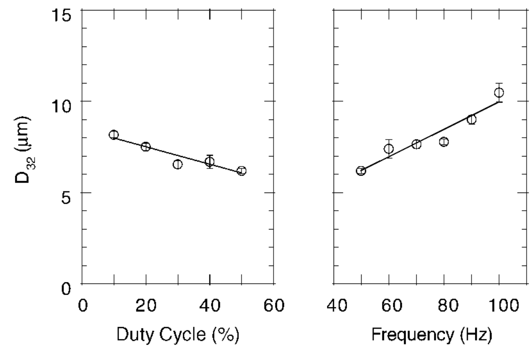


Fig. 10 Average droplet size of JP-10 sprays pulsed with the new actuators as a function of duty cycle and frequency: Δp_{fuel} = 150 psig and Δp_{air} = 100 psig.

the characteristic droplet size on ACC effectiveness. Whereas the new atomizing actuator produced very fine droplets, its frequency response was limited to 150 Hz. For most cases shown in this paper, the actuator was operated at 20% duty cycle.

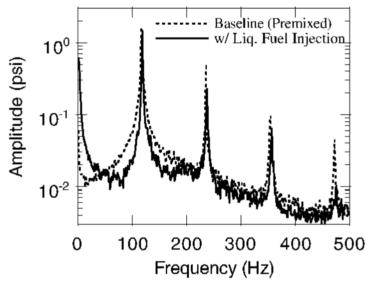
Further scale-up tests were conducted, and the controller fuel was changed to JP-10, which was considered a more practical fuel. In the last series of tests involving cases 5 and 6, the combustor thermal output was raised to the 1.3-MW condition. Because excess stress on the combustor wall was evident due to the high amount of volumetric heat release combined with a high level of instabilities, the total test duration for each run was limited to no more than 3 min. A typical test run for highest output cases consisted of establishing a limit cycle in the first 150 s followed by a brief period of data collection. Despite such a precaution, the combustor was occasionally damaged after a particularly intense instability or a slightly extended period of operation. As a result, the combustor configuration had to be changed a number of times. Also, to minimize the test duration and the number of tests, the data were often collected at predetermined fixed phase-delay settings without running a complete system identification procedure, which yielded the optimum controller setting experimentally.

Although no additional effort was made to optimize the control parameters, the data clearly showed that substantial reduction in instability amplitude was possible even under relatively high thermal output conditions. Also, the controller performed effectively, despite that the flow residence time was made much shorter and that the relative controller fuel flux was brought below the 8% level. The most critical change in these cases appeared to be due to the reduction in controller fuel droplet size.[47]

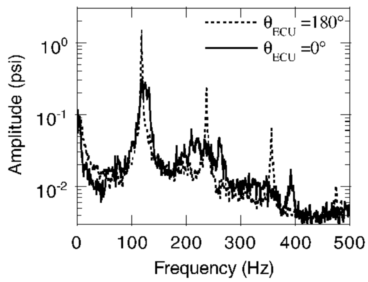
Controller Fuel Amount (Case 5)

Closed-loop ACC was applied to suppress the oscillations in case 5A. Figure 11 shows the combustor pressure spectra using various controller settings but under the identical flow conditions in the time-averaged sense, including the same equivalence ratio and the same power output. In Fig. 11a, pressure spectra for conditions with and without liquid-fuel injection are compared. The baseline premixed case, which is shown for reference, used an additional amount of ethylene, which was equivalent to the controller fuel amount in liquid-fuel injection case. The comparison shows that the advantage associated with direct liquid fuel injection would be rather limited unless the controller fuel was injected at the proper timing. Figure 11b shows that fuel injection at the proper timing reduced the peak amplitude substantially. Instability suppression was very effective even though the combustor power output was very high (630 kW) and the flow residence time very low (5.6 ms). Such results were expected in this case because a relatively large amount of fuel (15%) was supplied through the controller.

Figure 12 shows the variation in oscillation amplitude as a function of the ECU phase for three slightly different conditions. When the number of injectors was reduced by a factor of two each time, the amount of controller fuel was reduced systematically in cases 5B and 5C. The control effectiveness was affected relatively little by



a) With and without liquid fuel injection



b) Closed-loop controlled injection with various injection timings

Fig. 11 Combustor pressure spectra for case 5A.

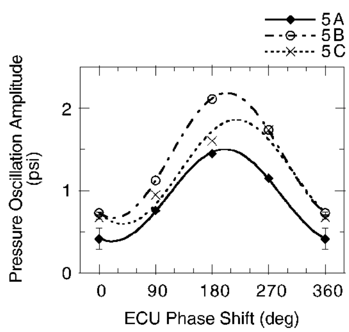


Fig. 12 Spectral amplitude variation as a function of pulsed injection timing for cases 5A–5C.

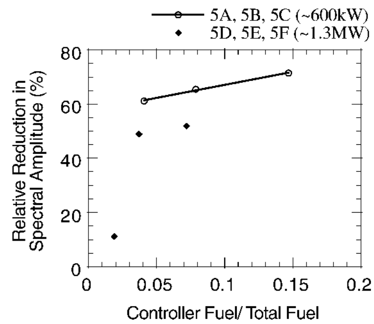


Fig. 13 Maximum reduction in spectral amplitude from four injection timings as a function of relative fuel amount.

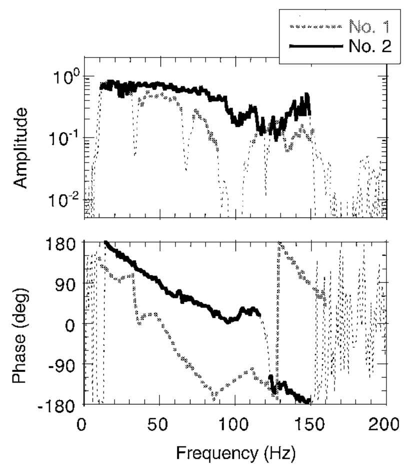


Fig. 14 Transfer function between combustor pressure and injector driving signal.

this change. Although the data were obtained only at four predetermined phase settings, they were consistent with the earlier plots showing the typical phase dependence. The data were fitted with sinusoidal curve fits to show that the control characteristics, including the optimum phase condition, remained relatively unchanged in this case. Both the relative amount of suppression and the proper phase setting remained similar, even when the controller fuel flux was reduced well below 8% of the total fuel flux, which, in the earlier experiments using injectors 1, was the critical fuel amount. In case 5C, the controller fuel flux was only about 4% of the total fuel flux, yet the control appeared to be quite effective. It appears that the control effectiveness was clearly enhanced by reduced fuel droplet size. To reduce the controller fuel flux even further without affecting the fuel atomization characteristics, the steady fuel flux had to be increased once again.

In cases 5D–5F, the combustor power output was scaled up to nearly 1.3-MW condition while holding the actuator conditions constant. Thus, the relative amount of controlled fuel flow was decreased, respectively, to 7.2, 3.7, and 1.9% of the total heat release potential. Figure 13 shows the relative amount of instability suppression using 0-deg ECU phase setting. Whereas the data showed a small shift in the level of controlled suppression between 600 kW and 1.3 MW conditions, indicative of the poorly optimized phase settings, the controller action was again effective for most conditions except in case 5F. When the controlled injection amount was reduced to 1.9%, flameout was often encountered especially under the improper phase setting. Because the operating condition was very close to the flammability limit, it was difficult to deduce the critical fuel flux more precisely. However, even under different injection timing, the instability was in general not very respondent to the injection phase shift in case 5F, and the oscillation amplitude changed very little. This indicated that, with the new actuators providing the given atomization characteristics, the critical fuel flux for suppressing the instability was around 2% of the total fuel flux.

Actuation at Harmonic Frequencies Using Alternating Injection (Case 6)

Although the new actuator (actuator 2) worked effectively for the most conditions considered so far, its frequency response was limited to 150 Hz. Within its frequency-response band, the actuator was effective in modulating combustion heat release. Figure 14 shows the experimental transfer function between the combustor pressure signal and the ECU signal. Within the operating range of up to 150 Hz, the response appears to be very good. For higher frequency actuation, an alternating injection approach can be utilized.

An experiment on alternating injection control was conducted with the configuration 6 combustor. Two pairs of injectors were driven at 180-deg out of phase with 20% duty cycle, which produced an equivalent effect as one pair of injectors driven at twice the frequency with 40% duty cycle. When this approach was used, apparent frequency response was extended by a factor of two. Also, this made it possible to explore open-loop injection control to frequencies beyond 150 Hz.

With the open-loop injection control, an interesting result was obtained particularly when the apparent injection frequency was close to the higher harmonics of the fundamental instability mode frequency. Figure 15 compares the pressure spectra between the baseline and the condition at which alternating open-loop injection was performed at 109 Hz with a corresponding frequency-doubling effect at 218 Hz. Apparently, the active forcing at frequencies close to the second harmonic of the instability promoted acoustic energy transfer from the 120-Hz instability mode to the injector driven mode at 218 Hz maintaining relatively low-amplitude oscillations

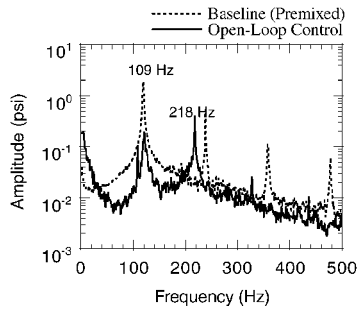


Fig. 15 Combustor power spectra for case 6 with open-loop alternating injection at 109 Hz that resulted in equivalent effect as 218-Hz actuation.

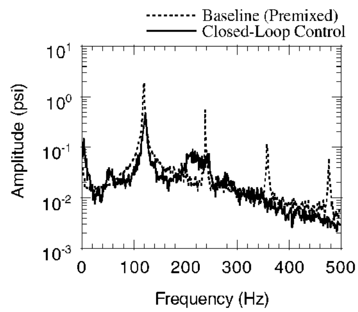


Fig. 16 Power spectra for closed-loop controlled alternating injection with effective actuation near 240 Hz.

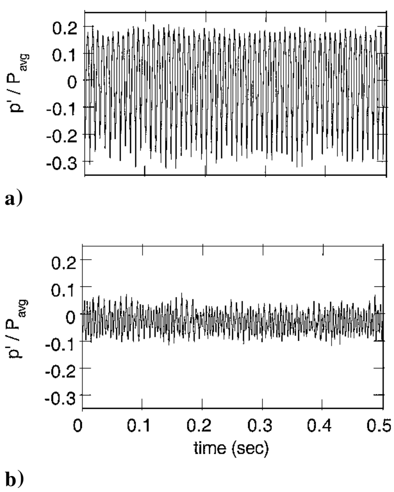


Fig. 17 Comparison of combustor pressure traces for case 6: a) under baseline operation with natural instability and b) with closed-loop injection control.

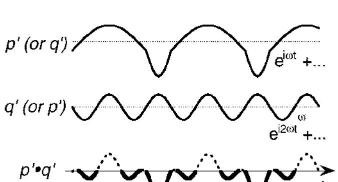


Fig. 18 Rayleigh's criterion when the main frequencies of pressure oscillation p' and controlled heat release oscillation q' are harmonics.

at both frequencies. However, as the injection frequency was made even closer to the second harmonic frequency, oscillation amplitude eventually became large at the second harmonic frequency.

Closed-loop controlled injection at twice the instability frequency is also very effective under certain conditions. Figures 16 and 17 show the pressure traces and spectra that indicate effective reduction of oscillation amplitude. In most cases involving high-amplitude combustion instability and control, neither the pressure oscillation signal nor the controlled heat release behave as pure sine waves. This makes it possible to use periodic heat release oscillations at one of the harmonic or subharmonic frequencies for controlling pressure oscillations at the fundamental frequency. Figure 18 illustrates this point. Even though the primary frequency components are different for p' and q', the integral of their product is not identically zero due to the presence of harmonic contents. Because an integral of the product of p' and q' is related to the change in acoustic energy in this case, a closed-loop ACC can be applied with pulsed fuel actuation at frequencies other than the instability frequency.

Such a characteristic adds to the practicality of applying ACC in realistic systems because some of the available actuators may have a limited repetition rate. Provided that the injection duration is short enough to produce a sudden pulse of heat release, sub-harmonic fuel injection can be used for controlling high-frequency oscillations.[48,49] Simply stated, if a burst of heat release can be produced at every other negative pressure cycle, the net product of p' and q' will be negative over multicycles leading to gradual reduction in total acoustic energy. Needless to say, this type of control strategy could also be used to extend the lifecycle time for actuators.

VI. Summary

An experimental study on liquid-fueled active instability suppression was conducted using a closed-loop pulsed fuel injection whose timing was adjusted with a simple phase delay. First, a demonstration experiment was performed in a model ramjet dump combustor operating at about 70-kW output level, where it developed natural instabilities. The results showed that combustion instabilities can be successfully suppressed using properly designed pulsed liquid-fuel injection. Two sets of scale-up experiments were performed taking the nominal output of the combustor first up to 360 kW and then up to 1.3 MW. The relative amount of instability suppression was compared as a function of various parameters at optimized fuel-injection timing. The results indicated that there was a minimum amount of pulsed fuel flux, which was required to obtain effective suppression. In the first set of experiments, effective instability suppression was obtained if the time-averaged amount of pulsed fuel flux was greater than about 8% of the total fuel flux. In the subsequent set of experiments, the average fuel droplet size was reduced by a factor of four by utilizing a new set of air-assisted fuel injectors for liquid-fuel actuation. The results showed that the critical amount of controller fuel flux was reduced when a finer spray was used. The limiting fuel flux in the latter case was about 2% of the total fuel flux.

The experiments were conducted over a wide range of combustor output conditions ranging between 70 kW and 1.3 MW. The results showed that liquid-fueled active instability suppression would be applicable even at higher output combustors provided that the controller fuel flux exceeded a critical amount. The quantitative results as well as some additional observations are summarized in the following.

1) The critical amount of controlled fuel flux for effectively suppressing the instability can be lowered by enhancing the atomization of fuel droplets. In the experiments, when pulsed heptane sprays of 40-μm Sauter mean diameter D_{32} were used as the controller fuel, the minimum required fuel flux was in the neighborhood of 8% of the total fuel flux. On the other hand, when pulsed JP-10 sprays with D_{32} of about 10 μm were used, the minimum fuel flux was lowered to a new limit, which was approximately 2% of the total fuel flux.

2) When multiple injectors are used, they can be phase delayed from each other resulting in an increase in the apparent frequency response. This will make the actuator system more practical because actuators with limited frequency response can be applied.

3) Combustion instability can be actively controlled with a closed-loop controlled fuel injection at frequencies other than the instability frequency. In the present experiment, closed-loop controlled injection at the second harmonic frequency was demonstrated for suppressing the instability at the fundamental frequency. The results are encouraging because they offer more flexibility in applying a closed-loop controller with fuel injection frequencies different than the instability frequency.

Acknowledgments

This study was sponsored by the Office of Naval Research with Gabriel D. Roy as the Scientific Officer. The authors acknowledge helpful discussion with Klaus Schadow from the U.S. Naval Air Warfare Center, who is now with Strategic Analysis, Inc. Some of the prototype fuel injectors in the experiment were provided by

Alan Casey from Split-Cycle Technology, Ltd. Fuel droplet sizing experiments were conducted in collaboration with Chris Brophy and David Netzer from the Naval Postgraduate School.

References

[1]Lang, W., Poinsot, T., and Candel, S., "Active Control of Combustion Instability," *Combustion and Flame*, Vol. 70, No. 3, 1987, pp. 281–289.

[2]Bloxsidge, G. J., Dowling, A. P., Hooper, N., and Langhorne, P. J., "Active Control of Reheat Buzz," *AIAA Journal*, Vol. 26, No. 7, 1988, pp. 783–790.

[3]Poinsot, T., Bourienne, F., Candel, S., and Esposito, E., "Suppression of Combustion Instabilities by Active Control," *Journal of Propulsion and Power*, Vol. 5, No. 1, 1989, pp. 14–20.

[4]Langhorne, P. J., Dowling, A. P., and Hooper, N., "Practical Active Control System for Combustion Oscillations," *Journal of Propulsion and Power*, Vol. 6, No. 3, 1990, pp. 324–333.

[5]Schadow, K. C., Gutmark, E., and Wilson, K. J., "Active Combustion Control in a Coaxial Dump Combustor," *Combustion Science and Technology*, Vol. 81, No. 4–6, 1992, pp. 285–300.

[6]Gulati, A., and Mani, R., "Active Control of Unsteady Combustion-Induced Oscillations," *Journal of Propulsion and Power*, Vol. 8, No. 5, 1992, pp. 1109–1115.

[7]Sivasegaram, S., Tsai, R.-F., and Whitelaw, J. H., "Control of Combustion Oscillations by Forced Oscillation of Part of the Fuel Supply," *Combustion Science and Technology*, Vol. 105, 1995, pp. 67–83.

[8]McManus, K. R., Vandsburger, U., and Bowman, C. T., "Combustor Performance Enhancement Through Direct Shear Layer Excitation," *Combustion and Flame*, Vol. 82, No. 1, 1990, pp. 75–92.

[9]Wilson, K. J., Gutmark, E., Schadow, K. C., and Smith, R. A., "Active Control of a Dump Combustor with Fuel Modulation," AIAA Paper 91-0368, Jan. 1991.

[10]Gutmark, E., Parr, T. P., Hanson-Parr, D. M., and Schadow, K. C., "Stabilization of Combustion by Controlling the Turbulent Shear Flow Structure," Seventh Symposium on Turbulent Shear Flows, Paper 23-1, 1989.

[11]Yu, K., Trouve, A., and Candel, S., "Combustion Enhancement of a Premixed Flame by Acoustic Forcing with Emphasis on Role of Large-Scale Vortical Structures," AIAA Paper 91-0367, Jan. 1991.

[12]Gutmark, E., Parr, T. P., Hanson-Parr, D. M., and Schadow, K. C., "Use of Chemiluminescence and Neural Networks in Active Combustion Control," *Proceedings of the Twenty-Third International Symposium on Combustion*, Combustion Inst., Pittsburgh, PA, 1990, pp. 1101–1106.

[13]Brouwer, J., Ault, B. A., Bobrow, J. E., and Samuelsen, G. S., "Active Control for Gas Turbine Combustors," *Proceedings of the Twenty-Third International Symposium on Combustion*, Combustion Inst., Pittsburgh, PA, 1990, pp. 1087–1092.

[14]Gutmark, E., Parr, T. P., Hanson-Parr, D. M., and Schadow, K. C., "Closed-Loop Amplitude Modulation Control of Reacting Premixed Turbulent Jet," *AIAA Journal*, Vol. 29, No. 12, 1991, pp. 2155–2162.

[15]Parr, T. P., Gutmark, E. J., Wilson, K. J., Yu, K., Smith, R. A., Hanson-Parr, D. M., and Schadow, K. C., "Compact Incinerator Afterburner Concept Based On Vortex Combustion," *Proceedings of the Twenty-Sixth International Symposium on Combustion*, Vol. 2, Combustion Inst., Pittsburgh, PA, 1996, pp. 2471–2477.

[16]Keller, J. O., and Hongo, I., "Pulse Combustion: The Mechanisms of NOx Production," *Combustion and Flame*, Vol. 80, Nos. 3 and 4, 1990, pp. 219–237.

[17]Sivasegaram, S., and Whitelaw, J. H., "Control of Flame and Emissions by Oscillation," *Proceedings of Ninth ONR Propulsion Meeting*, 1996, pp. 272–285.

[18]Yu, K. H., Parr, T. P., Wilson, K. J., Schadow, K. C., and Gutmark, E. J., "Active Control of Liquid-Fueled Combustion Using Periodic Vortex–Droplet Interaction," *Proceedings of the Twenty-Sixth International Symposium on Combustion*, Vol. 2, Combustion Inst., Pittsburgh, PA, 1996, pp. 2843–2850.

[19]Yu, K. H., Wilson, K. J., and Schadow, K. C., "Liquid-Fueled Active Instability Suppression," *Proceedings of the Twenty-Seventh International Symposium on Combustion*, Vol. 2, Combustion Inst., Pittsburgh, PA, 1998, pp. 2039–2046.

[20]Yu, K. H., and Schadow, K. C., "Active Combustion Control in a Liquid-Fueled Dump Combustor," AIAA Paper 97-0462, Jan. 1997.

[21]McManus, K. R., Magill, J. C., and Miller, M. F., "Combustion Instability Suppression in Liquid-Fueled Combustors," AIAA Paper 98-0642, Jan. 1998.

[22]Cohen, J. M., Rey, N. M., Jacobson, C. A., and Anderson, T. J., "Active Control of Combustion Instability in a Liquid-Fueled Low-NOx Combustor," *Journal of Engineering for Gas Turbines and Power*, Vol. 121, No. 2, 1999, pp. 281–284.

[23]Culick, F. E. C., "Combustion Instabilities in Propulsion Systems," *Combustion Instabilities Driven By Thermo-Chemical Acoustic Sources*, NCA-Vol. 4, HTD-Vol. 128, American Society of Mechanical Engineers, Fairfield, NJ, 1989, pp. 33–52.

[24]McManus, K. R., Poinsot, T., and Candel, S., "A Review of Active Control of Combustion Instabilities," *Progress in Energy and Combustion Science*, Vol. 19, No. 1, 1993, pp. 1–29.

[25]Candel, S. M., "Combustion Instabilities Coupled by Pressure Waves and Their Active Control," *Proceedings of the Twenty-Fourth International Symposium on Combustion*, Combustion Inst., Pittsburgh, PA, 1992, pp. 1277–1296.

[26]Yang, V., and Schadow, K. C., "AGARD Workshops on Active Combustion Control for Propulsion Systems," *Proceedings of NATO–RTO Symposium on Gas Turbine Engine Combustion, Emissions, and Alternative Fuels*, RTO-MP-14, 1998, pp. 36/1–36/20.

[27]Schadow, K. C., Yang, V., Culick, F., Rosfjord, T., Sturgess, G., and Zinn, B., "Active Combustion Control for Propulsion Systems," AGARD Rept. 820, 1997.

[28]Zinn, B. T., and Neumeier, Y., "An Overview of Active Control of Combustion Instabilities," AIAA Paper 97-0461, Jan. 1997.

[29]Lord Rayleigh, *The Theory of Sound*, Dover, New York, 1945, p. 227.

[30]Putnam, A., *Combustion Driven Oscillations in Industry*, Elsevier, New York, 1971, pp. 2, 3.

[31]Lazaro, B. J., and Lasheras, J. C., "Particle Dispersion in a Turbulent, Plane, Free Shear Layer," *Physics of Fluids A*, Vol. 1, June 1989, pp. 1035–1044.

[32]Longmire, E. K., and Eaton, J. K., "Structure of a Particle-Laden Round Jet," *Journal of Fluid Mechanics*, Vol. 236, March 1992, pp. 217–257.

[33]Glawe, D. D., and Samimy, M., "Dispersion of Solid Particles in Compressible Mixing Layers," *Journal of Propulsion and Power*, Vol. 9, No. 1, 1993, pp. 83–89.

[34]Chung, J. N., and Troutt, T. R., "Simulation of Particle Dispersion in an Axisymmetric Jet," *Journal of Fluid Mechanics*, Vol. 186, 1988, pp. 199–222.

[35]Chang, E., and Kaliasanath, K., "Simulations of Particle Dynamics in an Axisymmetric Ramjet Combustor," *AIAA Journal*, Vol. 34, No. 6, 1996, pp. 1160–1166.

[36]Parr, T. P., Gutmark, E. J., Hanson-Parr, D. M., and Yu, K., "Control of Sooty High Energy Density Fuel Combustion," *Proceedings of Eighth ONR Propulsion Meeting*, 1995, pp. 215– 224.

[37]Lefebvre, A. H., *Atomization and Sprays*, Taylor and Francis, Bristor, PA, 1989, p. 222.

[38]Billoud, G., Galland, M. A., Huynh Huu, C., and Candel, S., "Adaptive Active Control of Combustion Instabilities," *Combustion Science and Technology*, Vol. 81, No. 4–6, 1992, pp. 257–284.

[39]Yang, V., Sinha, A., and Fung, Y.-T., "State Feedback Control of Pressure Oscillations in Combustion Chambers," *Journal of Propulsion and Power*, Vol. 8, No. 1, 1992, pp. 66–73.

[40]Fung, Y.-T., and Yang, V., "Active Control of Nonlinear Pressure Oscillations in Combustion Chambers," *Journal of Propulsion and Power*, Vol. 8, No. 6, 1992, pp. 1282–1289.

[41]Annaswamy, A. M., Fleifil, M., Rumsey, J. W., Hathout, J. P., and Ghoniem, A. F., "An Input–Output Model of Thermoacoustic Instability and Active Control Design," Rept. 9705, Massachusetts Inst. of Technology, Cambridge, MA, 1997.

[42]Yu, K. H., Trouve, A., and Daily, J. W., "Low Frequency Pressure Oscillations in a Model Ramjet Combustor," *Journal of Fluid Mechanics*, Vol. 232, 1991, pp. 47–72.

[43]Yu, K. H., and Schadow, K. C., "Phase-Controlled Mie-Scattering Visualization for Studying Periodic Fuel Injection into Oscillating Flowfield," *Journal of Flow Visualization and Image Processing*, Vol. 4, No. 3, 1997, pp. 201–210.

[44]Yu, K., Wilson, K. J., and Schadow, K. C., "Active Combustion Control in a Liquid-Fueled Dump Combustor," AIAA Paper 97-0462, Jan. 1997.

[45]Sirignano, W. A., "Fuel Droplet Vaporization and Spray Combustion Theory," *Progress in Energy and Combustion Science*, Vol. 9, No. 4, 1983, pp. 291–322.

[46]Faeth, G. M., "Evaporation and Combustion of Sprays," *Progress in Energy and Combustion Science*, Vol. 9, No. 1/2, 1983, pp. 1–76.

[47]Yu, K. H., and Schadow, K. C., "A Study on Active Combustion Control for Advanced Combustors," *Naval Research Reviews*, Vol. 51, No. 3–4, 1999, pp. 4–13.

[48]Jones, C. M., Lee, J. G., and Santavicca, D. A., "Closed-Loop Active Control of Combustion Instabilities Using Subharmonic Secondary Fuel Injection," *Journal of Propulsion and Power*, Vol. 15, No. 4, 1999, pp. 584–590.

[49]Yu, K., Wilson, K. J., and Schadow, K. C., "Scale-Up Experiments on Liquid-Fueled Active Combustion Control," AIAA Paper 98-3211, July 1998.