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ACTIVE COMBUSTION CONTROL FOR PROPULSION SYSTEMS

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Abstract

Active combustion control (ACC) is increasingly becoming a candidate to meet the challenges of future combustor designs, which cannot be met within traditional (passive) design approaches. The paper will review the current status based on three recent activities: (1) a workshop, (2) a collaborative program to demonstrate closed-loop control of a generic dump combustor using diode laser sensors and advanced controller, and (3) two research programs to apply the detailed understanding of fluid dynamic/combustion/acoustics interactions to active control of liquid and gaseous fuel dump combustors. Pulsed fuel injection from an active control approach will be emphasized. At the present time, one successful full-scale ACC propulsion application has been openly reported for a lean premix combustor. For other applications, forecasts generally rest on laboratory demonstrations without full understanding of the scaling laws. Needs for research and development will be identified to improve physical understanding and to develop sensors, actuators, and control laws. The majority of the present work uses ACC to suppress oscillations. Other applications are equally important. One example is the use of actively controlled vortex combustion to enhance combustion and reduce pollution in compact designs. Closed-loop experiments and scale-up experiments of this approach are being discussed. This concept is also explored for instability control in liquid fuel ramjets by controlling the temporal and spatial droplet distribution.

1. Introduction

Significant progress has been made in the area of active combustion control (ACC) since the 18th ICAS Congress review paper on the same subject.[1] Active combustion control, which controls the combustion dynamics by proper use of sensors, actuators, and controllers, is increasingly becoming a candidate to meet the challenges for future combustor designs, which cannot be met within traditional (passive) design approaches. The paper will review the current status of this emerging technology based on three recent activities. These are (1) a recent workshop which was attended by leading experts from industry, government, and universities from Europe and the United States, (2) a Naval Air Warfare Center Weapons Division (NAWCWPNS) managed collaborative program to demonstrate closed-loop ACC of a generic dump combustor using diode laser sensors and a rule-based as well as model-based controller, and (3) two NAWCWPNS research programs to apply the detailed understanding of fluid dynamic/combustion/acoustics interactions to active control of liquid and gaseous fuel dump combustors. In order to manage the large quantity of information, this paper will focus on pulsed fuel injection from an active control approach. It has become a preferred method not only to suppress oscillations but also to enhance efficiency and reduce pollutant emissions. For instability suppression, pulsed fuel injection creates controlled heat release that oscillates out of phase with respect to the pressure oscillations to satisfy the Rayleigh's criterion; for efficiency and pollution control, pulsed fuel injection is synchronized with the development of large-scale air vortices as discussed in more detail later.

2. Workshop Summary

The workshop discussions and conclusions are presented in detail in Ref. 2. A brief summary of the following three topics is provided in this paper: (1) status of ACC, (2) potential ACC applications, and (3) research and development needs.

Status of Active Combustion Control

Active combustion control studies have addressed various combustion characteristics, including suppression of combustion instabilities, improving combustion efficiency, extending flammability limits, and minimizing pollution production. The workshop report summarizes the recent work in these areas which was also extensively reviewed in Refs. 3-5. In this paper new work on pulsed fuel injection will be briefly discussed, which is relevant to the following discussions of ACC applications. This work includes suppression of combustion instabilities in lean premix systems and performance enhancement and emission control in dump combustors.

The United Technology Research Center (UTRC) is conducting work on lean premix burners using both gaseous and liquid fuels. A small scale atmospheric pressure rig for screening of actuation and control concepts and a single nozzle rig for testing engine scale hardware at combustor operating pressures and temperatures are being utilized. The control system, which controls the pulsed delivery of a portion of the fuel flow, was evaluated at several different operational conditions directly corresponding to engine power settings. Instabilities were successfully attenuated by as much as 15 dB, while pollutant emission levels were unchanged and, in some cases, improved.[6] Pulsed pilot fuel was also applied to suppress combustion instabilities of a full-scale Siemens gas turbine. The control system, which was developed to

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acteristics. This controller will in particular address the variability of the air and fuel mass flows. Three approaches are being explored: a model-based, a rule-based, and a neural net based controller.

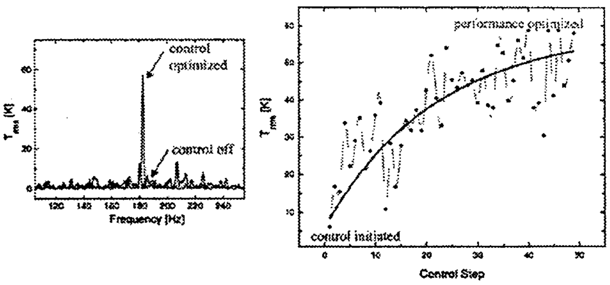

FIGURE 4. Diode-laser sensor system for closed-loop control in 50 kW dump combustor.

For the model based controller, the adaptation will automatically minimize emissions (CO measurement) as a function of the system inputs (primary and secondary air forcing frequencies, phases, and amplitudes). A hydrodynamic model from linear stability theory will be used to guide the adaptation toward the optimal forcing by providing initial and on-line predictions for optimum forcing.

The rule-based controller is based on a 1D unsteady engineering model.[12] The model was developed from LES (Large Eddy Simulation) and verified against 50 kW experimental data. Rules were defined for CO emission as state variable, and air and fuel forcing as control variables. The future goal of the controller will be to minimize CO for varying operational conditions.

Neural net is also being considered for operations, which allows proper training of the controller without detailed a priory knowledge of relationships among parameters.

Air flow modulation is presently achieved with an expensive electro-pneumatic valve. As a potential valve replacement, a high speed flow valve based on Rainbow™ piezo-electric drivers is being explored. The piezoelectric waffer oscillates when driven by a high voltage AC signal, which periodically chokes the circumferential region around the throat of the valve seat and modulates high speed flow. These actuators have been shown to be able to modulate the air flow at the 50 kW level.

4. NAWCWPNS Research Program

NAWCWPNS utilizes actively controlled vortex combustion for suppression of combustion instabilities using pulsed liquid fuel injection at varying phases relative to the oscillations and for combustion efficiency enhancement and pollution control using synchronized gaseous fuel injection into the air vortices. In both experiments with laboratory dump combustors, the physical understanding of flow/combustion/acoustics interactions are used to gain control authority.

The key for instability control is to create controlled heat release that oscillates out of phase with respect to the local pressure oscillations to satisfy the Rayleigh's criterion.[13-14] In the NAWCWPNS approach, the control of the heat release is achieved by controlling the spatial and temporal distribution of the liquid fuel droplets in the combustor. This is accomplished by timing the pulsed fuel injection into the large-scale vortices developing at the dump. This timing determines the slip velocity of the fuel droplets against the surrounding flow, thus the droplet dispersion characteristics. Figure 5 is an example of such interaction which shows the intensity contours obtained from phase-averaged planar Mie-scattering images of droplet timing.[15-16] When the droplet injection is synchronized with the vortex development, the droplets are entrained into the circumference of the large-scale vortices and dispersed in radial direction (Figure 5a); however, when the injection is out-of-phase and trailing the vortex development, the droplets are forced into the core flow of the combustor (Figure 5b). Based on this mechanism of droplet/vortex interaction, pressure oscillations in a dump combustor were suppressed.[17-18] In the present paper additional results of these experiments dealing with the controller aspects will be presented. In particular the limitations of using a simple fixed-phase controller will be discussed for these tests to suppress combustion instabilities with pulsed liquid fuel injection

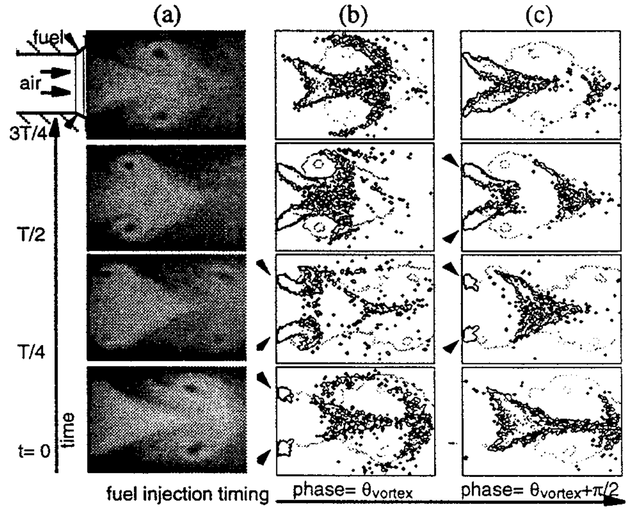

FIGURE 5. Fuel-droplet dispersion as a result of interaction with vortex. (a) air flow without fuel injection, (b) in-phase fuel injection, (c) out-of-phase fuel injection. The arrows in (b) and (c) indicate the timing at which the pulsed fuel injection is on.

The key for combustion efficiency enhancement and pollution reduction with actively controlled vortex combustion is to entrain the fuel into the core of the air vortices. Nearly complete combustion was obtained with gaseous fuels in an extremely short combustor length using a generic dump combustor with air and fuel flow forcing. The high performance was achieved using the

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adaptive varying parameter. Adaptation is required for example when instability frequency variations are encountered due to combustion temperature changes.

3. NAWCWPNS Managed Collaborative Program

Active combustion control of a generic dump combustor is being studied to increase the combustion efficiency and reduce toxic emissions by actively controlled vortex combustion. The key for this active control mechanism, which is discussed in detail in Section 4 (NAWCWPNS Research Program), is to entrain the fuel into the core of the acoustically stabilized air vortices and utilize intense mixing, long residence time, and high combustion temperatures in the vortex core.[8] Control components for these experiments with closed-loop control include diode laser based sensors (Stanford University), rule-based (Georgia Institute of Technology) and model-based (The Pennsylvania State University) controllers, and piezo-electro actuators (NAWCWPNS). These control components are integrated into the NAWCWPNS 50 kW combustor schematic shown in Figure 1. In this generic dump combustor, coherent primary-air vortices are periodically generated with a flow modulation actuator and the gaseous fuel injection is synchronized with the air-vortex development using acoustically pulsed secondary-air as gating mechanisms.

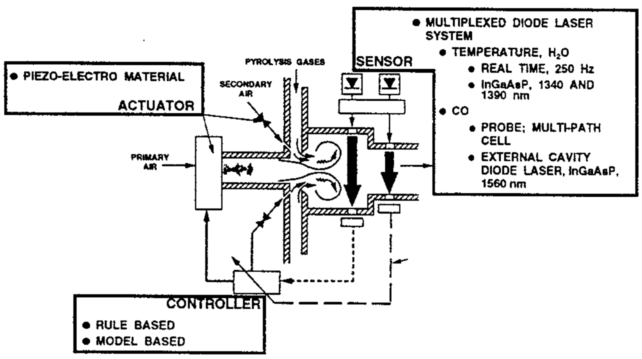

FIGURE 1. Closed-loop active control of generic dump combustor.

Figure 2 shows the drastic improvement of the flame characteristics with control (blue flame) relative to operation without control (yellow flame). With control, CO and NOx were reduced by a factor of 400 and 6, and the destruction efficiency of a benzene additive was increased from 2 "nines" (99%) to above 4 "nines" (99.99%) (Figure 3).[9]

The observed simultaneous reduction of CO and NOx was further investigated in 5 kW flame experiments.[9] It was shown that the active vortex combustion control provides rapid fuel and air mixing of an annular diffusion flame, while delaying combustion in the high stretch vortex braid region in the initial mixing region near the burner exit, where the potential for thermal NOx production is high due to high local temperature of near stoichiometric mixture ratio. With the initial combustion delayed, the actively controlled vortex combustion process resembles a lifted premixed flame, having both the advantages of a diffusion flame arrangement (no flashback) and premixed flame (low NOx at lean operation).

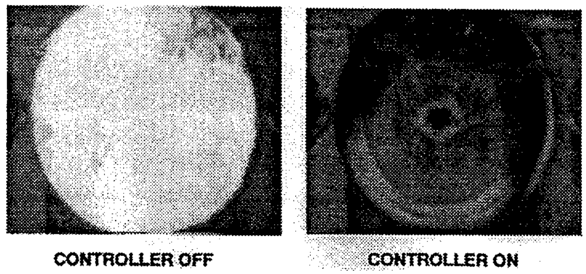

FIGURE 2. Flame characteristics of uncontrolled and controlled flame of 70 kW generic dump combustor.

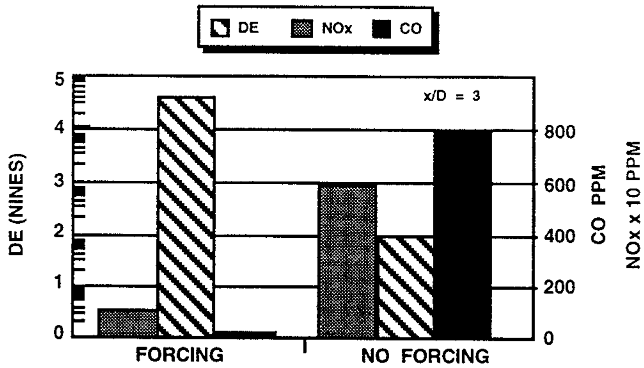

FIGURE 3. Destruction efficiency (DE) and emission for generic dump combustor (40 kW).

Closed-loop controlled experiments with the control components shown in Figure 1 are being prepared to minimize emissions at varying operational conditions. For the experiments diode laser sensors for real time temperature measurements and continuous CO measurements have been developed by Stanford University.[10] Figure 4 shows real-time temperature measurements at 10 kHz sampling rate using line-of-site spectroscopy with the diode laser sensors. With control, high rms temperature levels were achieved in the preliminary tests using NAWCWPNS 50 kW combustor, indicating the development of coherent vortices associated with high combustion efficiency. Without control, the low rms levels indicate incoherent, low-efficiency combustion. The controller was able to transition the combustion process from low rms to high rms levels (right side of Figure 4). The relationship between rms levels and combustion efficiency were confirmed by continuous CO measurements, also using diode laser sensors. At the highest rms level (highest vortex coherence) the CO was lowest. The response time of the diode laser sensor system was improved to 10 msec in 5 kW flame experiments.[11]

For the closed-loop experiments, a "multi-layer" controller is currently being developed to simultaneously maintain high flame stability and optimum emission char-

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viable solution to meet various future requirements. These include volume and weight reduction, while maintaining and reducing pollutant emissions within acceptable levels.

The review of future combustor needs revealed several challenges which may limit the growth potential of combustion systems. Some of the challenges, which likely cannot be met with standard design approaches, may be mitigated by successful application of ACC methodologies. A relative priority was determined for ACC applications based on current understanding, needs, and risks. A brief summary is given in the following.

A common combustion system challenge believed addressable by ACC is instability control. Application to surface power gas turbine instability control was considered a "high" relative priority because it is an acknowledged developmental challenge for all manufacturers. Also, laboratory and full-scale demonstrations have shown the potential for active control to mitigate it. The same "high" relative priority level was assigned to airbreathing missiles and solid-propellant rockets instability control, as well as for emission control for compact designs for burners and incinerators. This reflected developmental needs and a belief that the key physical phenomena were known in the systems. A "low" relative priority was assigned to aero-engine systems because other systems had a more immediate need and due to the perceived risk associated with man-rated systems. Aeroengines for unmanned aerial vehicles (UAV) may be more suitable systems for ACC application. A "low" relative priority was also assigned for liquid-propellant rockets because the perceived risk was very high in order to achieve a successful active control application.

The described instability controls in surface power gas turbines, airbreathing missiles, and solid fuel rockets were judged to be high impact ACC applications for the near term. For these applications active control methodology will expand the operational capabilities of each system to broader conditions while preserving attributes of high efficiency, stability, low emissions, etc. In the long term, active control applications to other aspects of combustion dynamics will be possible. These include fuel/air mixing control with minimum pressure loss penalties for emission control and compact designs, extension of operational limits at high and low air-to-fuel ratios for increased specific performance, and extension of turbine life by optimizing pattern factor.

Research and Development Needs. One of the main objectives of near term ACC research should be to demonstrate and quantify the advantages of ACC relative to other (passive) approaches. In this phase, the work should progressively shift to larger-scale devices featuring some or all of the conditions encountered in practice. Subsequent efforts should develop know-how to guide the development and optimization of practical ACC systems. Future work should focus on studying fundamental processes in uncontrolled and controlled combustors, developing sensors and actuators that satisfactorily perform in the harsh combustor environment, and developing models of controlled combustors.

Fundamental Processes. To effectively implement active control, it is desirable to understand the fundamental aerothermochemical processes that must be controlled. An important criterion for selecting control approaches is to minimize the energy input (for example amount of pulsed fuel) required to gain control authority. One important aspect is the identification of flow regions with high amplification of local disturbances, where seeding of small external disturbances results in substantial changes in macro flow dynamics and combustion processes. For dump combustors, these sensitive areas are the initial regimes of the shear-layer development. The needs exists to identify the sensitive regimes for other types of combustors and in systems with complex flow features. This information is required, for example, to optimize location and injector design for secondary pulsed fuel injection, conduct scaling experiments, and test ACC on larger facilities. Experimental and modeling approaches are required.

Sensors. Future developments will depend upon both adapting existing sensors (mainly pressure transducers and optical radiation detectors) to practical requirements such as simple design, reliability, and high robustness, and also developing novel sensors based on diode lasers, micro-machining, and image processing.

Actuators. A critical need exists for practical actuators, in particular for valves for gaseous and liquid flow modulation. Also required are acoustic drivers for sound generation, pulsed-combustion actuators for periodic heat release generation, and piezoelectric actuators for boundary control. For these actuators requirements for scale-up, time response, reliability, robustness, weight, size, survivability, and cost have to be evaluated. Novel actuators should explore different types of actuation, including magnetostriction, radical injection, and micro-machining to name a few.

Controller. Open loop control, where the actuation is independent of the state of the combustor, should be pursued if possible. Research is needed to determine the feasibility of such control approaches and the optimum frequency and magnitude of the required forcing. Closed loop control, where the actuation depends on and can adapt to the state of the combustor, is more complex, but it can realize the full potential of ACC. The state of the system is determined by the observer based on the sensor signals. This information is then used by the controller to determine the actuator's control signal. To attain effective closed-loop control, development of analytical/numerical approaches that can quickly interpret the measured data in terms of the governing equations to determine the state of the system are required. There is also the need to investigate whether the controller should have constant or

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operate at one frequency, achieved an 86% reduction of the pressure amplitudes for this lean premix burner operating near lean blowout.[7]

NAWCWPNS is applying pulsed fuel injection to dump combustors to suppress combustion instabilities in liquid fuel ramjets and to increase heat release density and reduce hazardous emissions in burners, which, for example, are applicable to a compact afterburner of a ship-board waste incinerator. This burner work is of interest in this propulsion related paper, since these burners have common features with propulsion systems. As described in detail in Sections 3 and 4, the detailed understanding of fluid dynamic/combustion/acoustics interactions is being used to gain control authority.

As an overall workshop conclusion on the status of ACC, it was noted that the forecasts on the potential of ACC generally rests on laboratory demonstrations and that well-defined demonstrations at larger scales with specific types of systems are needed to investigate feasibility and scaling laws. One exception is the Siemens and UTRC work to suppress instabilities on lean premix burners. Although this is an exciting accomplishment, additional research needs exists even for this application, such as minimizing the amount of pulsed fuel injection and making the control system adaptable to changing frequencies. Another example of successful scale-up is the NAWCWPNS actively controlled vortex combustion work, discussed in Sections 3 and 4. It was also noted at the workshop that the majority of the present work uses ACC to suppress oscillations, although other applications are equally important as in the NAWCWPNS work discussed later.

Potential Active Combustion Control Applications. Applications of ACC were explored in the workshop based on the projected needs and challenges for future combustors. The requirements for gas turbines, airbreathing missile propulsion, rockets, and burners and incinerators were considered and are briefly summarized in the following. Subsequently a relative priority of ACC applications was developed and will be briefly discussed based on current physical understanding of the combustion processes, risk, and benefits.

Gas Turbine Engines

Engines for either aeroengine propulsion (direct fuel injection) or surface power/propulsion (mainly fuel-air premixing) have been considered. The basic performance trends for aeroengine gas turbines have been toward increasing thrust-to-weight ratio to increase maneuverability for military devices, and to lower specific fuel consumption to reduce operating costs for commercial devices. Among the consequences common to both goals is the trend toward higher pressure ratios with higher temperatures at both the combustor inlet and exit. In order to preserve and improve the combustor performance at these severe conditions, means are required for promoting the mixing of fuel, air, and combustion products in the burner, and for preserving stable operation under both steady-state and transient conditions. In addition, it is desirable to minimize undesirable emissions of NOx, CO, and smoke at higher equivalence ratios.

Surface power/propulsion gas turbines provide either ground power or propulsion for ships. Among the critical requirements for these gas turbines is high power density, high durability, and extremely low emissions. The latter is distinctively different than for aeroengine gas turbines, which have allowed emission levels more than an order-of-magnitude higher. The lowest level of emissions is achieved by employing a premixed combustion strategy with operation near the lean blowout (LBO) where the flame temperature and the formation rate of NOx are minimum. However, as the fuel-air mixture approaches the LBO limit, thermoacoustic instabilities become more prevalent. In fact, premixed combustion with its intense heat release gradients provides greater opportunities for coupling with the acoustics and fluid mechanics, and remedies to combustion instabilities are a common development challenge.

Airbreathing Missile Propulsion. These systems have the potential for the highest performance per unit volume and weight and are considered for several different missions which have specific requirements. These include increased kinetic performance, increased energy per volume and per weight, increased propulsion energy management, and increased survivability. These applications of airbreathing propulsion to tactical missions drives the design to ever smaller combustors, which increases both the challenge to achieve high performance over a broad range of operational conditions, and the risk of combustion instabilities. Potential airbreathing missile propulsion systems include liquid-fuel and solid-fuel ramjets, ducted rockets, scramjets, expendable turbine engines, and pulsed-detonation engines.

Rocket Propulsion. These systems have been developed for two applications – missile propulsion and space launchers. Each of these may be powered by either solid or liquid propellants. The propulsion systems are designed to deliver the maximum thrust with the minimal volume or weight. Hence the energy release densities are extremely high, often causing coupling with the combustor acoustic modes to produce combustion instabilities. As a consequence, the global requirement for future rocket propulsion systems is to achieve stable, high power-density operations. Achieving high combustion efficiencies over wide operational range remains a challenge for liquid rockets.

Burners and Incinerators

These industrial systems were also considered, since these devices have common combustion features with propulsion systems and the use of active control offers a

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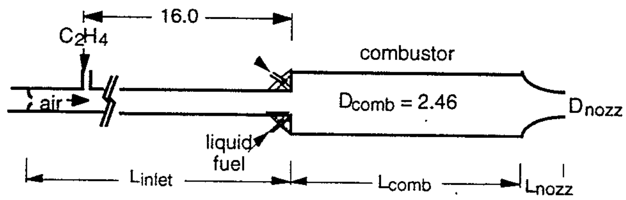
combustor type shown in Figure 1, when the dump combustor was operated at the proper air flow excitation frequency and fuel injection timing.[20]

In practical combustors the air flow excitation may be achieved by self-excited pressure oscillations at combustor resonant frequencies as demonstrated later. For studying this active control mechanism under controlled laboratory conditions, pressure oscillations were excited using air flow modulation. Using the active air-flow modulation, the control mechanism was scaled-up to 400 kW (combustor) and 1 MW (open flame).[19] During the scale-up, it was critical to maintain air jet forcing at a Strouhal number of about St=f d/u=0.3 → 0.4 (with forcing frequency, f, air inlet diameter, d, and air velocity, u), which is in the range of the preferred Strouhal number of jets.[21] At this Strouhal number, both vortex size abd required forcing energy can be optimized. In this paper additional experiments with the generic gaseous fuel dump combustor operating at 340 kW and 680 kW are discussed to clarify the relationship between preferred mode frequency, resonant frequency of the combustor, and additional driving frequencies. As pointed out before, air forcing is used in the present experiments to set up pressure oscillations. When air forcing is impractical, oscillating gaseous fuel jets could drive pressure oscillations as demonstrated in pulsed fuel dump combustor experiments.[22]

Dump Combustor with Pulsed Liquid Fuel Injection (Instability Suppression)

Experiments were performed in a 102-mm diameter axisymmetric dump combustor, which experienced combustion instabilities under certain flow velocity and combustor and inlet dimensions. Figure 6 shows the schematics of the rig and the combustor dimensions for two particular cases (Case 1 and 2) of naturally unstable operating conditions at which liquid-fueled active instability suppression technique was tested. Air was supplied through a sonic nozzle, which was placed in the upstream end of the inlet pipe having the inside diameter of 41.3 mm, to provide acoustic isolation. Fuels were supplied at two different locations along the inlet. First, gaseous ethylene (C_2H_4) was injected steadily into the inlet pipe through a choked orifice at 16 inlet diameters upstream of the dump plane. The partially premixed inlet flow was then augmented with periodic liquid-fuel injection at the dump plane. In Case 1 ethanol (C_2H_6O), in Case 2 heptane (C_7H_{16}) were used as the secondary liquid fuel in the experiments. In contrast to the ethylene flow which was held steady in time, secondary liquid-fuel flow was pulsated at the instability frequency and with 50% duty cycle.

Figure 7 shows the liquid-fuel injection system and the active control circuit that was used to control the injection scheduling. A Kistler pressure transducer, mounted at one inlet diameter downstream of the dump plane, was used to detect the oscillations in combustor pressure. Then, with the combustor pressure signal as reference, the phase shift for the injection cycle was digitally controlled using a Wavetek™ Variable Phase Synthesizer. To assist the phase-lock, the pressure signal was filtered using a Butterworth band-pass filter. It is important to point out that the filter introduces an additional phase shift, which is strongly frequency dependent. For operation with constant frequency during the control process, the additional (constant) phase shift from the filter can be accounted for and a simple fixed-phase-type controller can be effective. However, when the oscillation frequency is drifting during the control process (for example due to combustor temperature changes) a band-pass filter may prevent the use of this simple controller as discussed later.



Case	Liquid Fuel	L_{inlet}	L_{comb}	D_{nozz}	L_{nozz}
1	C_2H_6O	58.5	10.2	1.29	1.85
2	C_7H_{16}	25.8	12.9	0.862	1.32

All dimensions are in terms of D_{inlet} = 42.3 mm

FIGURE 6. Model ramjet dump combustor with direct liquid-fuel injection for control.

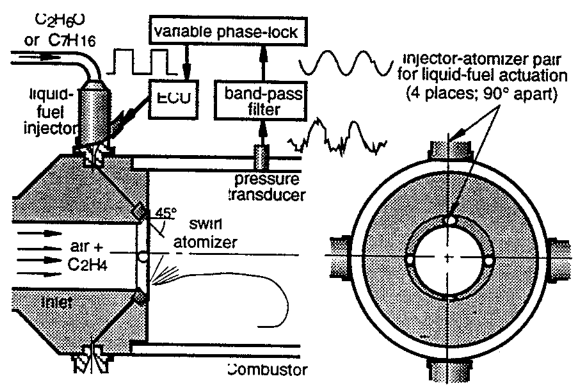


FIGURE 7. Liquid-fuel actuation system and a simple phase-delay closed-loop control.

The liquid fuel was injected through four fuel actuators that were spaced 90 degrees apart along the circumference of the inlet at the dump plane. Each actuator system consisted of a Bosch Jettronics™ injector and a swirl-based fog atomizer with 300 μm exit diameter. The initial injection angle was fixed at 45 degrees with respect to the air flow direction. The air flow was 45 g/sec and 146 g/sec, the equivalence ratio 0.5 and 0.6 for Case 1 and Case 2 respectively. The inlet flow was highly turbulent with Reynolds number, Re_D, ranging between 7.7×10^4 and 2.5×10^5.

For Case 1, the combustor output was relatively low with the average pressure in the combustor only 2% higher

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than the ambient pressure at the nozzle exit. Strong pressure oscillations at 35 Hz were observed in the vicinity of the lean-mixture flammability limit in the experiments with steady ethylene and pulsed liquid fuel injection. Acoustic analysis revealed that both the quarter-wave mode of the inlet and the Helmholtz mode of the combustor-inlet system occurred at 35 Hz based on phase and amplitude measurements at different axial locations. However the mode shape characteristics were neither pure quarter-wave nor Helmholtz mode oscillations, indicating a more complex interaction between the two acoustic modes with combustion heat release.

The closed-loop control was applied to suppress the amplitude of the 35 Hz oscillations occurring at phi = 0.5. The Butterworth band-pass filtered the pressure signal between 25 and 40 Hz. The sound pressure level was reduced up to 12 dB depending on injection timing or phase delay between pressure oscillation and periodic liquid fuel injection. The amplitude reached minimum when the start of the injection was synchronized with the pressure minimum and maximum when the pulsed injection started at phase $\pi/2$ after the pressure minimum.

Figure 8a shows the transient behavior of the combustor pressure as the proper phase-delay was applied at time t=0. The high-amplitude oscillations were quickly brought under control. Pressure spectra data showed that all of the harmonics as well as the fundamental were effectively suppressed and that the oscillation frequency did not vary during the control process. Under control, the RMS pressure amplitude was maintained well below 0.5 percent of the combustor pressure. Based on an analysis of the phase relationship between combustor pressure oscillations, and periodic fuel injection and the droplet/vortex interaction data in Figure 5, it was concluded that in the present case, pressure oscillations were suppressed when the fuel pulsing was in-phase with the air vortex shedding.[23]

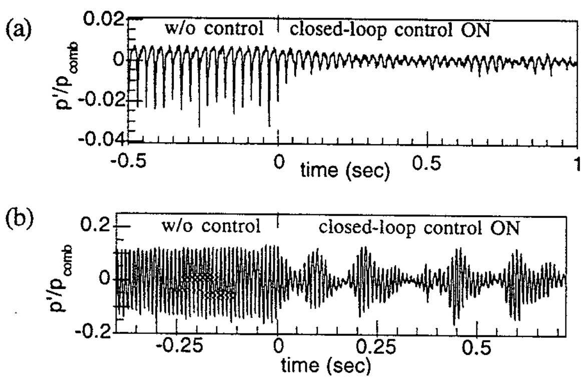

FIGURE 8. Comparison of uncontrolled and controlled pressure oscillations. Pressure-time trace for (a) Case 1 and (b) Case 2.

The simple fixed phase-delay controller was further tested in Case 2 under higher mass flux conditions and at a natural instability frequency of about 96 Hz. As in the previous case, the system behavior was characterized under a closed-loop control operation. The band-pass filter in this case was set between 80 and 120 Hz to achieve the phase-lock in the processor circuit. Both oscillation amplitude and main peak frequency shifted with the phase delay, and they are shown in Figure 9. The change in instability frequency for this case was related to the change in combustor temperature. Fitting the sine curve through the data, it can be seen that the two curves are roughly 70 degrees out of phase. This suggests that the amount of instability suppression can be optimized with respect to combustion efficiency. For instance, the ECU phase shift of 210 degree resulted in highest frequency but relatively low amplitude.

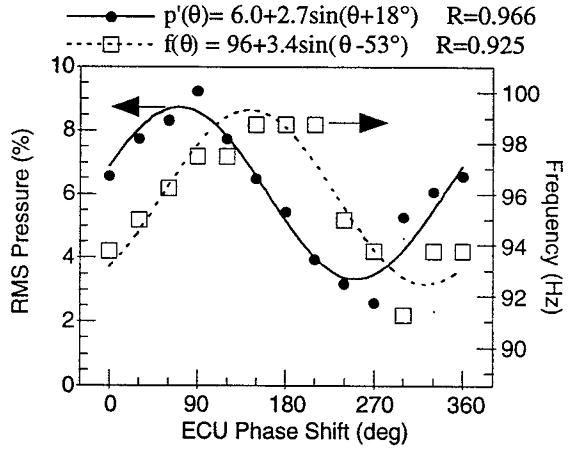

FIGURE 9. System characterization for Case 2 conditions.

Figure 8b shows the pressure-time trace during the control process. The RMS amplitude of pressure oscillations was significantly reduced with the closed-loop control, but the amount of suppression was much smaller in comparison with the previous case. Also, the examination of the transient behavior revealed a more serious problem in this case. At the onset of the control, the oscillation amplitude was suppressed within a few cycles. However, immediately after the suppression, the amplitude started to grow again reaching almost the uncontrolled level before the control was once again established. This behavior was repeated intermittently rendering concerns on the practical usefulness.

The investigation on this behavior revealed a limitation of the simple fixed-phase-type controller, particularly associated with the non-stationary instability frequency. While a band-pass filter was needed to obtain the phase lock, the filter would introduce an electronic phase shift which is not uniform within the frequency range of interest. As a consequence, an additional phase shift that depends on frequency would be added to the pre-assigned phase delay. Thus, if the oscillation frequencies were drifting, they could cause significant changes in phase shift and the loss of control. Measurements of the phase shift associated with the Butterworth band-pass filter used in the present setting showed that over the frequencies within the band-pass width, the phase was shifted by about 360 degrees.

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Figure 10 is used to explain the intermittent loss of control in the present case. Figure 10a shows the transient response of the measured pressure shortly before and after the onset of the control. In Figure 10b, the apparent frequency of the oscillations was deduced as a function of time by measuring the zero crossing. Two sets of data are plotted since every other zero crossing corresponds roughly to one period of oscillation. The curve fit coincides with the average of the two. Figure 10c shows the resulting phase shift associated with the frequency change in Figure 10b. At about 40 msec after the control was turned on, the oscillation amplitude reached the minimum value. At the same time, the apparent frequency of the oscillation was lowered by almost 20 Hz, about a half of the band-pass filter width. As a result, the overall phase shift was changed by 180 degrees, making the new phase delay more suitable for pressure amplification than suppression. As the amplitude grew, the oscillation frequency returned to the original level and once again the phase setting shifted into the suppression mode.

The pulsed liquid fuel tests to suppress instabilities showed, that a simple fixed-phase-type controller may not be effective in a combustor where the oscillation frequencies drift significantly with the control. The main problem is the frequency-dependent phase shift associated with the frequency filter. For such a case, an adaptive controller that can change the phase setting with the observed frequency would be useful. On the other hand for some applications it is possible to eliminate the filter as shown in the following gaseous fuel tests to enhance combustion efficiency.

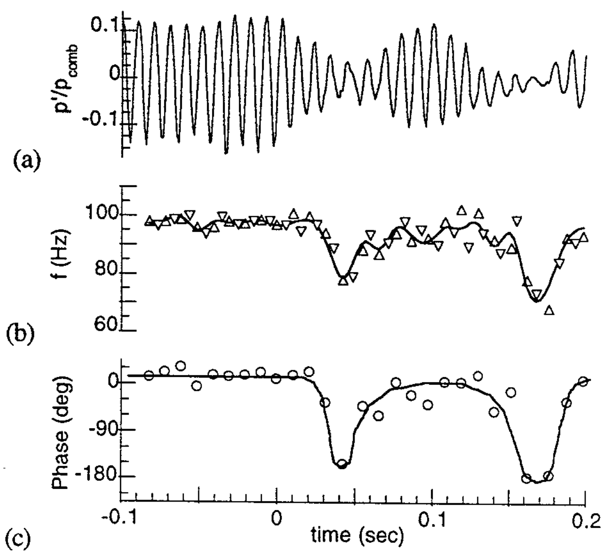

FIGURE 10. Transient system response to onset of control at time t=0. (a) measured amplitude, (b) apparent frequency of pressure oscillations, and (c) fuel injection phase based on the controller frequency response.

Generic Gaseous Fuel Dump Combustor (Enhanced Combustion Efficiency)

Combustion efficiency enhancement and hazardous emission reduction has been achieved using actively controlled vortex combustion with controlled air forcing.[9,20,24] The key for the improvement was the detailed understanding of fluid dynamic/combustion/acoustics interactions. In the following additional data on the important relationship between fluid dynamic instability frequencies, acoustic resonant frequencies, and additional (air) driving frequencies will be discussed. The fluid dynamic frequency in these experiments is the air flow preferred jet mode frequency. As pointed out earlier, driving at this frequency is important to develop optimal air vortices. In addition, the preferred mode instability plays a dominant role in driving self-excited resonant frequencies in dump combustors. It has been shown, that the oscillations related to the chamber acoustics (Helmholtz mode or organ pipe modes) will be excited, whose frequencies are near the air jet preferred mode frequency.[25]

The design of the generic dump combustor is shown in Figure 11, which is a simplified version of the combustor shown in Figure 1. Only the main air is modulated with an actuator, while the fuel is indirectly modulated by the natural air vortex dynamics.[9] The combustor was operated with 20% ethylene and 80% N_2 at a phi of 0.575 with an energy output of 350 kW (7.15 gm/s ethylene flow rate) and 680 kW (14.3 gm/s). The main air inlet diameter was 81 mm resulting in air velocities of 30 m/s (at 340 kW) and 60 m/s (at 680 kW). This corresponds to a jet preferred mode frequency of 130 Hz with a Strouhal number of 0.35. The insulated combustor was 311 mm in diameter and 1.17 m long. The measured chamber temperature was between about 1030°C at startup (cold walls) and 1180°C (hot walls). The performance of the combustor was determined with a continuous emissions monitor for CO, NOx, and unburned hydrocarbons (UHC) with the probe location at about 1 m, which lead to average residence times (plug flow) of 84 msec (340 kW) and 46 msec (680 kW).

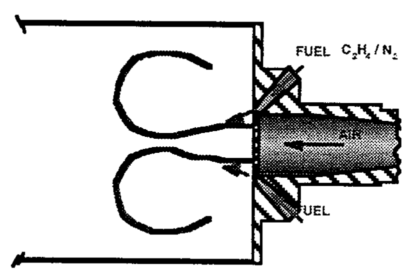

FIGURE 11. Generic gaseous fuel dump combustor.

The defining feature of this combustor was that it strongly self excited at the quarter wave acoustic mode, which, depending on the chamber temperature, was between 121 and 132 Hz. This was in the range of the preferred mode of the jet, a requirement for self-excitation

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as discussed before. Figure 12 shows the self-excited chamber pressure power spectrum under 340 kW operation without air forcing. The oscillations are relatively coherent (see time trace insert in Figure 12). With additional air forcing at this acoustic resonance frequency, the power spectrum is very narrow and pressure oscillations quite coherent (Figure 13). This high level of coherence is difficult to maintain with manual setting of the air forcing frequency, because the forcing frequency has to be within few tenths of a Hz within the acoustic resonant frequency at all times.

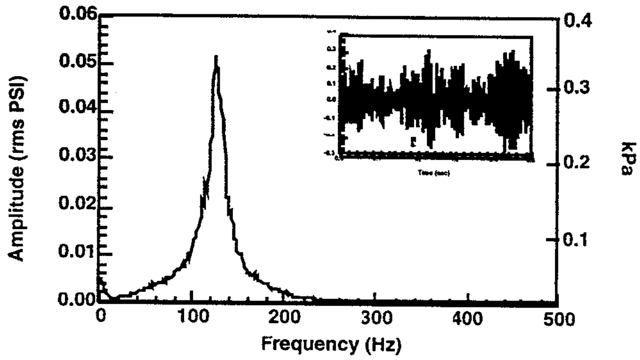

FIGURE 12. Dump combustor operating self-excited jet preferred mode near quarter wave acoustic mode.

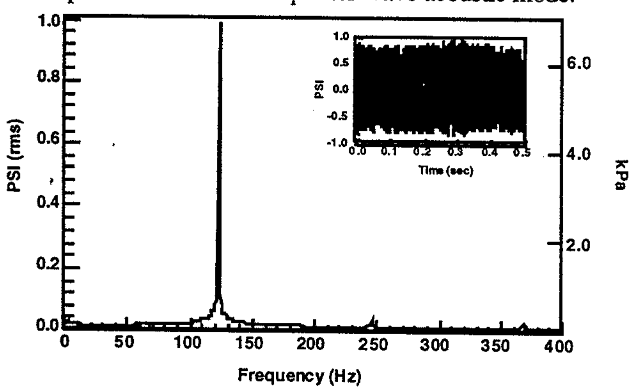

FIGURE 13. Dump combustor with primary-air forcing at acoustic mode.

The performance of the combustor was remarkably good despite the short residence times. The flame was entirely blue and, when the walls started to glow, nearly invisible. The emissions for 340 kW operation at a phi of 0.55 and a residence time of 84 msec were extremely low: CO 15 ppm, NOx < 15 ppm, UHC below detection. Figure 14 shows the performance as a function of combustor phi. In these tests with forcing (solid symbols), the air forcing frequency was manually set relative to the resonant frequency. The CO emissions rise at high phi was due to low excess oxygen and at low phi was due to lower flame stability. The NOx (Figure 15) decreases with phi due to lower flame temperature (5 ppm at phi = 0.42, 70 ppm at phi = 0.75). Also, the NOx increased significantly as the chamber walls heated (again a temperature factor).

With a strong chamber acoustic resonance close to the jet preferred mode, it was not possible to show great improvement with air forcing, as a coherent vortex was generated by self excitation. Because of the difficulty of manually maintaining the forcing frequency in few tenths of a Hz within the resonant frequency, CO may be even lower without forcing, because of loss of vortex coherence due to a frequency mismatch. In fact this is shown in Figure 14, where the CO is lower without air forcing (open symbol). Also, Figure 16 shows that forcing at relatively low levels reduced performance as the forcing fought for control over the natural acoustics. At high levels (even beyond the values shown in Figure 16) the performance reduces back to, or below, the unforced levels, because the driving dominates the self excitation. For this driving near the resonant frequency, the pressure spectra showed one pressure peak. For a significant mismatch between the driving and resonant frequencies, two frequencies are present in the pressure spectrum resulting in loss of vortex coherence (Figure 17).

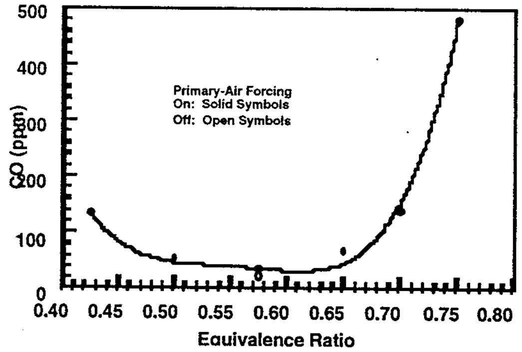

FIGURE 14. CO emissions as function of equivalence ratio.

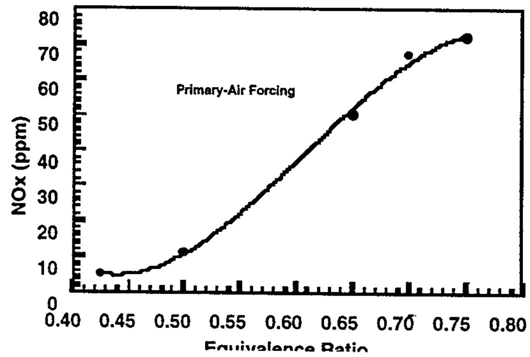

FIGURE 15. NOx emissions as function of equivalence ratio.

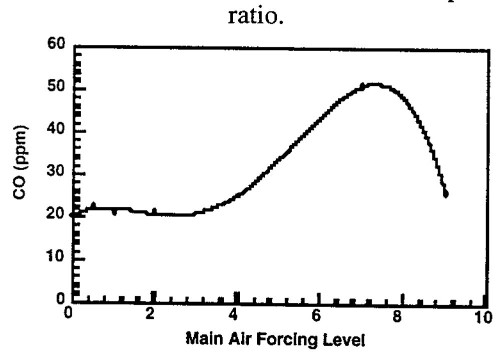

FIGURE 16. CO emissions as a function of forcing level when forced at the acoustic resonance.

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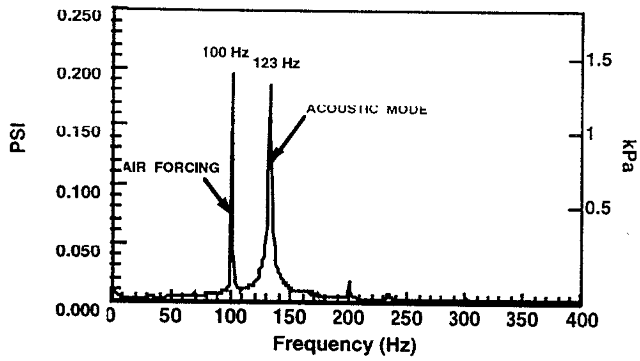

FIGURE 17. Frequency mismatch between primary-air forcing and acoustic resonant frequency.

One solution to exactly matching the driving to the acoustic resonance is a closed loop feed back system. The pressure transducer signal was fed, unfiltered, into the phase lock input of the main air modulator driving electronics so that the forcing could track changes in the acoustic resonance frequency, as the chamber heated for example. Figure 18 shows the extremely coherent result of this closed loop control. This coherence in pressure and corresponding coherence in vortex development can be maintained with changing combustor frequency by avoiding the drawbacks with the earlier discussed Butterworth band-pass filter.

This combustor was also operated at 680 kW with the same low emissions (CO 35 ppm, NOx < 15 ppm) at a residence time of only 46 ms. At this firing rate the central air velocity was 60 m/s. In this case, air forcing at high levels was necessary to stabilize the flame at its normal lifted position[8] and the forced performance was actually better than unforced (35 ppm vs. 66 ppm).

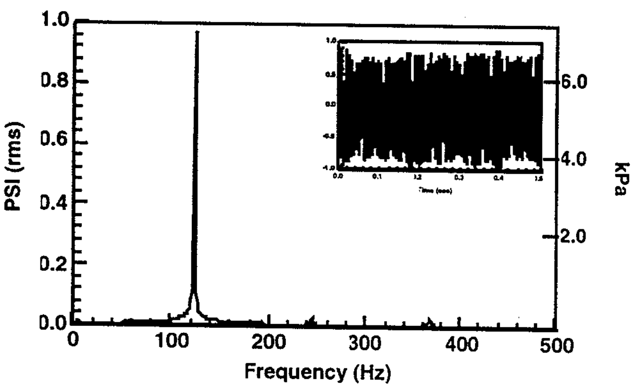

FIGURE 18. Generic dump combustor with closed loop primary-air forcing.

5. Summary

Workshop. The workshop participants concluded that future combustor demands likely cannot be met within traditional design methods. All the combustion systems discussed offer problems and characteristics that are candidates for ACC applications. At the present time, one successful full-scale ACC application has been openly reported. Other forecasts for potential applications generally rest on laboratory demonstrations without full understanding of the scaling laws. Needs for research and development have been identified to improve physical understanding and develop sensors, actuators, and control laws. At the present time the majority of work use ACC to suppress oscillations. Other applications are being addressed and are equally important. Finally, it was concluded that research should progressively shift to larger scale devices and realistic environments.

Collaboration. Several control components have been developed to demonstrate closed-loop control of the actively controlled afterburner. Components include diode laser based sensors, piezo-electro air actuator, and rule-based and model-based controller. The experiments are planned for the Summer of 1998 and will be reported at the ICAS meeting.

NAWCWPNS Research

In an effort to extend active control to liquid-fueled combustors and make it more practical, active instability suppression experiments were carried out using a periodic liquid-fuel injection system, which was closed-loop controlled with respect to the flow oscillations. The pulsed fuel injection system, which was designed to utilize timing-dependent interaction between fuel droplets and temporal flow features, was effective in suppressing pressure oscillations. In a controlled demonstration experiment, up to 15 dB reduction in sound pressure level was achieved with proper phasing of fuel injection and pressure. The tests also showed that a simple fixed-phase type controller may not be effective in a combustor where the oscillation frequencies drift significantly with the control. The main problem is the frequency-dependent phase shift associated with the frequency filter. For such a case, an adaptive controller that can change the phase setting with the observed frequency would be useful.

The actively controlled vortex combustion mechanism was successfully scaled-up to 680 kW. Extremely low CO and NOx emissions were simultaneously achieved at 46 msec residence time. For the scale-up the understanding of the relationships between fluid dynamic, resonant, and driving frequencies was critical. Optimum performance was achieved when both the resonant and driving frequencies were matched and in the range of the preferred air jet frequency. A closed-loop controller was required to match the driving frequency with the resonant frequency, which was varying with combustor temperature.

6. Acknowledgment

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