Active Combustion Control for Propulsion Systems

(AGARD R-820)

Executive Summary

Improving the combustion process is one of the most promising approaches for further improving the size/weight/power relationship in rockets, ramjets, afterburners, aero-engines, and stationary gas turbines for marine propulsion and power generation. Active control of combustion is being explored for various applications, including the civil industrial field. The workshop was organized to provide an overview of existing work and knowledge, and to discuss further possible strategies for the improvement of military equipment. There are very interesting prospects for the further enhancement of cooperation within the NATO nations, and other activities are planned. Areas for R&D needs have been identified.

Le contrôle actif de la combustion pour les systèmes de propulsion

(AGARD R-820)

Synthèse

L'amélioration du procédé de combustion est l'une des approches les plus prometteuses pour une optimisation plus poussée du rapport encombrement/masse/puissance dans les fusées, les statoréacteurs, les chambres de postcombustion, les moteurs d'avion et les turbomoteurs fixes pour la propulsion et la production d'énergie maritimes. Le contrôle actif de la combustion est à l'étude dans un éventail d'applications possibles, y compris dans le domaine industriel civil. Cet atelier a été organisé pour fournir un aperçu de l'état actuel des travaux et des connaissances dans ce domaine, ainsi que pour permettre de discuter plus avant des stratégies permettant l'amélioration du matériel militaire. Il existe des perspectives très intéressantes d'amélioration de la coopération entre les différents pays membres de l'OTAN. D'autres activités similaires sont prévues. Les domaines où il y aurait lieu de promouvoir les travaux de recherche et développement ont été identifiés.

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1. Introduction

This report summarizes the findings and conclusions of a four-day AGARD workshop on "Active Combustion Control for Propulsion Systems" that was held during May 6-9, 1996, in Athens, Greece. This workshop, organized in response to increased interest in application of active control in combustion systems, was attended by representatives from industry, government and universities in Europe and the United States.* The objectives of the workshop were to: (1) define the requirements of future combustors and combustion processes, (2) determine the status of active combustion control (ACC) systems, (3) assess the potential of ACC to meet the performance goals of the future combustors, and (4) determine near- and long-term ACC research and development needs. A special concern of the workshop was the confirmation of international collaborations between organizations working in this field.**

In contrast to passive control, the term 'active control' implies control of a system involving expenditure of energy from a source external to the system. Generally, the purpose is to minimize the difference or 'error' between the instantaneous desired and actual behavior of the system. Control may be exercised with feedback of information about the actual response of the system (closed-loop control) or without feedback (open-loop control). The field of active control of combustion is concerned both with control of dynamics, notably combustion instabilities, and with various forms of the 'regular' problem, for example maintaining operation to optimize some property of the performance. In any case open-loop control does not seem to be a useful strategy for the sort of applications envisioned for ACC.

Although the earliest proposals for active feedback control of combustors, and the initial experiments, were motivated by the intention to control combustion instabilities in rockets, ramjets, and afterburners, subsequent work has demonstrated other possible applications. Thus one can now conceive of situations in which the purpose of introducing ACC may be one or a combination of two or more of the following: (1) improve the performance of a combustor (e.g., reduce pollutant and/or noise emissions, reduce specific fuel consumption, increase combustion efficiency, improve pattern factors in gas turbine combustors, etc.); (2) permit modification of combustor design (e.g., reduce its length); (3) damp combustion instabilities; (4) increase combustor reliability; (5) extend operational limits of combustors (e.g., permit stable operation at lower equivalence ratios); and (6) improve performance of other military combustion processes such as shipboard incineration, and power and heat generation in the field. Because the practical problem of suppressing combustion instabilities has been the chief motivation for investigating ACC, it is useful to explain some broad aspects of the subject by considering feedback control of unsteady motions in a combustor. The essential reason for the presence of instabilities in a combustion system is the existence of internal feedback such that energy may be transferred to a

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* A list of participants is provided in Appendix A.

** The agenda is provided in Appendix B. Information about requesting copies of viewgraphs presented at the workshop is given in Appendix C.

fluctuation at a rate dependent on the fluctuation itself. Passive control involves changes of design, (e.g., in the composition or types of reactants, injection system, chamber geometry) either (1) to reduce the rate at which energy is transferred to the unsteady motions or (2) to increase losses of energy, for example by the use of suitable resonators to introduce a dissipative process. Use of active control may be effective by causing either (1) or (2) to occur by sensing the instabilities and then using a feedback control loop to modify one or more input parameters. What may be possible, or what actually happens in a particular case, can be established only by understanding the system in question.

In the experimental work reported to date, relatively simple laboratory burners are typically used, having relatively large length/diameter ratios. The undesirable oscillations often have motions largely in the axial direction. Control has been exercised, or at least the levels of oscillations have been reduced, by applying several methods of actuation, the most common being: forcing the motion of a portion of the boundary, for example of the inlet; injecting acoustic waves with a loudspeaker; and modulating the primary or a secondary fuel supply. A typical arrangement for active control of combustion instabilities in a dump combustor is sketched in Figure 1 involving actuation, A(t), achieved by modulating the flow through a fuel injector. The actual performance of the system is monitored by two pressure sensors, for the real-time, s(t), and time-average, $\overline{s}$ (t), condition monitoring, respectively . Three different levels of ACC are shown. The first (marked 1) shows an open-loop operation in which the actuator is used without any feedback. The second (marked 2) adds a fast sensor to provide real-time feedback for control of the actuator signal. The third (marked 3) employs an additional sensor to detect the overall performance in a time-averaged sense. This sensor output is used to adjust the controller parameter to adapt to changes in operating conditions. In general more than two sensors could be used, distributed in space and measuring several properties of the motions, for example velocity and radiation in addition to the pressure.

For the control circuit 2 shown in Figure 1, the information acquired by the sensor must be processed and used within the feedback loop to activate a controller whose output drives the actuator according to a control law. Most demonstrations to date have used simple control laws which dictate oscillatory actuation at some phase relative to the sensed response of the system, and at some amplitude found to give best results, i.e., lowest amplitude of oscillations. That approach is a special form of classical PID (proportional/integral/derivative) control in which the control signal is proportional to the error itself, its time-integral, and/or its derivative. The conditions for optimal control influence have always been obtained experimentally with little preparatory design work, a consequence of the lack of knowledge of the systems under investigation. One example of such simple control systems is illustrated in Figure 2 for a ducted premixed-flame experiment. The phase-delayed signal from a microphone was used to drive the acoustic actuator in the flame plenum chamber for suppressing pressure oscillations. It should be emphasized that the unsteady flow motions can be effectively reduced using only a small fraction of the mechanical energy of the oscillatory field, provided the control actions are exerted in regions that are most sensitive to actuations. In this flame experiment, the actuator suppresses velocity fluctuations at the flame base and thereby prevents the natural development of large-scale vortices responsible for driving instabilities. The evolution of vortex dynamics under conditions with and without external control forcing are shown in Figure 2 by means of the flame-radical flow visualization technique.

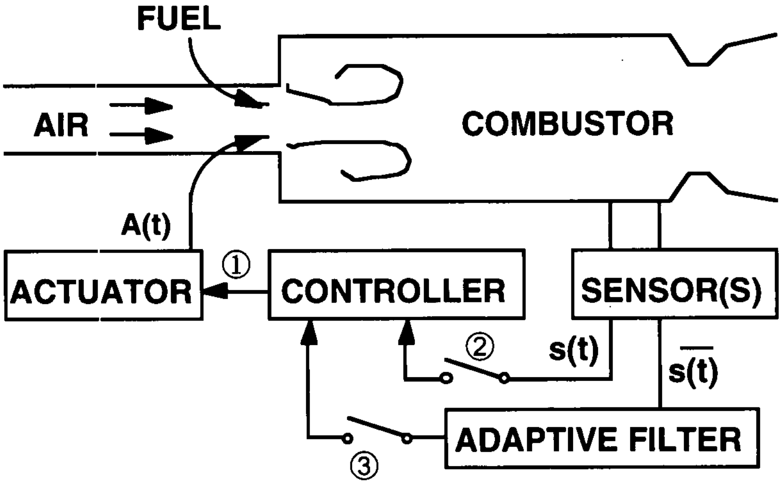

Fig. 1 Active Control Arrangement to Suppress Combustion Instabilities in Dump Combustor.

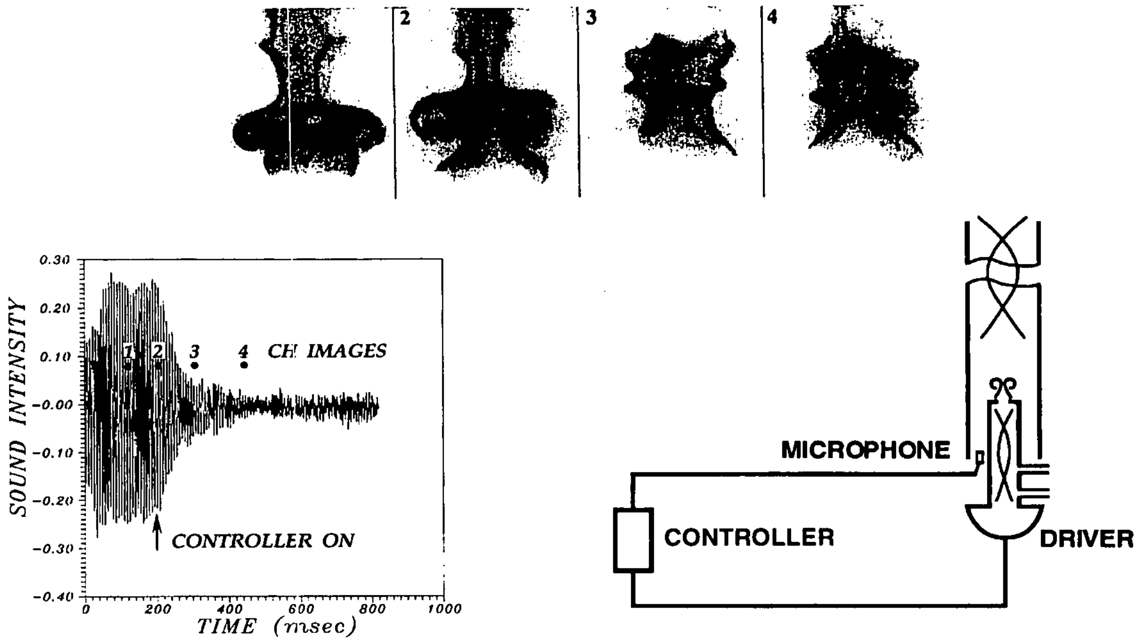

Fig. 2 Uncontrolled to Pressure Controlled Transition of Ducted Flame (Ref. 52).

According to the preceding remarks, there are broadly four areas in which research and development must proceed to form a firm basis for practical applications of ACC: sensing, actuation, formulation of control laws, and understanding of the systems to be controlled. As part of the progress required, it is essential to acquire understanding of the scaling laws, particularly with respect to the power density of a combustor. This report covers a broad range of issues ranging from future requirements of combustion systems to topics of basic research that must be addressed to realize the promise of active control of combustion.

2. Background

Although active feedback control had been posed and investigated for a restricted class of problems in the early 1950s for reasons cited in the preceding section, the idea was not pursued experimentally until the 1980s. It seems fair to recognize that the work at Cambridge University, supported by Rolls Royce with a view to application to afterburners, marked the beginning of the recent considerable activity in this area (see References 14 through 19 in Section 4). Indeed, the sequence of increasingly more elaborate experimental projects within the program introduced many of the novel ideas which have subsequently been vigorously pursued by a large number of research groups throughout the world. In particular, almost all of the types of sensing and actuation now being investigated were first used at Cambridge.

The general notion of active feedback control of combustion dynamics has recently attracted considerable interest of customers and manufacturers, mainly those producing systems for propulsion and stationary power generation. The chief reasons for this attention include: the trend toward higher combustor pressure (particularly in the past twenty years or so) not only for higher performance in some sense, but also for smaller size, improved efficiency, and reduced emissions of pollutants. While overall efficiency of a system has in the past been largely a matter of gaining a competitive advantage, independent of any regulatory practices, that is no longer the case. Increasingly stringent specifications on pollutant generation will likely be met not only by reducing the amount of pollution produced in combustion of a unit mass of fuel, but also by requiring less fuel to generate a unit of power output or thrust. Those requirements and the traditional methods of achieving desired improvement are discussed in Section 3. An implication of that discussion is that the customary methods of design changes (a strategy of ‘passive’ control) seem to be approaching their limits. Hence the interest in active control is a direct consequence of widespread practical motivations.

On the other hand, the subject of active control of combustion remains primarily a matter of research. Apart from a small number of relatively recent observations of emission levels, practically all work on ACC has been concerned with control of coherent pressure oscillations, i.e. combustion instabilities. There are however, no available reports of successful application of active control to suppression of combustion instabilities in full-scale systems of any sort. In fact, it appears that the available demonstrations of combustion instability control span a small range of scales, both of geometry and power density. Consequently, almost nothing is known about the appropriate scaling laws.

The general reasons why research on active control of combustion dynamics has concentrated on control of combustion instabilities are easy to understand. First, it is generally true that as designs of combustors are pressed to give higher performance – normally a matter of raising power density – the likelihood is also raised that combustion instabilities will occur. Many examples exist for rockets, ramjets, and afterburners. Second, in the past several years, instabilities have become a serious problem in gas turbine combustors under quite different circumstances. In order to reduce production of nitrogen oxides, it is desirable to consume much of the fuel with lean burning to reduce the temperature. That implies operating a combustor as close to lean blow-out as possible. But then the global combustion process – the flame – tends to become unstable. The consequent unsteady motions can couple to global motions in the chamber, producing combustion instabilities.

Finally, there is a class of practical applications including heaters and incinerators of waste, for which intentionally pulsed combustion is effective for improved efficiency. Active control of pulsed combustion is attractive to ensure optimum operating conditions, avoiding, for example, inadvertent operation when the pulsations can cause unacceptable rates of surface heat transfer or reduced efficiency.

Several reviews or summaries of the various works on active control have been published, but no extended discussion of the subject has been given in the context of practical needs. Moreover, prior to this workshop there has been no opportunity for the international community of researchers to meet together and discuss the central issues. It became clear in early 1995 that both the research community and the potential users of active control methods for combustion systems would benefit significantly by joining to exchange information and ideas. The state of the field was such that merely presenting and publishing papers would not serve the purpose. A more informal situation was desirable, to allow extended discussions.

Work on ACC is applied research which if successful seems to have virtually immediate application to real systems. However, that view has not been proven. Despite the enthusiasm of all concerned there has been, on the one hand, a substantial gap between the appreciation of researchers for the actual situations in which ACC would be used – the requirements of industry; and on the other hand, users seem not to have a thorough understanding of (1) what really has been accomplished in ACC research, and (2) what one can reasonably expect to accomplish with applications in the near future. A major intention of the workshop was to clarify this situation. Due to the international nature of the communities involved, AGARD offered the best opportunities for achieving that goal. Moreover, it was a hope of the organizers that a workshop would promote collaboration with international partners.

3. Requirements for Future Combustors

3.1 Introduction

Active combustion control is a technology that has been demonstrated in the laboratory but has not been scaled up to the conditions and size of operational devices. As discussed in Section 6 of this report, research and development needs exist for all components of an active control system – sensor, actuator and controller. It is therefore appropriate to identify the projected needs and challenges for future combustors when determining the application opportunities for active control. This section provides a brief assessment of the requirements for future combustors as used in aeroengine and surface gas turbines, ramjets, rockets, and military burners and incinerators. Section 5 combines these future combustor requirements with the current status of active combustion control technology (Section 4) to identify near- and long-term applications.

3.2 Aeroengine and Surface Power/Propulsion Gas Turbines

Gas turbine engines have been developed for either aeroengine propulsion or surface power/propulsion. The aeroengine device, which is used for both military and commercial aircraft, always uses direct fuel injection in the combustor. That is, the liquid fuel is injected (often by an airblast fuel nozzle) into the combustor, where the physical processes of atomization, vaporization and fuel-air mixing occur. In contrast, surface power/propulsion devices, which can be used for ground power generation or ship propulsion, may utilize either direct-fuel-injection or fuel-air premixing. The former is identical to aeroengine combustors, but in the premixed arrangement, the aforementioned physical processes are essentially completed prior to entering the combustor. One consequence of fuel-air premixing is that the heat release is more concentrated. Because of the differences in fuel preparation, the requirements for aeroengines and premixed surface power/propulsion gas turbine combustors may be different.

3.2.1 Aeroengine Gas Turbines

Aeroengine gas turbines provide propulsion for aircraft, both military and commercial. In addition to requirements on performance and emissions that accompany any powerplant, there is a premium on achieving them in a compact, light-weight device that is very fuel efficient and highly reliable. These demands are projected to become increasingly severe for future aeroengine gas turbines. It is important to determine enabling technologies that might mitigate these challenges.

The basic performance trends for aeroengine gas turbines have been toward increasing thrust-to-weight ratio for military devices, and lower specific fuel consumption (i.e. fuel flow rate per pound of thrust) for commercial devices. The former is sought to increase maneuverability, while the latter supports reduced operating costs. Among the consequences common to both goals is the trend toward higher pressure ratios, with higher temperatures at both the combustor inlet and exit.

Based on these performance trends and mission-driven engine configuration studies, it is concluded that operating conditions for combustion systems will continue their historical trends toward increasing stringency. With long-term goals of doubling thrust-to-weight ratio and reducing specific fuel consumption by 25 to 50 pct, overall pressure ratios in the range of 50 to 75 are virtually certain, and values up to 100 are possible. For commercial applications, bypass ratios could increase to as high as 25 using gear-driven fans. For military applications bypass ratios will be more modest, but turbine inlet temperatures will increase significantly to values associated with combustor equivalence ratios of 0.5 - 0.7. These targets reflect the range of set-point operation over the power curve. The desire for military systems with shorter acceleration/deceleration response times imposes additional demands for more rapid transients between the set-point conditions. At times, the static stability of the combustor, and its adjacent components, will be exceeded.

These projected performance trends will impact the combustor design. Burning-length-to-dome-height ratios will approach 1.5, with a mean radius in the range of 216 to 250 mm (8.5 to 10 in.), regardless of engine airflow; dome heights will be in the range of 50 - 150 mm (2 to 6 in.) depending on the core engine airflow. Combustion intensities will range from 100 to 160 MW / m^3 / bar (10 to 16 MBtu / hr / ft^3 / atm). While the general combustor configuration will likely remain annular, the combustor inlet section diffuser may be changed for overall engine pressure ratios above 70. Specifically, passage heights in axial-flow compressors at very high pressures can become so small (depending on core engine airflow) that losses due to secondary flow begin to dominate, preventing final high efficiencies from being achieved. Under such circumstances, the final stages of compression might necessarily be done through one or more centrifugal-flow stages. This could have severe impacts on combustor configuration. At high pressures, secondary flow losses might also present difficulties for feeding shower-head cooling schemes in the leading edges of turbine inlet guide vanes. Therefore, shower-head cooling requirements might preclude the use of ultra-low pressure loss combustors in engines with very high overall pressure ratios. Also, the high fuel turndown ratio associated with high temperature turbines will make fuel-staged combustion systems common.

In order to cope with the requirements for future combustors, enabling technologies must be identified. For the demands discussed above, advances in high pressure fuel pumps, high temperature combustor liner materials, and fuel systems capable of handling super-critical fuels are required. Furthermore, 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. That is, the critical requirement for achieving the high combustion intensities associated with high pressure conditions, in reduced-size devices, is improved mixing of fuel and air inside the burner. Fuel-air premixing, such as used in some surface power/propulsion gas turbines, is precluded because of the very short autoignition time associated with very high pressure ratio cycles. While adequate mixing and an extremely high combustion efficiency is readily achieved for very fuel-lean operation, efficiency could become mixing-limited for higher equivalence ratios. Improved mixing is also necessary to minimize undesirable emissions of NOx, CO, and smoke at higher equivalence ratios. Further, the increased combustion intensity at any set-point may increase the likelihood of coupling with acoustic waves, promoting combustor dynamics problems. Such problems may also be exacerbated by faster transient responses.

The chemical reactions that determine energy release and pollutant formation occur on the molecular scale. However, the flow in a combustor is turbulent, and the mixing process must cascade down to the smallest eddy before molecular processes can become significant. The minimum turbulent length scale (Kolmogorov) determines the smallest mixing length scale. At atmospheric conditions, this scale is approximately 0.4 mm (0.015 in.) and decreases by three-orders-of-magnitude at 100 atm. In contrast, the dimension of the flow field structures are of the same order as the combustor geometry, which are on the order of 100 mm (4 in.). Hence, the mixing process must progress through an enormous dynamic range before molecular reactions can occur in significant amounts. While a wide range of eddies always exists in the combustor, achieving the stringent standards for efficiency and emission control requires that this mixing cascade occurs quickly and efficiently. That is, to achieve worthwhile improvements in mixing at fixed pressure loss will demand dramatic reduction in the characteristic "integral" turbulent length-scale associated with combustors. Radical geometric changes, such as reducing the combustor characteristic length scale by an order of magnitude, or greatly increasing the number of active shear layers to promote many length scales, appear to be essential.

3.2.2 Premixed Surface Power/Propulsion Gas Turbines

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 (power per occupied volume), high durability, and extremely low emissions. The latter is distinctively different than for aeroengine gas turbines, with allowed emission levels more than an order-of-magnitude lower. While this standard may not be required of all surface gas turbines (e.g. emission goals for ship propulsion are currently less strict than for ground power gas turbines), economics should drive manufacturers to develop only one surface gas turbine design. Since the lowest levels of emissions are obtained through the flame temperature control achieved with premixed combustion, and ground power gas turbines must strive for the lowest emissions levels to be competitive, the industry standard for new surface gas turbines is premixed combustion. The trend in development of surface gas turbines is toward lower emissions levels and higher cycle efficiencies. The former is driven by (real and anticipated) air quality regulations, while the latter affects operating cost (i.e. "cost of electricity"). Currently, many ground power gas turbines guarantee NOx and CO exhaust concentrations limited to 25 ppm @ 15 pct oxygen (i.e. parts per million at a standard exhaust flow dilution to achieve 15 mole pct oxygen). Future products will strive for "single digit" (e.g. 9 ppm) guarantees. Depending on the application, such emission goals may result in engine cycles other than the "simple (Brayton) cycle" – cycles which, for example, extract heat of compression (i.e. "intercool") between two compressors.

The lowest level of emissions is achieved by employing a premixed combustion strategy. Generally, a fixed distribution of effective flow area divides the combustor airflow and delivers the greatest fraction to the set of premixing fuel nozzles. The maximum airflow fraction, or leanest fuel-air mixture, is limited by the lean blowout (LBO) mixture, which is the leanest mixture which will sustain combustion. If the premixing airflow fraction is increased (starting from a high fuel-air ratio), then the fuel-air ratio, the flame temperature, and the formation rate of NOx all decrease. However, as the fuel-air ratio approaches the LBO level, the flame temperature will not support sufficiently fast CO oxidation rates and its concentration in the combustor exhaust increases. That is, CO acts as a precursor to marginal stability, reflecting either globally reduced oxidation or the presence of sub-LBO fuel-air pockets which have extinguished. Hence, as depicted in Figure 3, there is a "window" of fuel-air ratio, and of corresponding flame temperature, that will simultaneously result in low NOx and CO. The width of the window will depend on both the inherent combustor stability characteristics and the level of desired emissions control. The figure shows the window width for sub-25 ppm levels; the window is clearly narrower for lower limits. Generally, homogeneous (i.e. non-catalytic) combustion systems do not provide a window width covering the full mixture (or temperature) range experienced from low to baseload gas turbine power. Hence, to preserve ultra-low emissions over a wide power range will require shifting the premixing airflow fraction as the overall fuel-air ratio changes to remain within the desired flame temperature window. It is also true that as the fuel-air mixture approaches the LBO limit, thermoacoustic instabilities become more prevalent. Indeed, 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.

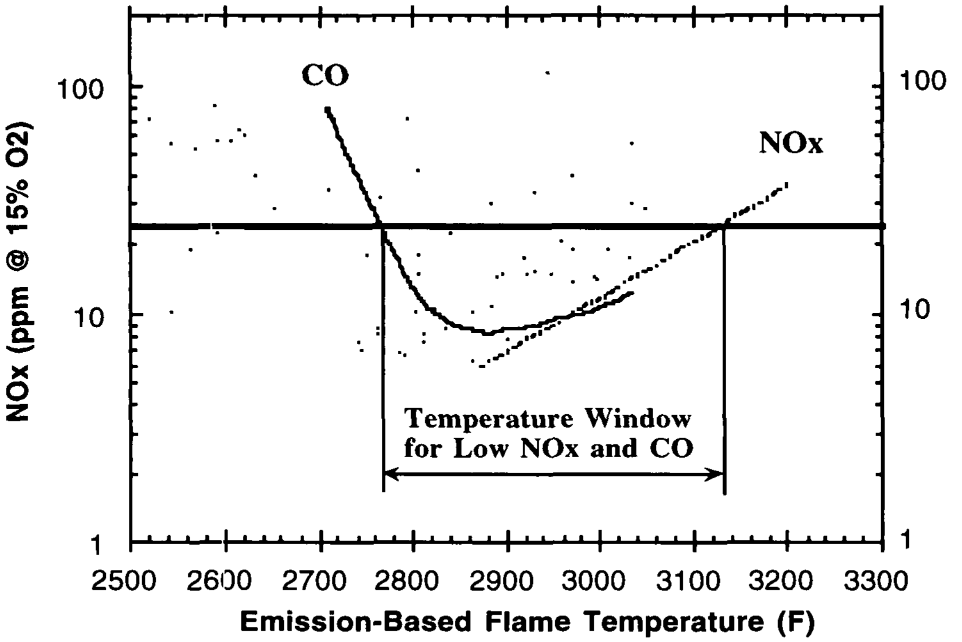

Fig. 3 Flame Temperature Window for Both Low NOx and CO from Premixed Combustion.

3.3 Tactical Airbreathing Missile Propulsion

Airbreathing propulsion will receive increasing emphasis to meet future requirements for tactical missiles, with several different types of airbreathing propulsion systems being considered. Most attention is given to the liquid-fuel ramjets and gas-generator ramjets (ducted rockets). Liquid-fuel ramjets are operational in France (ASMP), Russia (Mosquito), and China (Silkworm), and advanced developments/demonstrations are currently being conducted in France (ASLP/ASMP) and USA (Low Drag Ramjet). Advanced development programs for ducted-rocket propulsion are being conducted in fewer countries, such as France (MPSR2) and USA (VFDR). Other potential systems are solid-fuel ramjets, scramjets, expendable turbine engines, and pulsed-detonation engines (PDE). The PDE is a device that can increase thermodynamic cycle efficiency by more than 30 pct compared to the constant pressure burn cycle (Brayton cycle) of the other systems, and has self-boost capability. Based on its advanced level of maturity, emphasis will be placed on discerning future combustor requirements for liquid-fuel ramjets based on mission demands.

Airbreathing propulsion has the potential for the highest performance per unit volume and weight and is considered for several different missions, including:

(a) *Precision Strike* over long range with high sustained velocity and high warhead weight,
(b) *Air Superiority* with increased range and maneuverability, and reduced time to target,
(c) *Naval Surface Fire Support* with increased range of gun-launched missiles,
(d) *Ship-Based Defense* with high velocities and reduced time to target, and
(e) *Surface Air Warfare (Anti-Air)* with mission flexibility and long duration.

Generally, modern tactical weapons systems are being driven to longer ranges at minimum volume and weight. These general guidelines translate into specific requirements of: (1) increased kinetic performance to provide increased range and higher sustained and average velocity; (2) increased energy per volume and per weight to reduce weapons size and increase warhead weight; (3) increased propulsion energy management to enhance maneuverability and mission flexibility, (4) increased survivability through longer range launches, increased propulsion duration, higher velocities, and reduced plume signature, and (5) reduced cost.

As indicated in (2), the application 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. The performance challenge derives from meeting the same high standards for combustion efficiency in higher through-put devices, over broader operational conditions, but with no increase in pressure loss. The risk of instability is a product of both broader operational conditions which drive the burner closer to blow-out, and increased energy release density which enhances the potential for its coupling with fluid dynamic and acoustic features of the burner.

A number of specific requirements can be identified for liquid-fuel ramjets. Future missions will require operation between sea level and 30 km (100,000 ft) altitude with a potential variation of the equivalence ratio between 0.5 and 1.0. Highly efficient and stable combustion must be achieved over the entire operation envelope. For current combustors, efficiency is high at the high Mach number design point but falls off as the mission moves the fuel-air ratio toward either the lean or rich blow-off limits. Combustion instability is often encountered at either a medium frequency range (300 Hz corresponding to a longitudinal mode) or a high frequency range (3000 Hz corresponding to a tangential mode). Currently, the pressure oscillations and mechanical vibration arising from the instabilities (which also impose adverse fluid mechanical effects on the inlet margin) are solved by baffles, aerogrids, and tailored fuel distributions, but at the expense of combustion efficiency and pressure loss penalties. An enabling technology for current and future ramjet propulsion systems is a methodology to sustain stable operation, through either passive design or active control, over a wide range of operational conditions.

Alternative tactical missile propulsion systems include solid-fuel ramjets, scramjets, expendable turbine engines, and pulsed-detonation engines. Specific combustor requirements for ducted rocket propulsion systems are similar to those for liquid-fuel ramjets, while efficient ignition and combustion of liquid hydrocarbon fuels in dual-mode operation of compact designs are technical challenges for scramjets. Expendable turbine engines require increased performance per volume, possibly through the use of short L/D afterburners, highly energetic fuels, and shorter inlets. Liquid-fuel pulse detonation engines must enhance many features including fine-scale and large-scale mixing, fuel vaporization, two-phase detonation and shock-wave propagation, and continuous thrust generation. Clearly, these systems are not as mature as the liquid fuel ramjet.

3.4 Rocket Propulsion

Rocket propulsion 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. While both solid- and liquid-propellant systems have this common need, the controlling processes are not the same, and as such the means to achieve stable operation will be different.

3.4.1 Solid-Propellant Rockets

Solid-propellant rocket propulsion systems can be divided in three main applications – tactical missiles, strategic missiles and solid rocket motors (SRM) for large space launchers. This variety results in wide ranges of size and operational conditions, and hence in a wide range of conditions for instabilities. Potentially unstable frequencies can be well predicted from acoustic mode analyses, but identifying which frequencies become amplified, and the resulting oscillatory levels, remains a challenge, although predictions have been made for simples cases. Such predictions depend on non-linear influences of various phenomena which often depend on frequency (e.g.

propellant response, nozzle damping, particle damping, flow turning loss, vortex shedding driving). As a consequence, scaling rules are non-linear, and the extrapolation of results from smaller scale to larger scale devices can be uncertain. Recent CFD analyses of vortex shedding processes in solid-propellant rockets have increased an understanding of some of the influences.

Large segmented motors for space launchers (e.g., Space Shuttle SRB, Titan SRB and SRMU, Ariane 5 MPS P230) also display acoustic instabilities characterized by low-level pressure and thrust oscillations at the first acoustic modes. Such modes are experienced despite being predicted stable by conventional analyses. Attempts to expand classical acoustic-balance computer codes to include the vortex-shedding effects have shown some limitations that preclude their routine use. An ongoing work in France, carried out under the ASSM program supported by CNES, is attempting to validate a full numerical approach for instability prediction at conditions with vortex shedding. Moderate success has been achieved for axisymmetric conditions in a small scale research motor. However, the quality of these results is not sufficiently accurate for industrial purposes, especially considering the required extrapolation to larger scale where both under-predictions and incorrect trends have been obtained.

3.4.2 Liquid-Propellant Rockets

Liquid rocket motors are mainly used in space launchers. They use a variety of propellants, from storable propellants to cryogenic or semi-cryogenic propellants, and can be used for all stages of the launcher. The main challenges for liquid-propellant rockets include increasing performance and reliability, particularly of turbopumps, and decreasing costs and overall weight. Issues to be mastered include turbopump reliability, wall cooling, combustion efficiency and combustion instability. Techniques to eliminate liquid-propellant rocket instabilities are critical since their occurrence can be quickly catastrophic to the system. Modifications of injection designs and/or propellant formulation have been proposed as potential means to suppress the instabilities by altering the heat release distribution. Baffles have been used to shift the motor acoustic frequencies and to avoid the coupling between unsteady combustion and local flow oscillations. All of these approaches to eliminate instabilities are highly empirical. While CFD approaches to predict the modes and coupling mechanisms are being developed, their physical basis is immature.

3.5 Military Burners and Incinerators

The military will be required to comply with emerging regulations for all types of combustion devices, including burners and incinerators. Since these devices have common combustion features with propulsion systems, the use of ACC offers a viable solution to meet various future requirements.

Incineration is widely accepted for solid and liquid waste treatment on cruise ships. However, the US Navy has concluded that the present technology based on commercially available incinerators may significantly degrade military operations due to their physical volume and weight. Also, potential problems with emerging emission standards were cited and have caused a delay in implementing international regulations. The main requirements for future marine incinerators are size and weight reduction, while maintaining pollutant emissions within acceptable levels, which are expected to be more strict that the present marine regulations for CO, NOx, and other hazardous species. In addition, continuous monitoring of selected species in real time may be required.

4. Status of Active Combustion Control

4.1 Overview

The concept of active combustion control has appeared in several forms over the past four decades. The first attempt was made by Tsien[11] in an effort to apply control theories to suppress the chugging instability in a liquid-propellant rocket engine. His analysis was based on a combustion model which considered a pressure-dependent time lag between the instants of propellant injection and burning. Stabilization of the combustion conditions was achieved by modulating the propellant injection rate through a capacitor controlled by a servomechanism with pressure feedback. The problem of intrinsic stability was studied using the Nyquist plot to determine the suitable servo coefficients. Similar approaches were used by Marble and Cox[12] and Lee et al.[13] to control the low-frequency instabilities in bipropellant liquid rocket engines. However, no experimental results based on this "servo-stabilization" concept have been published, primarily because of the limitations of instrumentation at that time.

With recent developments in fast-response sensors and actuators, some interesting studies on the active control of various problems have been reported. Ffowcs-Williams[14] described the concept of "anti-sound" — the elimination of unwanted oscillations in an acoustic field by means of acoustic interference. The basic idea is to first determine the characteristics of a given acoustic field, and then to use that information to manipulate a secondary source of sound which serves as an acoustic actuator. Control is achieved by producing waves out of phase with the unwanted oscillations. In principle, this wave-cancellation technique is applicable to combustion systems; however, implementation to a full-scale combustor is quite unlikely because the energy density of the oscillatory flow field may well exceed that which can be matched by such acoustic actuators as loudspeakers. Furthermore, as a result of the intrinsic richness of the thermo-acoustic interactions, implementation of a control system in a combustion chamber is much more complicated than for normal temperature and pressure environments.

Practical applications of the active control of combustion instabilities have been demonstrated in several research experiments. At Cambridge University, Dine[15] showed that the instabilities of a flame burning on a gauze in a Rijke tube can be eliminated as follows. First, the light emitted from CH free radicals was monitored as a measure of the unsteady heat-release rate from the flame. This information was then processed and fed back to a loudspeaker placed near one end of the tube to increase the acoustic energy dissipation from the boundary. The same problem was studied by Heckl.[16,17] However, instead of a photo-multiplier, a microphone was used as the sensor to excite the loudspeaker. Results indicated that instabilities can be suppressed over a wide range of phase difference between unsteady oscillations and actuating pressure waves, provided the control gain is sufficiently large. This observation clearly demonstrated that the control of combustion instabilities can not be explained simply by the principle of anti-sound, which requires that the control excitation be precisely out of phase with existing oscillations.

More recently, Bloxsidge et al.[18,19] reported the control of low-frequency combustion instabilities in a laboratory jet-engine afterburner. The mass flow into the combustion chamber was varied by oscillating a center body inserted in the choked inlet nozzle, thereby exerting the necessary modifications on the unsteady flow fields. The system was partially successful in suppressing the instabilities, with the amplitude of the fundamental mode reduced by fifty percent.

Lang et al.[20] and Poinsot et al.[21,22] explored the active control of instabilities in a small laboratory burner, using a loudspeaker as the control actuator. Both experiments used the same gaseous reactants, but with two different types of flame holders: a multiple orifice plate with 80 holes placed in a premixed propane-air stream; and an array of three rearward-facing steps through which fuel was injected into the air flow. Acoustic pressure was measured by a microphone located upstream of the chamber. The signal was then filtered, phased-shifted, amplified, and sent to a loudspeaker attached to the burner. In addition to the demonstration of instability control, their work showed that the active control technique can be used effectively to study the initial transient behavior of instabilities.

One feature common to the above approaches is that they all used mechanical means, such as loudspeakers or moving bodies, to suppress instabilities. For practical systems containing high energy density, implementation of these means may not be feasible due to the relatively large amount of power required to drive control actuators. It appears that the most direct method of control should be based on the manipulation of energy sources of oscillatory flow fields. Langhorne et al.[23] reported that pressure oscillations in a laboratory afterburner can be reduced significantly by a controlled secondary supply of fuel which is effective in generating the energy necessary for instability control. This method offers a promising solution to problems of low-frequency oscillations in full-scale combustors. Sivasegaram et al.,[24] Billoud et al.,[25] Wilson et al.,[26] and Schadow et al.[27] have all demonstrated experimentally the effectiveness of this technique. The theoretical study of Yang et al.[28] and Fung et al.[29] and the numerical simulations of Menon,[30] Shyy et al.,[31] and Neumeier and Zinn[32] have also demonstrated the viability of controlled fuel injection. For detailed reviews of active control of combustion instabilities, see Culick,[33] Candel,[2] and McManus et al.[1]

In addition to its applications for propulsion systems, active control technology has been used to enhance mixing in incinerator afterburners and to increase the DRE (destruction and removal efficiency) for waste materials. Parr et al.[9] have conducted a detailed study of the concept of utilizing vortex combustion for incineration in a small-scale gaseous fuel system and an extension to a more practical system using liquid fuels. Acoustic excitation was used to stabilize coherent vortices in the air flow, with the fuel modulated and introduced into the air vortex exactly at the instant of vortex formation. This concept has demonstrated its effectiveness in improving waste destruction. The DRE for liquid benzene exceeded 99.999% for a afterburner/incinerator of 56 kW energy release, even when the waste surrogate constituted 17% of the total fuel content. The controller also reduced emissions: CO dropped from 2900 ppm to as low as 2 ppm and NOx was reduced to 12 ppm. Parameters critical to the controller performance were the forcing level of the fuel injection, the fraction of the circumferentially entrained air, and the phase angle of the fuel injection with respect to the air vortex roll-ups.

The most common sensor used in ACC is the pressure transducer. For controlling combustion instability this is a natural choice, as the instability is characterized by the chamber pressure oscillations. Experimentally, photomultipliers have also been successfully used, since their signals can give a measure of the unsteady heat release which is at the root of the instability. The placement of either type of sensor is important. For example, the shapes of the chamber acoustic modes should be sufficiently well-known to avoid placing a pressure sensor at a pressure node point. Also, a photomultiplier's signal could be misleading if the sensor is positioned so that its field of view does not completely cover the entire range of motion of a spatially varying reaction zone. Recent advances in machine vision applied to an array of optical sensors may offer a solution, and also provide the controller with information regarding the global distribution of unsteady heat release. Of course, optical access (including interference by sooty flames) is another problem. Other optical sensors, such as laser-induced fluorescence for species measurement and LDV for velocity sensing are probably unfeasible for practical applications, but may be useful in experimental control systems. Optical sensors may be key in pattern factor control, since the temperature distribution throughout the cross section of a chamber is desired.

For combustion instability control, most ACC actuators attack either the acoustics (directly with mechanical acoustic actuation or indirectly through controlled fuel flow), or the hydrodynamics of a reacting shear layer in a dump combustor (by fluid dynamic forcing near the origin of the shear layer). The former approach is sensible in that chamber acoustics play a defining role in the energy feedback loop which causes high-frequency instabilities. The latter approach also has intuitive merit since the spatial and temporal unsteadiness of the heat release (source of energy for the instability) is strongly tied to the turbulent hydrodynamics of the shear layer. Both actuators have demonstrated varying degrees of success in closed-loop control, and shear layer actuation has exhibited positive influence in open-loop mode. Perhaps tandem acoustic and hydrodynamic actuation could accomplish more than either one alone.

In regard to controller design, most studies have used either fixed-parameter or adaptive approaches:

(1) In a fixed parameter controller, the parameters which define the behavior of the controller do not change with time or with the state of the system. If a reliable model is available, the design of this type of controller can take advantage of well-developed and powerful control and optimization theories. The robustness issue is also most easily addressed for such control design.

Unfortunately, no complete model for practical combustors exists, and the closest approaches (i.e. CFD simulations) are far too complex for direct incorporation into viable controllers. Reduced-order models may be used to develop the controller,[28,29,34,35] but these models usually contain unknown parameters. System identification can help to define these unknowns by effectively matching the behavior of the model to that of the actual system. Fundamental empirical studies may also aid in this way. Fixed-parameter controllers do not need to be model-based. For example, intuitive gain/phase relationships between the sensor measurements and required actuator signals have been assumed in many successful experiments. Although the controller gain and phase are adjusted for optimal damping of the combustion instability ("manual adaptation"), the controller would be essentially fixed-parameter in application. This approach was apparently also taken in Ref. 30, where a CFD-simulated "virtual combustor" was used to adjust the controller. This underscores the emerging value of CFD as a means of developing and testing controllers, as well as for increasing physical insight and understanding.

(2) An adaptive controller automatically adjusts its own parameters to achieve desired performance of the controller. In direct adaptation, the control parameters are changed based only on a measured performance function. First demonstration of this concept was reported by Billoud[25]. This approach is demonstrated in Padmanabhan et al.,[36] where the Downhill Simplex method was used to seek control parameters which minimized the instability through shear layer actuation. In indirect adaptation, on-line system identification is performed continuously to maintain a locally accurate, updated model of the system; then the controller uses the model's parameters to adjust the control parameters and generate the actuator signal. The model in this case can be a generalized one detached from the physics of the problem (such as an FIR filter used by Billoud[25]), or it can incorporate physical understanding. Although adaptive controllers are more complicated, their flexibility may be crucial for combustion instability control in the face of changing operating conditions, imperfect knowledge of the system, and changing or multiple modes of instability. Adaptive approaches have demonstrated practical success in the related field of noise control, and appear feasible in combustion control as well. More advanced control involving artificial intelligence techniques such as fuzzy logic and neural networks may eventually offer new solutions to the ACC problem. Although such schemes have been practically demonstrated in noise control, their ill-understood nature makes them unlikely candidates for systematic application in reliable ACC systems, at least in the near future.

Physical modeling can enhance the control design, and is a necessary component of some controllers. Many modeling efforts have concentrated on a specific process, such as acoustics or shear layer hydrodynamics. However, studies such as Cohen and Anderson[38] suggest that both acoustics and shear layer hydrodynamics are important in some instabilities. Instances of hysteresis in combustion chambers and significant changes in the nature of the unsteady heat release (such as the "pinching-off" of burning lumps of fuel[21]) also suggest acoustic/hydrodynamic interaction. The consideration of entropy modes may also be appropriate in some systems.

Although liquid fuel feed systems typically respond only to low-frequency (<100 Hz) chamber oscillations, the gas-filled volume of a premixer may respond to chamber acoustic modes, causing unsteady flow of fuel-air premixture into the chamber and hence feed-system like instabilities. In addition to the combustor itself, modeling the actuator can be an important issue, especially for injection of controlled fuel.[34]

Finally, in any controller, it is important to squeeze the maximum amount of (accurate) information from the available sensor data to determine the state of the system being controlled. This issue of observer design has been explicitly addressed in Ref. 32. The presence of noise in a combustor, system uncertainties, and what information must be known a priori about the system are important considerations in observer design.

4.2 Recent Results

The status of the various ACC programs currently being conducted within the AGARD community was summarized at the workshop. These programs cover a broad spectrum of problems related to combustion instability and pollutant emissions. Schadow and his coworkers at the US Naval Air Warfare Center have been working on the detailed understanding of fluid dynamic/acoustics/combustion interactions. In particular, the effects of large-scale structures and their transition to fine-scale mixing are being considered. The ACC is applied to a variety of combustion devices, including ramjet dump combustors and incinerator afterburners. Both systems have similar combustion characteristics with flame stabilization at a backward facing step or dump region. For these flow conditions the development of jet shear layers is critical for the combustion processes, including flammability limits, combustion efficiency, and flame stability (combustion instability). The ACC work is therefore based on controlling jet shear-flow dynamics, which are characterized by flow instability frequencies associated with initial vortex shedding and subsequent vortex merging, as well as the jet preferred mode at the end of the jet core. The physical understanding of the relationship of these flow instability frequencies and acoustic driving frequencies is critical for the control process.

The initial vortex frequency is associated with the generation of small scale vortices, which are critical for molecular mixing and flame stability. Premixed flame experiments showed that open-loop forcing at the initial vortex shedding frequency, which scales with the momentum thickness and jet velocity, significantly extended the flame stability limits.[52] The preferred mode frequency is associated with the generation of large-scale structures. When this flow instability frequency, which scales with the jet diameter and jet velocity, is near one of the acoustic resonant frequencies of the chamber, the large-scale structures are highly coherent and can cause periodic heat release. Under certain conditions this can lead to the driving of combustion instabilities. ACC was used to damp these oscillations using a variety of actuators, including acoustic drivers, pulsating fuel injection, and periodic secondary heat release. Both gaseous and liquid pulsed fuel injection[53] were used. The same technique is also used to enhance combustion efficiency.[54] In this approach gaseous and/or liquid fuel is injected at the right time into acoustically stabilized vortices using

ACC. Tests are being conducted to enhance efficiency in ramjet dump combustors and in incinerator afterburners. For the latter application it was shown that performance of an incinerator can be significantly increased, even when energy density of the system was reduced by a factor of 200 relative to present systems. The ACC mechanism was scaled up by a factor of 10 to a 50kW system and is currently being scaled up by a factor of 200 to a 1MW system.[55] In the present flame and combustor experiments simple time-delay controllers are being used. Also, limited experiments have been done with a neural net based controller.

The application of ACC to suppression of combustion instability was also employed by Zinn of the Georgia Institute of Technology.[8] The system consists of an observer that uses an iterative, Fourier-like approach to determine the amplitudes, frequencies and phases of unstable combustor modes in real time. This information is sent to a controller where open-loop test data are used to determine the gain and phase shift that are added to each unstable mode. The modified modes are combined into a control signal that is delivered to a fast response fuel injector actuator that varies the length of a magneto-strictive material and, thus, modulates the injection rate of a secondary fuel stream into the combustor. The latter damps the unstable combustor modes by generating secondary heat addition oscillations out of phase with the pressure oscillations. To date, open loop tests have been performed to determine the frequency response of the fuel injector actuator, which was subsequently used in the closed-loop control tests. These tests showed that the developed system effectively damps large amplitude instabilities. For example, the amplitude of the most unstable combustor mode was damped by 26 dB within 40 milliseconds after activating the control.

In a research project sponsored by the US Navy, Yang and his colleagues of the Pennsylvania State University have been working on the development of integrated control methodologies for gas-turbine combustors in order to enhance performance in terms of lean blowout and combustion stability characteristics, while maintaining pollutant emissions within permissible limits.[56] A variety of active control techniques are systematically evaluated and implemented in a hierarchical approach. The control strategies are established at two levels. High-level control is carried out using modulated secondary fuel injection directly into the flame stabilization zone. Their process is appropriately synchronized with local heat release and pressure oscillations in order to stabilize the combustion flowfield and consequently extend the operating range. Low-level control is carried out using variable air swirl. This is used to change the degree of fuel-air mixing at the combustor inlet in order to achieve minimum emissions over the entire operating range of the combustor. The two-level strategy, together with appropriate combustion transient sensors, will be part of an ACC system which will extend the stable operating range of the combustor and reduce emissions. In addition, innovative concepts for diagnostic and prognostic decision-making will be incorporated into the control system to enhance engine reliability. Optimization of combustor operations will be conducted based on requirements for flame stability and pollutant emissions. When coupled with a global engine control system, this combustor control system will allow for the development of fuel-efficient and clean gas turbine engines.

Several research groups have discovered the presence of hysteretic behavior in the vicinity of the stability boundary for oscillations in a dump combustor. The phenomenon is observed as the fuel air ratio is changed with all other parameters fixed. The existence of the hysteresis loop is the basis for a strategy of nonlinear control recently demonstrated by Culick[57] of the California Institute of Technology. When the system is operating on the upper branch of the hysteresis loop, the system can be forced to make the transition to the lower branch by injecting a single pulse of secondary fuel at the dump plane. Thus, by applying active control, the region of stable operation can be extended. Perhaps the most significant aspect of these results is that successful control has been achieved because the dynamics of the system are understood, and the control law was suitably constructed. It is particularly important to notice that the behavior treated with this method is intrinsically nonlinear. Application of linear control ideas would be inappropriate and much less successful. A fundamental matter is the extent to which truly nonlinear control can be extended outside the region of hysteresis.

California Institute of Technology also attempted to find chaotic behavior in an air-breathing combustor.[58] Sterling analyzed pressure records taken in a dump combustor showing no strange attractors that might indicate chaotic behavior. In contrast, a model, which was based on some of the characteristics of the pressure records, including a nonlinear combustion response with time delay, did produce chaotic behavior. Presently there is insufficient experimental data to rule out unequivocally chaotic behavior in combustors, but the available information suggests that the noisy background in combustors is due to stochastic sources such as flow separation and turbulence.

The ACC research conducted by Whitelaw and his associates at the Imperial College attempts to suppress combustion instabilities, extend flammability limits, and minimize emissions in a variety of geometric conditions.[24] These include ducted premixed flames behind one or more bluff-body stabilizers; a model of an industrial burner; a model of an annular gas turbine combustor; and an opposed jet flame. Discrete-frequency oscillations are imposed on the flows using actuators such as acoustic drivers, periodic spark ignition of part of the fuel, and devices to oscillate liquid and gaseous fuel flows and a spray of water. The frequency limitation of the injectors was overcome by fuel injection at half the dominant frequency and the sequential operation of injectors. Control of the oscillations also led to a reduction in NOx emissions by 5% with oscillations of liquid fuel and by 50% with a spray of water. The latter is due to heat removal. The rich flammability limits of a model industrial burner was extended from an equivalence ratio of 1 to greater than 3 by the addition of oscillations by a loudspeaker. At the same time the flame was more stable and more compact. Imposed oscillations had an adverse effect on the lean flammability limits which was partly overcome by the dilution of the fuel with air.

Burkhardt of the Technical University in Hamburg-Harburg studied active combustion control of a bunsen burner flame using image processing sensors which can be superior to point sensors.[59]

Using a CCD camera with 250000 diodes, it is possible to carefully characterize the state of the combustion process, for example, by analyzing turbulent and non-homogeneous reaction zones. In his experiments non-optimal burning states are recognized and corrected/optimized by closed-loop active control. Two different approaches, namely optimization techniques, and fuzzy logic and neural networks, were used to analyze changes in the image sequences. Both control strategies are able to "learn" an optimal state which is set up by a human expert and determine necessary actions for active control to optimize the reaction process. For the optimization technique, the image of a non-sooting flame was selected as the optimal burning state. By proper application of image processing techniques they continuously extract image features from the combustion process to compare with features from an optimum state obtained by a learning procedure. They use a quadratic, multispectral performance criterion to optimize on-line using the modified Newton-Raphson algorithm. For the fuzzy logic technique,[60] a small number of features (such as flame height and brightness) which are closely related to the state variables, are extracted. These features were compared with those obtained in the optimum combustion state, and the deviations are sent to the neural-network-based controller. The implementation of the fuzzy controller in the form of a neural network provides the possibility that the system can learn from the environment and improve the robustness against the environmental disturbances through updating of the network's weights. The system determines a control action by using a neural network which implements fuzzy inference. In this way, prior experts' knowledge can be incorporated easily.

ACC research is being conducted at UTRC under internal and DARPA funding on lean premix burners using both gaseous and liquid fuels. The focus of the research is on the control of combustion instabilities. The research is experimentally based, using a small scale atmospheric pressure rig for screening of actuation and control concepts, and a single nozzle rig running engine scale hardware at combustor operating pressures and temperatures. Actuation concepts involving fuel flow control are being evaluated. Methodology and hardware have been developed that have sufficient bandwidth to control instability frequencies up to about 200 Hz. Significant reductions in instability pressure levels have been demonstrated. For example, during screening tests on the atmospheric pressure rig operating on gas fuel, up to 8 dB reduction in combustion instability pressure oscillations were achieved using a pilot for control.

Active control has been investigated at Ecole Centrale de Paris as a means for reducing the level of nitric oxides emitted by liquid fuel combustors.[61,62,63] Experiments carried out on a 25kW domestic boilers and on a 850 kW furnace indicate that reductions of up to 30% may be obtained by open loop control techniques. This demonstrates that active control principles may be used to improve combustion in practical systems.

Work on ACC has been carried out at IST, Lisboa, Portugal, aimed at suppressing oscillations and reducing NO and CO emissions. The technique used was the sinusoidal forcing of the gaseous fuel stream with phase shift control. A wall static pressure probe was used to detect the pressure in a tube and disc burner. It was shown that different disc sizes and geometries were effective to reduce NO and CO production. This ACC work is related to earlier passive control work where pressure oscillations were reduced using different bluff body geometries.[64]

ACC research has been conducted at the Munich University of Technology, Germany, for more than 10 years. The main aspect of this research, which was started with a joint project with Ecole Centrale de Paris,[20,21] is the active suppression of self-excited combustion instabilities and exploring the onset of instabilities.[65] Current research includes the design and testing of practical actuators.[66,67] The research is the basis for an industrial application of ACC to a full-size stationary gas turbine with an electric power output of 170 MW. This project is producing very encouraging results, which will be published at the ASME ASIA 97 Conference and the "18 Deutsch-Niederlaendische Flammentag."

5. Active Combustion Control Applications

5.1 Introduction

The review of future needs presented in Section 3 described several challenges which may limit the growth potential of combustion systems. For example, the evolution of aeroengine gas turbine combustors with very high pressure ratios may depend on achieving greatly accelerated mixing rates to preserve highly efficient operation at such high combustion intensity conditions. Some of the challenges may be mitigated by successful application of active combustion control methodologies. The following table depicts, for the major combustion systems, such challenges and the relative priority determined at the AGARD Workshop, based on a composite consideration of basic understanding, risk, and benefit. As indicated, a common combustion system challenge believed addressable by ACC was instability control; it was identified for all systems. The reason for "low" relative priorities assigned to aeroengine systems was because other systems had a more immediate need. A "low" relative priority for liquid-propellant rockets was assigned because the perceived risk was very high in order to achieve a successful active control application. The reason for "high" relative priority for instability control for both surface power gas turbine and airbreathing missiles was because it is an acknowledged developmental challenge for all manufacturers, and also laboratory demonstrations have shown the potential for active control to mitigate it. The "medium" relative priority for solid-propellant rockets instability control, as well as compact design for burner and incinerator emission control, reflected developmental needs and a belief that the key physical phenomena were known.

Together, instability controls in surface power gas turbines, airbreathing missiles, and solid fuel rockets were judged to be high impact applications for active combustion control. Successful application of 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 pursuit of these applications, developments in sensor and actuator technology will be required to provide highly responsive, precise, and reliable devices. Further, it is important to expand the experience base for the applications from laboratory scale and conditions to realistic hardware and conditions. For example, actuator capacity which may be suitable for atmospheric operating conditions may not function at elevated pressures and flowrates. Moreover, neither the identification of the key physical instability coupling phenomena, nor their scaling to other conditions, are known. Hence, the potential demonstrated at reduced conditions does not guarantee any payoff at real conditions. The logical development of all elements of the active control system, and their use in more realistic devices, will result in new options for the combustion system designer, and permit growth of the system's potential. In the following sections, active combustion control applications specific to surface power gas turbines, airbreathing missiles, solid propellant rockets, and military burners and incinerators are discussed.

Table 1. Relative Priority for Active Combustion Control

Combustion System	Operational Challenge Addressable by Active Control	Relative Priority
Aeroengine Gas Turbines	Enhanced Mixing	Low
	Instability Control	Low
Surface Power Gas Turbines	Instability Control	High
	Flame Temperature Control	Medium
Airbreathing Missiles	Instability Control	High
Solid Propellant Rockets	Instability Control	Medium
Liquid Propellant Rockets	Instability Control	Low
Burners/Incinerators	Compact Design for Emission Control	Medium

5.2 Surface Power Gas Turbines

Increasingly stringent emissions standards will raise the challenge for surface power gas turbines to operate stably. That is, in order to meet lower emissions goals for NOx and CO, premixed combustion systems will be used and operated at very lean fuel-air ratios. As previously discussed, the leanest mixture will be set by the stability characteristics of the combustor – both the static stability characterized by lean blowout and the dynamic stability characterized by lean-limit, acoustic-coupled instabilities. Both of these narrow the operational flame temperature window, and are currently encountered by most manufacturers of industrial gas turbines. Active combustion control is a technique believed capable of mitigating the lean-limit instabilities.

Subscale demonstrations of suppressed combustion instability have been performed at reduced pressure and temperature operating conditions. Such tests, performed for premixed and direct-injection systems, have shown that significant reductions in the combustor pressure oscillation can be achieved for instabilities experienced at frequencies up to approximately 300 Hz. While the coupling driving the instabilities is often termed thermo-acoustic, a detailed understanding of the key processes is not available; successful demonstrations have not relied upon this knowledge. Generally the approach is to modulate a secondary fuel injection (or pilot) in a manner to either interfere with the coupling mechanism or cancel the pressure perturbations. Control algorithms often adapt to the instability because of the wide range over which stable operation must be preserved, and both electro-mechanical- and advanced material- (e.g. magnetostrictive) based actuators have displayed sufficient capacity and responsiveness for these demonstrations. While such subscale tests have shown the promise of achieving instability control of premixed combustion, these studies must be extended to realistic operating conditions. Both reliable, durable actuators with capacities consistent with real operating conditions, and control strategies capable of breaking the coupling mechanism, must be achieved. Further, the actuator authority must be sufficient such that any fuel perturbation does not compromise the combustor emissions goals. Ongoing studies suggest that the desired attributes of active stability control are achievable.

5.3 Airbreathing Missiles

Future requirements for tactical missiles will drive the design to even smaller combustors that must maintain high-level and stable combustion over even broader ranges of operation. Active combustion control has the potential to meet these challenges. In the near term, suppression of low-frequency combustion instabilities by active control should be achievable, while in the long term, the extension of lean blow-out limits may also be realized. This promising outlook is based on the fact that the critical role of shear-flow dynamics (or the development of large-scale structures and their break-down into fine-scale turbulence) for the combustion characteristics in ramjets (the airbreathing missile combustor) is well understood. While this is particularly the case for the center-dump combustors, an understanding of the underlying unsteady fluid dynamics found in annular and side dump combustors needs further research.

Methodology to suppress low-frequency combustion instabilities in center-dump combustors has been successfully demonstrated in laboratory tests, suggesting that its application to full-scale combustors is a realistic goal. The suppression of these oscillations are critical, because they can reduce the inlet margin, resulting in inlet unstart. While scale-up and transition to realistic operational conditions remain a technical challenge, current physical understanding and control strategies for vortex-driven combustion instabilities make near-term success likely. The demand on missile system actuators and sensors to control instabilities in the frequency range of 100 to 300 Hz is reasonably within capabilities. Higher frequency-response pressure and emission sensors and liquid fuel actuators for periodic fuel modulation are being explored in the current laboratory experiments. Simple fixed parameter controllers will be used for initial experiments to determine their adequacy, with neural net and model-based adaptive controllers being considered as future alternatives.

The role of shear-flow dynamics in influencing flame blow-out limits is less understood than for combustion instabilities. Therefore, the application of active control to extend blow-out remains a longer term goal. In limited experimental experiences, flammability limits were extended by increasing fine-scale turbulence, and hence molecular mixing, by high-frequency acoustic excitation. However, practical actuators would require a higher bandwidth performance than for the combustion instability control.

5.4 Solid-Propellant Rocket Motors

Combustion instabilities remain a major concern in the development of solid-propellant rocket motors. This is particularly true for large motors including strategic missiles (about two meters in diameter) and space launchers (about three to four meters in diameter with large aspect ratio) loaded with metallized composite propellants, where modifications are more expensive and time-consuming. Active control may play an important role in curing the instability problems for this type of motor, since the pressure oscillations are dominated by low-frequency longitudinal modes, which are more accessible to control than higher-frequency oscillations associated with smaller motors. A concerted program for active control of combustion instabilities in large motors is currently being prepared by French laboratories with possible participation of a United States company or laboratory. The control strategy is based on modulated injection of liquid monopropellant at the head-end in a closed-loop system.

5.5 Military Burners and Incinerators

Successful application of ACC to military burners and incinerators will provide a promising opportunity to meet emerging emission standards. In particular, real-time monitoring of selected species should be included as an integral part of the control system. As demonstrated in a compact incinerator program, ACC implementation into burners with high energy densities can yield environmentally sound combustion processes which are not possible based on presently available technologies. Since the control strategy was established through detailed understanding of the combustion dynamics involved, the ACC approaches for incinerators can be readily applied to other burners for minimizing hazardous emissions.

6. Research and Development Needs

6.1 Introduction

Since the potential benefits of ACC are still uncertain, one of the main objectives of near term ACC research should be to demonstrate and quantify the advantages of ACC relative to other 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. Such information must be obtained from research and development programs which investigate problems unique to the systems at hand (e.g. rocket, gas turbine, and ramjet combustors and military incinerators), and from active control studies in related engineering applications (e.g., active noise and vibrations control). Combustor-related ACC studies may be used, for example, to investigate fundamental processes in uncontrolled and controlled combustors, develop sensors and actuators that satisfactorily perform in the harsh combustor environment, and develop models of controlled combustors. Parallel studies will have to address more general issues such as development capabilities for real time data acquisition and analysis, microelectronics, computers, software, and nonlinear control. These research needs are discussed in the remainder of this section.

6.2 Understanding Fundamental ACC Processes

To effectively implement ACC, it is desirable to understand the fundamental aerothermochemical processes that must be controlled. In particular, detailed understanding of fluid dynamic processes, which are associated with large-scale structures and their breakdown into fine-scale mixing, should be first achieved as this opens up the potential for effective combustion control. Comprehensive information about these fluid dynamic processes and their passive and active control is available for combustion processes associated with shear layers generated at rear-facing steps (e.g., dump combustors) as illustrated in the following example. Research remains needed to develop the same level of understanding for other combustion processes, for example swirl stabilized flames.

It is well known that combustion instabilities in dump combustors are driven by a feedback process involving periodic vortex formation and combustion processes.[39-41] During an instability, a decrease in the combustor pressure increases the velocity of the reactants flow into the combustor. This is followed by the formation of coherent vortical structures that are ignited, after a time delay, as they entrain hot gases and/or burning gas pockets. Ignition is followed by a "sudden" vortex breakdown and nearly instantaneous heat release in phase with the local pressure oscillations, which provides the energy needed to drive the pressure oscillations, according to Rayleigh's criterion. The cycle repeats itself when a subsequent combustor pressure drop near the dump plane produces another increase in the reactant flow rate into the combustor and vortex formation. This understanding of the driving process could be used to guide the development of ACC approaches for controlling such instabilities. Candidate schemes include: developing a process that prevents periodic formation of vortices; generating a secondary, periodic, combustion process within the combustor (e.g., by periodic fuel injection[1,2,8]) that damps the instability by releasing energy 180 degrees out of phase with respect to the unstable pressure oscillations; or using mechanical drivers (e.g., oscillating valves, speakers) to excite pressure oscillations out of phase with respect to the combustor pressure oscillations (i.e., anti-sound[3]). Research must be performed to determine which of these proposed (or other) approaches will provide the most effective ACC.

One important criterion for selecting control approaches is to minimize the energy input required to gain control authority on the physico-chemical processes involved. In the case of shear-layer control for preventing the development of large-scale vortices, it is important to identify the regions with high amplification of local flow disturbances. For dump combustors, these are the initial regimes of the shear-layer development, where seeding of small instability waves results in substantial changes in subsequent flow dynamics and combustion processes. In the case of modulating fuel injection[1,2,8] to control combustion instabilities, a fundamental understanding of the combustion process is critical, as discussed in the following.

Many ACC systems modulate the injection rate of a secondary fuel stream into the combustor, generally at the frequency of the unstable oscillation, to generate a secondary heat release process that damps the instability. Practical applications of this ACC technique will seek maximum damping with a minimum secondary (control) fuel flow rate. Therefore, the following questions must be addressed: (1) Does the secondary fuel injection modify the nonlinear combustion process that drives the instability and/or does it generate "another" (independent) combustion process that excites "separate" heat release oscillations out of phase with respect to the unstable pressure oscillations? (2) What is the optimum location(s) for secondary fuel injection? (3) What is the interaction mechanism of pulsed-sprays with large-scale flow structures in the combustor? (4) What is the optimum secondary fuel flow rate? (5) If a liquid fuel is used to damp the instability, what should be the characteristics of its spray to optimize damping? (6) What is the optimum number, diameter, orientation and velocity of the secondary fuel jets?

To realistically evaluate a proposed ACC approach, it should be initially investigated in a small scale experiment that closely simulates the full scale system design and operating conditions. Ideally, this could be accomplished by requiring that the following parameters be the same (or close) in the experimental and full scale setup: (1) the Mach, Reynolds and Strouhal numbers of the flows, (2) the reactants and injectors, (3) the Damkohler number of the combustion process, (4) the combustor's temperature, pressure, velocity and concentration fields distributions, and (5) the boundary conditions. The small scale studies should obtain complete information about the spatial and temporal variations of, for example, the fuel spray, reaction rate, and velocity, temperature, pressure and composition fields under controlled and uncontrolled operating conditions. This information together with results of visualization studies should then be used to identify specific characteristics of the combustor that could be controlled by ACC to improve its performance. Such characteristics may include the large and small scale vortical structures that drive combustion instabilities or enhance combustion, regions of slow mixing that impede combustion, and hot spots that enhance NOx emissions and/or distort the pattern factor causing damage to turbine blades.

The above discussions were primarily related to combustion devices using sudden flow expansions for flame stabilization, such as ramjets, military burners and afterburners for incineration, etc. Examples of additional ACC applications whose development requires further investigation of their controlling mechanisms include: (1) control of mixing, combustion, liner heating and ignition (i.e., relight)[42] processes in gas turbines, which could result in safer operation, longer life time, reduction of combustor length and weight, emissions and liner heating, and improved pattern factor, (2) control of vortex formation in solid rockets to reduce the onset of combustion instabilities, (3) control of reactant feed processes, sprays and combustion processes in liquid rockets operating at sub- or super-critical conditions to increase combustion efficiency, reduce combustion instabilities and prevent damage to the injector face and combustor walls, and (4) control of combustion problems in various propulsive devices to reduce signature. Investigations of these control problems will elucidate the fundamental processes in both the uncontrolled system, to help identify appropriate control approaches, and in the controlled system, to help in the optimization of ACC. The results of such studies will determine, for example, processes that must be excited or "canceled" within the combustor to attain the ACC goals, the time response of the ACC, and the types, number and locations of the actuators and sensors that will optimize the ACC performance. These studies will also indicate whether available sensors, controllers and actuators could be used in proposed ACC applications or whether new components must be developed.

6.3 ACC Models

There is also a need to develop models of actively controlled combustors. Such models, together with experimental data should be used to: (1) identify the fundamental processes that determine the performance of controlled combustors, (2) optimize the performance of ACC systems by, for example, predicting the optimal distributions and performance requirements of ACC sensors and actuators, (3) improve the design of ACC systems, and (4) develop ACC control approaches.

To pursue the above objectives, ACC models of various complexity will have to be developed. It is desirable to develop numerical simulations that fully account for all processes in controlled combustors; e.g., rapid time variations, three dimensionality of the flow, vortex dynamics, acoustics, turbulence, chemical kinetics, nonlinearities, flow-actuators interactions and effects of boundary conditions. Numerical predictions could be compared with experimental data to identify the mechanisms that determine the performance of controlled combustors. They could also serve as bench marks for the development of simplified (e.g., low order) models of controlled combustors that will be needed for ACC applications. The development of numerical simulations that can fully describe the behavior of controlled combustors will require additional research on such topics as efficient numerical solution techniques and efficient computational approaches (e.g., parallel computing).

Simplified ACC models must be developed to determine the instantaneous combustion chamber dynamics based on measured signals such as pressure and heat-release rate. The models shall not only provide the capability of monitoring the entire flowfields of concern in real time, but also serve as a basis for designing active control loops. The formulation should extend the nonlinear combustion dynamics model described in Refs. 29, 34, and 35 to include vortex formation and evolution. All three modes of flow motions (i.e., acoustic, vortical, and entropy waves) in practical systems need to be treated in such a unified fashion that the various processes involved in combustion chambers under external control actions can be investigated systematically. In addition, stochastic processes arising from combustion noise and intrinsic flow disturbances should be included to provide a faithful description of the flow development, as well as to accommodate the effects of model uncertainties.

6.4 ACC Sensors

ACC sensors continuously measure specific system properties that are subsequently used to determine the state of the system. Fast response pressure transducers and/or photomultipliers have been used to measure pressure and radiation from radicals (e.g., CH or CC), respectively, in small-scale ACC experiments on combustion instability control. The measured data was used to determine the characteristics of the instability. It is expected, that as interest in ACC applications grows, the performance of existing sensors will have to be upgraded and new sensors will have to be developed to measure the temporal and/or spatial dependence of combustor properties (e.g., temperature, pressure, equivalence ratio, species and radical concentrations, and magnitudes of electric currents and magnetic fields). Any sensor must have a time response that is consistent with the goals of the ACC. For instance, fast response pressure transducers are required for active control of combustion instabilities, while slow response sensors are adequate for ACC systems that control pattern factor and emissions in gas turbines. ACC applications which require spatial resolution of combustor properties along with adequate time response may possibly employ proper distribution of sensors or MEMS (micro-electronic mechanical systems) sensor arrays. In all ACC applications, sensors will have to satisfy all or some of the following requirements: simple design, reliability, high robustness, high sensitivity, low weight, low cost, high frequency response, ability to continuously operate in harsh engine environments over long periods of time, and no or minimal need for optical windows.

Future developments of ACC will critically depend upon the availability of suitable sensors. Short term research should adapt existing sensors to practical ACC applications while long term research should develop novel sensors in response to evolving ACC needs. Examples of short term ACC sensors research include: (1) development of robust sensors for measuring various combustor properties (e.g., distributions of equivalence ratio, temperature and various species), (2) sensor miniaturization, (3) optical sensors[46] based on diode lasers (4) sensors materials, (5) sensors cooling methods, and (6) sensor arrays for measuring spatial distributions of properties. Long term research should address issues such as: (1) novel sensors and measurement techniques, (2) identification of optimum sensors for different ACC applications, and (3) development of approaches for combining sensor measurements with an appropriate model to determine spatial distributions of required properties (e.g., radial temperature distribution at the combustor exit for control).

6.5 ACC Actuators

The role of an ACC actuator is to “actively force” the combustor to bring about desired performance. ACC actuators that have been used to date include: (1) injectors that rapidly modulate the flow rate of a secondary fuel stream into the combustor for control of combustion instabilities,[1,2,8,54] (2) valves that modulate the air flow rate into an unstable combustor to modify its acoustics and/or increase its damping,[47] (3) speakers that excite sound within the combustor or near its boundary[1,2] to cause destructive interference with unstable pressure oscillations, modify the instability driving process, or increase system damping,* (4) valves that vary the air flow rate in a blast atomizer to control the fuel spray characteristics,[48] (5) acoustic drivers that excite sound waves to control mixing processes,[49] (6) pulsed-combustion actuators that generate periodic heat release and sound waves,[53] (7) piezoelectric actuators that control boundary layer flow,[50] and (7) valves that produce phased, periodic air and/or waste injection to improve waste incineration.[9,10]

In contrast to existing ACC sensors, which are generally based upon available combustion diagnostic techniques, the development of ACC actuators was stimulated by evolving needs of ACC. Future research in this area will have to determine the type of actuation needed for different ACC applications (e.g., piezoelectric, magnetostrictive, electric, magnetic, radicals injection, flow rate control). Such studies would help answer such questions as: should we use piezoelectric actuators or acoustic drivers to control mixing and, thus, emissions and the pattern factor in gas turbine combustors? Can we use electric or magnetic fields to control the combustion processes, or should we use air flow rate modulation or ultrasonic forcing to control the characteristics of the spray in air blast atomizers? Research is also needed to determine whether or not an MEMS-type array of actuators is required for a specific application, and if so, what its configuration would be to optimize ACC performance. For applications with individual actuators, the number and locations of the actuators should also be optimal.

Once developed, the performance of actuators will have to be evaluated in open and closed loop control experiments. The former will determine whether the actuators can force the system with adequate amplitude and time response; this will be an indication of the system's controllability.[51] The latter will assess the actuators' capabilities and limitations for closed loop ACC. Once the actuators for a specific application have been chosen, their application will require additional efforts to address the actuators' scale-up, time response, reliability, robustness, weight, size, survivability in the harsh combustor environment, packaging and cost.

6.6 ACC Controller

The controller is the "brain" of an ACC system whose task is to determine the characteristics of the control signal to the actuator. These characteristics depend on whether the ACC operates in an open or closed loop control mode, and on the type of control. As stated earlier, the control signal in open loop ACC is independent of the state of the combustor and is determined a priori. In contrast, the control signal to the actuator in closed loop ACC depends upon the state of the system, which is determined from the sensor measurements.

Since open loop control is considerably simpler than closed loop control, the development of viable open loop ACC should be pursued. Such efforts will have to develop an understanding of the basic mechanisms involved in the process that needs to be controlled, and the manner in which

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* In many instances, the mechanisms through which the actuator attains its objectives is not fully understood.

it can be optimally "forced" to attain the ACC objectives. For example, there is evidence suggesting that combustion instabilities can be damped by open loop ACC that excites pulsations within the combustor at a frequency not equal to any of the unstable combustor mode frequencies; the period of the forced oscillation need only be of the same order as either the periods of the unstable modes, or a multiple of the period of the most unstable mode. Research is needed to determine the feasibility of such control approaches and the optimum frequency and magnitude of the required forcing. It is also necessary to determine whether such approaches can satisfactorily stabilize combustors over wide ranges of operating conditions without producing adverse effects (e.g., undesirable signature).

Closed loop control generally consists of several steps. First, the signal measured by the sensors is used by the observer to determine the state of the system[49]. Next, the observed state of the system is used to determine an "error" signal, representing the deviation from the desired state. The error signal is then used to determine the actuator's control signal, in a way determined by the controller design.

To attain effective closed loop control, the following two tasks must be accomplished: (1) the observer must determine the state of the system within a "relevant" time period that depends upon the controller's objective and characteristics of the controlled system, and (2) the controller must determine an appropriate control signal. Since the performance of practical combustors is generally described by a system of nonlinear partial differential equations (PDEs), the timely "observation" of its state would require the development of analytical/numerical approaches that can swiftly interpret the measured data in terms of the governing equations to determine the state of the system. The development of effective "observation" methods for ACC is urgently needed. These methods should account for multiple sensors in arbitrary number and locations, noise (e.g., turbulence), and the effects of process nonlinearities upon the accuracy of the "observed" state of the system. There is also a need for alternate "observation" approaches, which will not require solution of complex PDEs. Such approaches may use reduced order models or take advantage of qualitative understanding of the physics of the system. The latter approach was applied in Ref. 8 where a wavelet type analysis is used to "observe" the amplitudes, frequencies and phases of the unstable combustor modes in real time.

Improved algorithms for the determination of the control signals are also needed. Such studies should develop control approaches that take into account the effects of such phenomena as system nonlinearities and noise. There is also a need to investigate whether the controller should have constant parameters or adaptively varying parameters. The developed controllers will have to meet the ACC objectives within a specified time period[*] and with limited resource expenditures (e.g., actuator power input).

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[*] In applications such as combustion instability it is mandatory that the ACC rapidly damp the instability before it causes system or mission failure.

Finally, possible application of newer control approaches such as neural network, fuzzy and chaotic control in ACC should be investigated.

6.7 ACC System Integration

Practical aspects of integrating an ACC system with the engine and flight vehicle must also be studied. Specific issues that should be addressed include: (1) the packaging of the ACC and space available for its installation in the engine, (2) protection (e.g., cooling) of the ACC in the harsh engine environment, (3) added weight of the ACC and its effect upon the system's overall performance, (4) integration of the ACC with the engine's and flight vehicle's control systems, and (5) the effect of the ACC upon the system's operation and maintenance.

Acceptance of ACC by the engineering community will require demonstration of its effectiveness under practical operating conditions. The performance of full scale ACC systems will have to be demonstrated on practical combustors in their real environments (e.g., shipboard incinerators, jet engines, rocket motors). Such tests will have to quantify the benefits of the ACC and demonstrate that it can survive in the harsh engine environment over periods of time comparable to the duration of the mission or life time of the combustor.

7. Concluding Remarks

This workshop was concerned broadly with three topics:

(1) Possible applications of active control and the future requirements of combustors;

(2) The current status of active control of combustor dynamics; and

(3) The needs of research and development in order to close the gap between (1) and (2).

Participants came from all NATO countries and gave broad representation of industry, the research community, and government defense agencies. All three topics were addressed thoroughly by a group comprising most of the world's leading researchers and responsible officials from the user community.

With respect to the three topics, the participants agreed upon the following broad conclusions:

(1) The demands to be placed upon the performance and behavior of future combustors are such that they likely cannot be met within the traditional design methods. All combustion systems offer problems or characteristics that seem to be candidates for application of active control.

(2) To the present time, no full-scale applications of active control of combustion dynamics have been publicly reported, but several are planned. Consequently, forecasts of the future of ACC rest entirely on results of laboratory demonstrations; essentially nothing is understood about scaling laws.

(3) The needs of research and development can reasonably be divided into near-term and long-term. The former must be based primarily on existing knowledge and resources, and consist mainly of well-defined demonstrations with specific types of systems, investigating feasibility and scaling laws. In the long-term, there is a wide array of

research needs comprising investigations of fundamental processes (both theoretically and experimentally) and development of sensors, actuators, and control laws.

For reasons which are clear from the discussion in Section 3, "Requirements for Future Combustors," and Section 5, "Applications," there is considerable enthusiasm for introducing methods of active control in virtually the entire spectrum of combustion systems. Moreover, that aggressive view by some potential users is encouraged by optimism flowing from a growing number of successful laboratory demonstrations, the majority of which have shown that active control can be used to reduce the amplitudes of oscillations in combustion instabilities. The emphasis on combustion instabilities is partly historical and partly because of pressing practical needs but should not be allowed to obscure the fact that other applications may be equally important. For example, some success has been achieved in using ACC to maintain an incineration process at optimum conditions.

There are some, however, who caution against full-scale tests too soon. Their reason is that, as stated several times in this report, the scaling laws are not known and any tests must be designed on the basis of results obtained in laboratory devices that have far smaller combustion energy densities than those in combustors intended for full-scale use. The primary and extremely important point to realize is that under these conditions, while success with a full-scale test would be an obvious advance, failure would not signify that ACC cannot be used – only that the particular instance was unsuccessful. Thus the financial and strategic costs must be carefully weighed.

It is quite clear that the matter of scaling is a central issue. Construction of the scaling laws can be done expensively by testing only, but practical considerations, and experience, demand that the most productive approach combine testing and theory. At the present time, theory and analysis lag far behind experimental work. And, as it happens, so also does understanding. There is, for example, no framework for interpreting quantitatively any of the experimental results reported to date. In particular, ACC has been used to reduce the amplitudes of various combustion instabilities, but no serious attempts have been made to predict the amplitudes before or after control is applied. That fact is symptomatic of the difficulties that must be recognized when full-scale tests are contemplated.

The field of active control of combustor dynamics has enormous potential. Sufficient favorable laboratory results have been generated to consider possible applications to full-scale systems. However, the state of progress in general is such that considerable research and development, both in theory and of hardware, will likely be required to achieve practical success. The workshop has shown that international collaborations promise to be highly effective to produce that success.

8. Collaborations

This first AGARD workshop provides the catalyst for future international collaborations to advance the ACC technology. With the decrease of available R&D funding, cooperation at both national and international levels is gaining increasing importance for advancement of emerging technologies.

International collaboration can be accomplished through the following three activities:

(1) additional workshops on ACC;
(2) ACC R&D presentations at AGARD Symposia; and
(3) special events.

The following actions have been taken following the first workshop:

A second workshop has been approved by PEP for Fall 1997 in conjunction with the AGARD Symposium “Advanced Non-Instrusive Instrumentation for Propulsion Engines” in Belgium. The workshop will be held at the Von Karman Institute from 17 and 18 October 1997.

A session for ACC presentations has been reserved at the AGARD Symposium "Gas Turbine Engines Combustion, Emissions, and Alternative Fuels" to be held in Lisbon, Portugal in October 1998. This will also provide an opportunity to present results of the first and second workshop to a wider audience.

To make R&D possibilities known to decision makers from industry, university, and government on a national and/or international basis, the status and the potential of active combustion control could be presented in special events. The new RTO of NATO can play a critical role in this regard. Possible arrangements of such events are under discussion.

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APPENDIX A

AGARD WORKSHOP ON ACTIVE COMBUSTION CONTROL-Participants
May 6-9, 1996, Athens, Greece

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APPENDIX B

AGARD WORKSHOP
Active Combustion Control for Propulsion Systems
May 6-9, 1996, Athens, Greece

OBJECTIVES:

1. Define Requirements for Future Combustors and Related Combustion
2. Determine Status of Active Combustion Control (ACC)
3. Discuss Potential of ACC to Meet Future Combustor Requirements
4. Determine Near- and Long Term R&D Needs for ACC
5. Publish AGARD Report
6. Explore Potential of International Collaborations
7. Establish AGARD Steering Group on ACC

WORKSHOP SUMMARY:

May 6	1030-1100	1. Introductions
	1100-1200	2. Requirements for Future Combustors and Related Combustion
	1330-1500	
	1530-1700	3. Current Status of Active Combustion Control
May 7	0830-1000	
	1030-1200	4. "Brainstorming"
	1330-1500	
	1530-1700	
May 8	0830-1000	5. Discussions
	1030-1200	
	1330-1700	Technical Tour
May 9	0830-1000	6. Wrap-up Discussions

AGENDA:

1. Introductions - 30 min.

2. Requirements for Future Combustors and Related Combustion - 2 hrs 30 min.

   Session Chairmen: Weyer, GE, and Bruno, IT

   a. Gas Turbine - Sturgess, US (Enclosure (1))*
   b. Gas Turbine - Garwood, UK (Enclosure (2))
   c. Missile Propulsion (solid, liquid, airbreathing) - Kuentzmann, FR (Enclosure (3))
   d. General Comments - Culick, US (Enclosure (4). Viewgraphs not available.)
   e. Summary - Bruno, IT (Enclosure (5))

***The information on enclosures is related to Appendix C.**

3. Current Status of Active Combustion Control (Presentations and Discussions) - 3 hrs

   Session Chairmen: Culick, US, and Vuillot, FR

   a. Candel, FR (Introduction, Overview) (Enclosure (6))
   b. Jacobson, US (Control Applications) (Enclosure (7))
   c. Gleis, GE (Control Applications) (Enclosure (8))
   d. Yang, US (Controller Aspect) (Enclosure (9))
   e. Zinn, US (Combustion Instabilities) (Enclosure (10))
   f. Schadow, US (Fluid Dynamic/Combustion Interactions) (Enclosure (11))
   g. Koschel, GE (Combustion Kinetics) (Enclosure (12))
   h. Yang, US (Modeling Aspect) (Enclosure (13))
   i. Taylor, UK (Control Experiments) (Enclosure (14))
   j. Nina, PO (ACC Research) (Enclosure (15))
   k. Benelli, IT (Gas Turbine Power Generation) (Enclosure (16))
   l. Burkhardt, GE (Image Sensors) (Enclosure (17))
   m. Papailiou, GR (LES) (Enclosure (18))
   n. Vuillot, FR (Summary) (Enclosure (19))

4. "Brainstorming" - 4 hrs and 30 min.

   Session Chairmen: Brehm, GE, and Bruno, IT

   a. Physical Understanding/Modeling - Moderators: Candel, FR, and Taylor, UK
   b. System Integration - Rosfjord, US, and Simon, GE
   c. Controller - Yang, US, and Jacobson, US
   d. Sensor/Actuator - Gleis, GE, and Zinn, US
   e. Diagnostics/Experimental Methods - Cohen, US, and Gleis, GE
   f. Summary - Bruno, IT (Enclosure (20))

5. Discussions - 4 hrs

   a. Determine Current ACC Application Potential and Short Term R&D Needs
      Rosfjord, US, and Taylor, UK

   b. Determine Long Term R&D Needs
      Candel, FR

6. Wrap-up Discussions - 2 hrs

   a. Conclusions/ Recommendations - Rosfjord, US
   b. Summary Viewgraphs - Schadow, US (Enclosure (21))

APPENDIX C

VIEWGRAPHS PRESENTED AT AGARD WORKSHOP

ACTIVE COMBUSTION CONTROL FOR PROPULSION SYSTEMS

6—9 MAY 1996
ATHENS, GREECE

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Missile propulsion
Rocket propulsion
Incinerators

14. Abstract

Active combustion control is one of the most promising approaches to further optimize the size/weight/power relationship in rockets, ramjets, afterburners, aero-engines, and marine propulsion. A workshop was organized in Athens in spring 1996 under the sponsorship of the AGARD Propulsion and Energetics Panel. It covered the existing knowledge, and further possible strategies for military equipment were discussed within the NATO nations. Further activities are planned.