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ABSTRACTS

1977 AFOSR CONTRACTORS MEETING ON AIR-BREATHING COMBUSTION DYNAMICS.

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PREMIXING/PREVAPORIZING COMBUSTION
CATALYTIC COMBUSTION
RAPID EXPANSION BURNING
DETONATION
FUEL AIR EXPLOSIONS
SUPERSONIC COMBUSTION
EXTERMAL BURNING

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The report consists of a collection of abstracts of the numerous research progress reports given by AFOSR contractors and of invited papers from other governmental agencies and contractors. These papers presented over a five-day period composed the 1977 annual contractors meeting on air-breathing combustion dynamics. The principal investigators and their organizational association are also identified.

TENTATIVE AGENDA

1977 AFOSR CONTRACTORS MEETING
on
AIR-BREATHING COMBUSTION DYNAMICS
PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA
12-15 September 1977

12 Sep 77
Monday AM

8:30	Official Registration	Hilton Inn West Lafayette, IN
9:00	Welcome - Technical Host (Purdue)	To be announced
9:10	Welcome - AFOSR	Dr B T Wolfson (Program Manager Directorate of Aerospace Scienc Bolling AFB, DC 20332
9:15	Morning Chairman	Dr B T Wolfson/AFOSR
9:20	Air Force Air-Breathing Combustion Research, Development Trends and Research Needs	Mr R. Henderson AFAPL/TBC Wright-Patterson AFB, OH 45433
9:50	Navy Supported Research and Needs in Air-Breathing Combustion	Mr J. Patton/ONR Dr S.N.B. Murthy/Purdue Univ
10:20	BREAK	
10:35	Army Supported Research and Needs in Air-Breathing Combustion	Dr J. Murray/Army Research Offi Durham, NC
11:05	NASA Supported Research and Needs in Air-Breathing Combustion	Drs E.W. Reck/L.A. Diehl NASA-Lewis Center Cleveland, OH
11:35	ERDA Supported Research and Needs in Air-Breathing Combustion	Dr K. Bastress/ERDA Washington, DC
12:05	EPA Supported Research and Needs in Air-Breathing Combustion	Dr S. Lanier Environmental P[illegible]ection Agency Durham, NC
12:35	LUNCH	

12 September 1977
Monday PM

2:00	Afternoon Chairman	Dr J. Patton/ONR Arlington, VA
2:05	Injection, Atomization, Ignition and Combustion of Liquid Fuels in High-Speed Air Streams	Dr J.A. Schetz VPI & State University (AFOSR-74-2584)
2:30	Mixing, Ignition and Combustion in Flowing Reacting Fuel - Air Mixtures	Drs R. Edelman/P.T. Harsha Sciences Applications Assoc (F49620-77-C-0044)
2:55	Turbulent Mixing and Combustion in High-Speed Flows	Drs C.E. Peters/D.E. Criss and M.L. Laster - AEDC (ARO) (PO-77-0015)
3:20	BREAK	
3:35	Research on Ramjet Combustion at AFAPL	Drs R.R. Craig/F.D. Stull AFAPL/RJT (In-House)
4:00	Fundamental Studies of Dump Combustion Phenomena at AFAPL	Dr J.E. Drewry AFAPL/RJT - WPAFB, OH
4:25	Turbulent Vortex Flame Stability and Spreading with Gas Jet Impingement	Dr A. R. Choudhury Univ of Southern California (AFOSR-77-3354)
4:50	Flow Flame Interactions and Transient Flame Phenomena	Dr M. Gerstein Univ of Southern California (AFOSR-77-3354)
5:15	ADJOURN	

13 Sep 77
Tuesday AM

8:30	Morning Chairman	Dr J.E. Drewry AFAPL/RJT - WPAFB, OH
8:35	Combustion Studies of Fast Flow Reactive Systems	Dr R. Cookson Cranfield University, England (AFOSR-74-2698)
9:00	Research on Mechanisms of Supersonic Combustion and External Burning Relevant to US Navy and Air Force Requirements	Drs R.C. Orth, P.J. Waltrup, F. Billig, R.T. Cusick and J.A. Schetz Applied Physics Lab Johns Hopkins University

13 Sep 77
Tuesday AM

9:30	Summary of External and Base Burning JANNAF Workshop	Dr C.E. Peters AEDC (ARO) (PO 77-0015)
9:55	AFAPL Turbojet Combustor Program Overview	Mr R. Henderson and Capt R.M. McGregor AFAPL - WPAFB, OH (In-House)
10:20	BREAK	
10:35	Fundamental Modeling of Kinetics Mixing, Evaporation and Combustion in Gas Turbine Combustors	Dr J. Swithenbank Univ of Sheffield, England (AFOSR-74-2682)
11:00	Low Frequency Combustion Instability in Gas Turbine Augmentors	Capt F.N. Underwood AFAPL (In-House) WPAFB, OH and Dr J. Rusnak P&W Aircraft, Florida
11:25	Mechanisms of Radiation Augmented Ignition and Combustion	Dr A.E. Cerkanowicz Exxon (F49620-77-C-0085)
11:50	Combustion Dynamics of Advanced Chemical Lasing Systems	Dr F. Culick Calif Inst of Tech (AFOSR-74-2694)
12:15	LUNCH	

13 Sep 77
Tuesday PM

1:45	Afternoon Chairman	Dr J. Murray Army Research Office Durham, NC
1:50	Fundamental Mechanisms of Carbon Formation on Hydrocarbon and Synthetic Fuel Combustion	Dr H. Calcote AeroChem (F49620-77-C-0029)
2:15	Mechanisms of Exhaust Pollutant and Plume Formation in Continuous Combustion	Dr G.S. Samuelson Univ of Calif-Irvine (AFOSR-74-2710)
2:40	Combustion Dynamic Effects on Ignition, Combustion, Extinction and Smoke Production	Dr F.A. Williams Univ of Calif-La Jolla (AFOSR-77-3362)

13 Sep 77
Tuesday PM

3:05	BREAK	
3:20	Consideration of Widened Specification Fuels for Air-Breathing Gas Turbine Engines	Capt T. Rosjford AFAPL/SFF (In-House) Wright-Patterson AFB, OH
3:55	Pyrolysis of Hydrocarbon Fuels	Dr W. Blazowski Exxon (AFAPL Contract)
4:20	ADJOURN	
7:00	Social Hour (Cash Bar) BANQUET	

14 Sep 77
Wednesday AM

8:30	Morning Chairman	Dr S. Lanier EPA - Durham, NC
8:35	Design Criteria for Catalytic Combustors; Overview 2nd EPA Catalytic Combustion Workshop	Drs J.P. Kesselring/R.M. Kendall Aucrex/Aerotherms Corp
9:05	Experimental and Theoretical Aspects of Hybrid Catalytic Combustion	Drs A.E. Cerkanowicz, V.J. Siminski and H. Shaw Exxon
9:30	Investigation of Air-Breathing Engine Catalytic Combustion - Joint NASA/AFAPL Program	Dr E. Mularz NASA-Lewis
9:55	Air Force Research Studies and Needs in Catalytic Combustion	Capt T. Rosjford AFAPL (In-House)
10:20	BREAK	
10:35	Mechanisms of High Temperature Catalytic Combustion	Dr F. V. Bracco Princeton University (AFOSR-76-3052)
11:00	Contributions of Surface Catalysis and Gas Phase Kinetics to Catalyst Combustor Performance	Drs H. Wise and C.M. Ablow Stanford Research Institute (F49620-77-C-0123)

14 Sep 77
Wednesday AM

11:25	Flame Efficiency, Stabilization and Performance in Premixing/Prevaporizing Combustors	Dr A.M. Mellor Purdue University (AFOSR-76-2936)
11:50	LUNCH	

14 Sep 77
Wednesday PM

1:30	Afternoon Chairman	Dr J.R. Manheim AFAPL/SFH - WPAFB, OH
1:35	Air Force Supported Research Development Trends and Needs in Aircraft Fire and Explosion Technology	Dr J.R. Manheim and B.P. Botteri AFAPL (In-House)
2:00	Aircraft Fuel Fires in Flight	Dr L. Mahood Falcoln R&D Company
2:25	Ignition of Fuel Sprays by Incendiary Metal Particles	Drs W.A. Sirignano and H.S. Homan Princeton University (AFOSR-76-3041)
2:50	Ignition of Liquid Fuels by High Intensity Radiation	Dr T. Kashiwagi National Bureau of Standards (ISSA-77-0016)
3:15	BREAK	
3:30	Ignition of Fuel Sprays by Hot Surfaces and Stabilization of Aircraft Fires	Drs A. Lefebvre/J. Skifstad Purdue University (AFOSR-77-3446)
3:55	Ignition, Combustion, Detonation and Quenching of Combustible Mixtures	Dr R. Edse Ohio State University (AFOSR-73-2511)
4:20	Basic Instability Mechanisms in Chemically Reacting Systems	Dr T. Y. Toong Massachusetts Inst of Tech (AFOSR-74-2619)
4:45	ADJOURN	

15 Sep 77
Thursday AM

8:30	Morning Chairman	Dr M. Roquemore AFAPL/SFF - WPAFB, OH
8:35	State-of-the-Art of Cumbustion Diagnostics and Future Requirements	Dr R. Goulard George Washington University (AFOSR-77-3439)
9:05	Diagnostic Assessments for Air-Breathing Combustion Systems	Dr Dan L. Hartley Sandia-Livermore
9:35	Review of Laser Raman and Fluorescence Techniques for *Practical Combustion Diagnostics*	Dr A.C. Eckbreth United Technology Research Cor[illegible]
10:05	Evaluation of Improved Diagnostic Techniques and Future Needs for Combustion Flows	Dr W.K. McGreggor AFRPL/RTSC and AEDC (ARO)
10:35	BREAK	
10:50	AFAPL Research and Needs in Combustion Diagnostics	Drs M. Roquemore, A. Garscadden and Schrieber AFAPL (In-House)
11:20	Laser Holographic Techniques for Particle and Droplet Size Measurements and Analysis in Chemically Reacting Flows	Dr D. George AFRPL/DYSC (In-House)
11:45	Laser Induced Fluorescence Spectroscopy for Species Concentration Measurements in Turbulent Combustion Flows	Dr J.W. Daily Univ of Calif-Berkeley (AFOSR-77-3357)
12:10	LUNCH	

15 Sep 77
Thursday PM

1:30	Afternoon Chairman	Dr B. T. Wolfson AFOSR/NA (Program Manager)
1:35	Raman Scattering Measurements for Time and Space Resolved Data in Combustion Systems	Dr M. Lapp General Electric - Schenectady (F49620-77-C-0094)
2:00	Application of Tunable Lasers for Accurate Measurements of Reacting Flow Parameters Under Combustion Conditions	Drs R. Eustis, C. Kruger, M. Mitchner and S.A. Sel[illegible] Stanford University (F44620-76-C-0024)

15 Sep 77
Thursday PM

2:25	Coherent Structures in Turbulent Flames by Laser Anemometry	Dr N. Chigier Univ of Sheffield, England (AFOSR-77-3424)
2:50	LDV Measurements and Analysis in Turbulent and Mixing Flows	Dr Doyle Thompson Purdue University (AFAPL Contract)
3:15	BREAK	
3:30	Multi-Angular Scanning Absorption-Emission Techniques for 3-D Combustion Diagnostics	Dr R. Goulard George Washington University (AFOSR-77-3439)
3:55	Executive Session AFOSR Contractors and Grantees Only	Dr B. T. Wolfson AFOSR/NA (Program Manager)
4:30	ADJOURN	

AIRBREATHING PROPULSION COMBUSTION
"What's Next?"

Robert E. Henderson
Manager, Combustion Technology Group
Turbine Engine Division
Air Force Aero Propulsion Laboratory

During the 1976 AFOSR Contractor's Conference, Dr. Hans von Ohain, Chief Scientist of the Air Force Aero-Propulsion Laboratory, presented a historical summary of Airbreathing Propulsion Combustion. He described many of the early problems encountered with the combustion system of the first jet engine developed in Germany during the late 1930's and early 1940's. The purpose of this presentation is to highlight where we are today in the areas of Ramjet Combustion, Fuels Combustion Research and Turbopropulsion Combustion as sponsored by the Air Force Aero Propulsion Laboratory and what we expect the future will hold/require.

1. Ramjet Combustion Technology

Ramjet combustion technology programs being conducted at the AFAPL fall into three main product lines.

a. The first and most advanced is that of the high performance ramjet, where high speed and long range potential make it an ideal candidate for strategic missions. Currently there are two major ramjet engine programs being conducted, one by the Marquardt Corporation and the other by Chemical Systems Division, both of which are in support of ASALM. Future high performance ramjets may involve advanced combustors which will have high performance with very short L/D's and capable of withstanding very high temperatures (without ablative liners) over longer durations. In addition, variable geometry inlets and nozzles will allow the ramjet to take advantage of its maximum cycle potential without being penalized for off design operation, thereby extending range.

b. The tactical missile propulsion area is relatively new to the Air Force effort. The tactical ramjet combustor offers a much wider range of combustion problems due to the distinct differenoes between the liquid fuel ramjet, ducted rocket, and solid fuel ramjet.

(1) The liquid fuel ramjet can employ the same coaxial center dump combustor or it can have multiple side dumps.

(2) The ducted rocket consisting of a fuel rich gas generator provides a high temperature gas pilot which can aid in flame stabilization.

(3) The solid fuel ramjet, in which a solid hydrocarbon fuel is cast within the ramjet combustor, is a relatively simple engine but with a very complicated combustor process. In this case, the fuel injection

is coupled to the combustion process and careful matching of the grain burn rate to the desired flight mission profile is necessary.

c. The high speed propulsion area has been dormant in the Air Force since the late 1960's when several small scale scramjet and dual mode engines were tested. Recent interest in hypersonics between the Air Force and NASA, and the emergence of the National Hypersonics Flight Research Facility (former X-24C program), has revived interest in the high speed propulsion area. Combustor programs are currently planned for the Mach 3-6 subsonic combustion ramjet followed by small research efforts in the dual mode scramjet area.

2. Fuels Combustion Research

Three topics are currently receiving much attention in the fuels combustion research area at the AFAPL. The first subject concerns efforts to assess the impact of future "wide-spec fuels" on current combustion systems as well as to develop improved hardware with increased fuel flexibility. Catalytic combustion is the second topic. While initial investigation of this new concept focused on NO_x control, realization that utilization may offer significant performance improvements has also spurred development. Finally, recent advances in laser, spectroscopic instrument, and time-gating electronics technology have allowed significant gains to be made in the combustion diagnostics area.

a. Wide-Spec Fuels Research -- Because of the global nature of aircraft operations, jet fuels of the future are likely to be produced from a combination of basic synthetic crudes, ie, coal, oil, shale, tar sand, etc. Production of fuels from blends of synthetic crudes and natural crudes may also be expected. In light of the wide variations in materials from which world-wide jet fuel production can draw, it is anticipated that economics will dictate the acceptance of future fuels with properties other than those of currently used JP-4, JP-5, and Jet A. Much additional technical information will be required to identify fuel specifications which provide the optimum solution to the following objectives:

(1) Allow usage of key world-wide resources to assure availability

(2) Minimize the total cost of aircraft system operation

(3) Avoid sacrifice of engine performance, flight safety, or environmental impact.

b. Catalytic Combustion Research -- In response to the concern for aircraft gas turbine engine exhaust emissions, AFAPL initiated an investigation of catalytic combustion in 1972. This concept is based upon the alternate reaction paths available to catalyze reactions. As applied to gas turbine engines, it permits the combustion of fuel/air mixtures leaner than the low flammability limit. Further considerations of the concept have indicated advantages in performance, component life, stability and emissions. Current AFAPL programs are pursuing the application of catalytic combustion to gas turbine engine main burners and afterburners.

c. Combustion Diagnostics Research -- An improved technology base is necessary to generate new ideas and improved approaches which will eventually satisfy future turbopropulsion combustion requirements. This technology base, as in the case of any science, must be established through the strong interaction of experiment and theory. Well designed experiments providing insight into the fundamental processes occurring in practical combustion devices are needed. Theories explaining these results and capable of predicting future experimental results are also essential. The intent of combustion diagnostics is to provide the tools needed to collect the necessary data. Programs at AFAPL are currently underway to utilize optical diagnostics to acquire this information.

3. Turbopropulsion Combustion Technology

The evaluation of the aircraft gas turbine combustor over the past forty years has been extremely impressive. While the combustion system was the primary limitation in development of the first aircraft gas turbine in 1939, the complexity and hardware costs associated with current rotating engine components (compressor and turbine) now far exceed that of the combustion system. Recent developments, however, have once again caused significant shifts in development emphasis toward combustion technology. New concepts and technology improvements will be necessary to satisfy recently legislated exhaust pollutant regulations. Moreover, future emphasis on engines which can utilize fuels with a broader range of characteristics are expected to require additional combustor technology development.

In order to provide a better appreciation for the role of the gas turbine combustor in the overall development process, a summary of the propulsion system development activity is given. Beyond those externally imposed combustor requirements cited above are the combustion system performance improvements necessary to keep pace with new engine developments. Further reductions in combustor physical size and weight are expected to continue as firm requirements. Performance improvements, especially with respect to engine thrust/weight ratio and specific fuel consumption, will require higher combustor temperature rise, greater average turbine inlet temperatures, and closer adherence to the design temperature profile at the turbine inlet. High performance designs must also permit greater Mach number operation within and around the combustor to reduce pressure drop and minimize the physical size of compressor exit diffuser hardware. Likewise the augmentor is a fairly simple combustion device but with today's complex high performance augmented turbofan engines, the augmentor structural design and fuel distribution system has become increasingly complex -- and is further aggravated by a requirement that the hardware design cannot be finalized until all upstream componentry has been well characterized. Costs (both initial and operating) must be minimized, as experiences with high temperature engines have confirmed the necessity to consider reliability and maintenance aspects of life cycle cost as well as performance and fuel consumption.

4. Requirements/Trends/Research Needs

The airbreathing propulsion combustion technology area is literally exploding today and the demands of tommorrow's system will place even greater challenges on this rapidly advancing field. Environmental quality and energy conservation measures are requiring a thorough understanding of all aspects of combustion -- chemistry, thermodynamics, gas dynamics, etc. Consequently, the research community must continue to take an aggressive role in the investigation and study of such relevant areas as improved fuel-air mixing, staged combustion, catalytics, diagnostics and fuel chemistry. A brief list of some specific research needs of interest is given below:

a. Ramjet Combustion

(1) Development of liquid fuel ramjet scaling criteria, droplet combustion and determination of fuel-air distributions, interactions of flameholder/dump recirculation regions, hysteresis and combustion instability.

(2) Investigation of new concepts such as swirl and jet impingement for improved ramjet combustor performance.

(3) Studies of alternate ramjet cycles such as solid fuel, ducted rocket and dual mode supersonic combustion ramjet.

(4) Improved ramjet modeling techniques supported by detailed flow field characterization.

b. Fuels Combustion Research

(1) Improved understanding of practical hydrocarbon fuel pyrolysis to permit inclusion of gross fuel chemistry effects in combustor design models.

(2) Enhanced modeling capability for prediction of wide-spec fuel effects on combustor performance.

(3) Investigation of processes responsible for chemical, thermal, and physical degradation of catalyst systems.

(4) Study of the influence of liquid fuel impingement on catalytic surfaces.

(5) Determination of effects of turbulence on CARS, fluorescence, LARS and other remote diagnostic measurements.

(6) Systematic evaluation of the performance of conventional diagnostic probe designs when making measurements of various species in chemically reactive environments.

c. Turbopropulsion Combustion

(1) Improved understanding of combustor inlet diffuser aerodynamics, ie., boundary layer bleed systems, vortex-controlled diffusers, diffusion with swirl, etc.

(2) Improved aerodynamic mixing for high temperature rise systems to assure exit temperature uniformity.

(3) Improved ignition for wide-spec fuels under cold start, high altitude operation.

(4) Improved fuel injection techniques for large turn-down ratio systems designed to accommodate wide-spec fuels.

Air Breathing Combustion:

An Overview of Power Program (ONR) Projects and Interests.

J. R. Patton and S. M. B. Murthy

An overview of current projects and future interests will be presented.

ARMY SUPPORTED RESEARCH AND NEEDS IN AIR-BREATHING COMBUSTION

James J. Murray

U. S. Army Research Office
Research Triangle Park, North Carolina

Overview of the US Army Tank-Automotive Research and Development Command Propulsion Activities

Power systems continue to be a priority item in terms of required intensive research and advanced development to ptorude military equipment with even greater performance potential. Current thrusts in developing advanced military engines seek to reduce fuel consumption and increase fuel tolerance with engines of smaller size, lighter weight, lower cost and higher RAM-D. Engine systems and component technology can make advances from several directions. Advances can be made by continuous injection and control systems, by use of improved materials allowing high temperature-high efficiency-high output combustion and through studies of improved combustion systems for wider fuel tolerance. The ability of the engine combustion system to provide this advanced higher output with even wider fuel tolerance has significant impacts on the military logistics problem. This requires a broad based fuels research and engine research program to provide the widest possible base of knowledge to proceed into the future.

Of high current interest are also the wide variety of methods possible to provide for increasing horsepower and response of engines at lower speeds with resulting improvement in acceleration and agility.

It is intended that military and commercial fuels be similar in order to simplify the total logistic support of the Department of Defense and permit full operation with a minimum of restrictions on fuel properties. The value of having capability to use several different fuels in military engines has long been understood, and a flexible fuel policy has been under implementation for several years.

The Tank-Automotive Research and Development Command (TARADCOM) has current research programs in four primary advanced engine development areas with goals of providing for better fuel economy, wider fuel tolerance and increased performance. These advanced engine programs are:

a. Advanced diesel technology development (fuel injection, variable area turbocharger for high efficiency and turbocompounding).

b. Advanced stratified-charge engine development (small bore and large bore stratified-charged engines).

c. Advanced turbine studies (advanced turbine cycles, turbine idle fuel reduction, reheat combustor investigation and turbine combustion research).

d. Advanced engine studies (Hot Engine).

The long range diesel engine investigations with the most advanced goals for improved fuel economy explore operation of a hot piston and cylinder with minimum cooling and conversion of maximum possible energy to useful power.

From the above it can be seen that TARADCOM is interested in the use of high temperature ceramics for diesel and turbine engines and that investigations are proceeding into new areas of higher temperature, higher output combustion required for military engines of the future.

Overview of the US Army Fuels and Lubricants Research Laboratory Activities*

DoD Fuel Policy assures that engines for tactical and combat vehicles will be designed to operate on widely available commercial fuels. This policy also advises that R&D on new fuels and engine work cycles is not to be restricted. The most common performance objectives are to improve fuel economy, fuel tolerance, and reduce engine size or weight.

Approaches can also be taken whereby the performance of engines already in service would be improved by making changes in the fuel composition. Some fuel composition approaches can be shown to be far better than engine design approaches for increasing the operating range of a given vehicle. Other fuel-oriented approaches show promise of increasing engine power outputs for short periods of operations. Some fuel formulations offer fire safety under combat conditions, and others show promise of preventing fuel degradation under long-term storage conditions. These approaches could result in the development of novel, special purpose, and/or emergency fuels. In order to be appropriate for investigation, a concept should satisfy certain prerequisites. It should show promise of improving the vehicle range, engine power, vehicle fire safety, or fuel storage stability. A resulting finished fuel should be able to operate as an alternate to a widely available commercial fuel and have adequate availability for special combat or reconnaissance missions. If an approach were to be undertaken that involved a fuel composition that could not be used in existing engines, then it should offer unusual potential benefits, such as reduction of the vehicle configuration applying to a new engine design, and for improvement in defensive and offensive capabilities.

Three principal areas of AFLRL research are:

High-Energy Fuels. The present military requirement of increasingly

* The US Army Fuels and Lubricants Research Laboratory (AFLRL) is a contract operated activity of the US Army Mobility Equipment Research and Development Command, and is located at Southwest Research Institute.

rapid disposition and movement of ground-powered equipment portends more extended supply lines and other support functions. Furthermore, the present and future use of fuel additives that impart specific beneficial properties to diesel fuel (such as improved fire safety or enhanced long-term storage stability) may lead to diminished vehicular power and/or range because of reduced combustion energy content. Accordingly, the development of diesel fuels having enhanced combustion energy content could allay the aforementioned problems and provide an additional degree of freedom in the formulation of diesel fuels.

Experiments conducted by AFLRL have tentatively demonstrated the feasibility of utilizing colloidal carbon as an energy-augmenting ingredient. These evaluations were conducted in conjunction with the use of a water-containing "heat-sink" fire-safety fuel in a single-cylinder diesel engine. Preliminary results indicated that the added carbon mullified most of the energy-content loss caused by the presence of water in the fuel. The performance of the diesel engine was not adversely affected by the presence of the colloidal carbon.

Fire-Safety Fuels. When Army mobility equipment is subjected to incendiary ballistic attack, the fuel system is vulnerable to fire and explosion. Because of this, both the mobility and range of such combat equipment are penalized because of the additional weight resulting from the use of ballistic-deterrent armor. In the case of fires caused or intensified by fuel release, fire vulnerability reduction can be achieved by the use of fire-safety fuels. Various fire-safety fuels have been investigated by the Army and other organizations. The approaches have included nonreversible fuel gellation, use of semi-rigid, but pumpable, fuel gels and aqueous-external-phase fuel emulsions, use of halogenated fire suppressants at relatively high concentrations, and use of organic-polymer antimist agents at low concentrations.

At present, the most promising approach for developing a fire-safety fuel at AFLRL is based upon utilization of a hybrid heat-sink/inert-blanket mechanism to retard or prevent ignition and flame propagation. Flammability evaluations conducted by AFLRL have demonstrated that water-containing diesel fuel is more fire resistant than the same fuel without the added water. This resistance is evident even at temperatures somewhat higher than the fuel-water flash point.

Long-Term Fuel Storage Stability. Diesel fuel, when subjected to long periods of storage or abusive use conditions peculiar to military operations, can both influence container corrosion and deteriorate to form both soluble and insoluble deleterious products. These deleterious products can promote metallic corrosion, plug filters, and stick injectors. Fuel composition as well as environment, container design, water bottoms, and inorganic and biological contaminants, interact by various mechanism s to various degrees during long-term storage. Field tests to identify deteriorated fuels or potentially unstable, problem-causing fuels are under development. A better definition, through basic studies, of the mechanisms of diesel fuel degradation is needed to alleviate field-identified fuel storage stability problems. Such information could better establish the role of sulfur, unstable organic compounds and impurities, container composition and condition, and of additives that counteract the deterioration process. Similar studies directed toward the storage stability of gasolines, jet fuels, and fuels from alternate sources are also needed to varying degress.

Army Research Office Engine Research Projects

"Influence of Fuel Specifications on Aspects of Gas Turbine Engine Performance," A. M. Mellor, Purdue University

"Instantaneous Heat Transfer Rates in the Exhaust Port of an I.C.E.", S. C. Sorenson, University of Illinois at Urbana-Champaign

"Improved Engine ... through Heat Transfer Control", R. G. Murray, Oklahoma State Un...

"Diesel Combustion Analysis Using Rapid Sampling Techniques", O. A. Uyehara and G. L. Borman, University of Wisconsin

"Combustion Processes of Reciprocating Engines Using Laser Raman Scattering", J.W.L. Lewis, Arnold Research Center

"Ignition and Flame Propagation in Sprays", W. A. Sirignano, Princeton University

"High Pressure Atomization", F. V. Bracco, Princeton University

"Wall Effects on Combustion in an Engine", F. E. Fendell, TRW Systems

"Studies in Rotational Flows Especially Asymptotic Methods", G. S. S. Ludford, Cornell University

"Bifurcation and Stability Theory with Applications to Problems of Combustion and Flame Propagation," B. J. Matkowsky, Rensselaer Polytechnic Institute

NASA SUPPORTED AIR-BREATHING COMBUSTION RESEARCH

Gregory M. Reck

NASA Lewis Research Center
Cleveland, Ohio

ABSTRACT

The Combustion Branch of the Airbreathing Engines Division at the Lewis Research Center is currently conducting research in the following areas: (1) advanced combustors and augmentors, (2) alternate fuels for aviation, and (3) emissions reduction technology. Activities in each of these areas will be summarized; however, attention will be focused on the emissions reduction area which contains much of the combustion fundamentals research conducted by the branch.

Research in the first area, combustors and augmentors, is directed toward developing combustor technology to achieve high performance, low emissions, and good durability in both commercial and military advanced gas turbine engines. A new facility for high pressure combustion research is nearing completion at Lewis which will have a capability of nearly 40 atm. Combustion studies in this facility will focus on the effects of pressure on flame radiation, liner heat flux, NO_x and smoke emissions, and combustor space rate. A number of combustor concepts including swirl-can and staged combustors with features including heat pipes and rich-burning pilots are being studied in sector rigs and low pressure annular rigs for eventual evaluation at higher pressures. Additional studies are underway to examine advanced diffuser designs, new combustor liner approaches, advanced fuel injector designs, and variable geometry concepts.

Research in the second area, alternate fuels, was initiated approximately 3 years ago with the objectives of evaluating the potential characteristics of future jet aircraft fuels, determining the effects of those fuels on engine components, and evolving new component technology if needed. As part of this effort, a joint program with the Air Force Aero-Propulsion Laboratory is underway which is aimed at investigating the effects of using alternate fuels on both commercial and military aircraft. Another program will examine an approach to minimizing refinery energy consumption (thus reducing fuel costs) by relaxing fuel specifications. Another joint effort coordinated by the Navy and involving several government agencies is investigating the feasibility of converting shale oil and coal into military grade fuels. However, before these alternate fuels can be reliably used, more information is needed in the areas of combustor technology, fuel system technology, fuel thermal stability data, materials compatibility, fuels toxicity, and engine endurance.

In the third area, emission reduction technology, Lewis has initiated a number of programs which address both near-term and far-term solutions to environmental standards for most classes of aircraft engines. The engine demonstrations of the staged combustors developed in the Experimental Clean Combustor Programs are nearing completion, and similar efforts for the T1, T4, and P2 classes of aircraft engines have been conducted. These programs were intended to evolve and demonstrate near-term technology capable of reaching emission levels approximately equivalent to the EPA 1979 emission standards. Concurrently, both in-house and contracted activities have been conducted and are continuing to investigate the feasibility of several approaches to ultra-low emissions levels. These approaches include forced circulation, premixed-prevaporized, and catalytic combustor schemes. Grant activities are also underway with the University of California at Berkeley,Massachusetts Institute of Technology, University of Michigan and Cornell University to study more fundamental aspects of lean combustion and stability.

In response to recommendations for reduced NO_x emissions over the entire engine operating cycle as well as the landing-takeoff cycle, Lewis is conducting the Stratospheric Cruise Emission Reduction Program (SCERP). The SCERP objective is to develop and demonstrate the technology necessary to reduce cruise NO_x emissions by a factor of 6 or more from current levels, in addition to meeting the EPA 1979 emission standards. The activity will be targeted for the high bypass ratio, high pressure ratio engines currently powering the wide body subsonic transports.

The premixed-prevaporized technique for emission reduction will be explored in the SCERP activity. The results from other studies indicate that this technique has the potential to meet or exceed the program goal. However, in considering off-design conditions it is apparent that a form of variable geometry will be necessary to maintain acceptable combustor performance as well as low emissions over the entire flight envelope.

The program outline for SCERP is broken into four successive phases leading to an engine demonstration. The initial phase will consist of a number of fundamental studies to establish design criteria for premixed-prevaporized combustors eventually leading to the development and assessment of a number of combustor concepts. In the next phase, a number of variations of each concept will be experimentally screened to identify the most promising. These designs will then be further developed in Phase III to optimize off-design performance, ignition, liner cooling, altitude relight, etc. The best design will be selected for full-scale engine demonstration in Phase IV.

The Phase I activities will be most critical to program success. A number of fundamental studies are being initiated to examine four key problem areas associated with the practical application of the premixing-prevaporing concept. These areas are identified as I - Lean Combustion Studies, II - Fuel-Air Preparation, III - Autoignition and Flashback, and IV - Engine Interfaces.

The first element, Lean Combustion, deals with the operation and emissions performance of premixing-prevaporizing combustors operating at extremely lean equivalence ratios. Several contracted flametube studies are underway to examine aspects of lean combustion. The General Applied Science Laboratories (GASL) is operating a propane-fueled premixed burner to examine the effects of pressure, temperature, equivalence ratio, and hot gas residence time on emissions.

Another GASL study will utilize a similar rig to examine the performance of a number of flameholder designs including cones, swirlers, grids, etc. A third contracted effort will be awarded soon to investigate several techniques for extending the lean stability limit of premixing-prevaporizing combustors, including pilots, catalysts, and heat recirculation.

Several in-house experimental activities related to the first element are also underway. The effect of the degree of prevaporization, fuel-air distribution, dropsize distribution, and flameholder geometry on emissions will be studied in a circular pipe rig.

Another in-house study will employ a rectangular sector combustor to examine variable geometry techniques and fuel-injector-flameholder combinations.

The second element, Fuel-Air Preparation, deals with the problem of providing the desired fuel-air mixture characteristics at all operating conditions.

An initial contract is being awarded to SOLAR to provide detailed fuel spray measurements from several types of injectors. A laser morphokinetometer will be used to obtain droplet size and velocity data. A second contracted effort is planned to develop an analytical model of fuel-spray mixtures in premixing-prevaporizing systems. An in-house fuel spray measurement technique is also under development employing a forward scattering technique to determine dropsize distribution.

In the third element, Autoignition and Flashback, a contracted program is underway at UTRC to measure the autoignition delay times of several fuels over a range of conditions. The experimental apparatus has been assembled and data on Jet A, JP-4, and No. 2 diesel oil at conditions up to 900K and 30 atm will be acquired over the next year.

An in-house program has been initiated to study flashback characteristics in a premixing-prevaporizing flame-tube. The test rig incorporates a flat plate in a windowed section and will examine boundary layer flashback and the effects of heated surfaces on autoignition limits.

The fourth element, Engine Interfaces, deals with problems or constraints imposed on the combustor as a result of its integration into the aircraft engine. In two contracted efforts with Pratt & Whitney Aircraft and General Electric, attempts were made to measure the turbulence characteristics at the combustor inlet. Several types of hot wires and hot films have been tried, but to date, data have been obtained only up to approach power settings.

In-house efforts in the area of engine interfaces are targeted toward identification of engine transient characteristics and determination of the

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effects of transients on the combustor. Fast response instrumentation has been installed on an in-house engine to monitor combustor inlet conditions during engine stalls. In a related effort, a test apparatus is being developed with the capability to simulate short-term transient characteristics in a test combustor.

As the results of the Phase I studies become available, the design data will be applied to combustor concepts. Variable geometry techniques and controls will be incorporated into the designs as required. As the designs evolve, an assessment of their potential with regard to both emissions reduction and practical application will be made. The most promising concepts will then be selected for experimental screening.

OVERVIEW OF ERDA COMBUSTION RESEARCH PROGRAM

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Introduction

The ERDA Combustion Research Program consists of three separate programs:

1. Division of Basic Energy Sciences (BES) - basic combustion research.

2. Division of Conservation Research and Technology (CONTR) - combustion research applied to end-use applications.

3. Division of Materials and Exploratory Research (MER) - combustion research applied to combustion of coal-derived fuels.

These three programs are coordinated through a Combustion Research Coordinating Panel consisting of representatives from the three divisions. The scope of the Combustion Research Program is the result of individual assessments by the Program Managers of the critical problems in their respective program areas.

Combustion Research Program of the Division of Basic Energy Sciences

It is necessary to recognize that the best use of today's fossil fuels and coming coal-derived fuels will require more knowledge and more precise data for burning different types of fuels. The BES Combustion Research Program supports research aimed at both obtaining the basic data needed by the applied scientist and expanding combustion research in new directions.

The BES goals in Combustion Research are as follows;

- Chemical Kinetics - to obtain an understanding, on the molecular level, of elementary combustion reactions and to derive rate constants usable in combustion modeling studies. To support the compilation and critical evaluation of data existing in the scientific literature.

- Hydrodynamics and Turbulence - to develop mathematical and computational techniques for the treatment of these phenomena and to experimentally test their validity in simple systems.

- o Turbulent Combustion Processes - to investigate the combined processes of chemical kinetics and turbulence in systems such as flames, burners and internal combustion engines.

- o Diagnostics - to develop techniques for quantitative measurements on combustion systems, particularly techniques using lasers. To study energy transfer processes in molecules involved in combustion processes.

- o New Advances - to encourage new ideas and developments in the combustion area.

Combustion Research Program of the Division of Combustion Research And Technology

The goals of the CONRT Combustion Research Program are to develop technology necessary to increase efficiency and alternate fuel utilization in combustion equipment. The strategy employed to achieve these goals involves end-use technology projects with specifically defined project approaches and objectives and balanced R&D efforts. Five end-use project areas have been defined corresponding to classes of combustion equipment with high potentials for energy conservation.

o Intermittent Combustion Engines

The objective of the IC Engine effort is to develop advanced technology for reducing fuel consumption and environmental impacts through control of combustion processes. Effort is directed toward five engine classes: (a) homogeneous charge (conventional), (b) stratified charge, (c) diesel, (d) divided chamber, and (e) engines using modified fuels.

o Continuous Combustion Engines

The objective of the Continuous Combustion Engine effort is to develop combustor design technology for (a) operation at high turbine inlet temperatures, (b) reduction of pollutant emissions, and (c) operation with alternate fuels. Effort is directed toward control of combustion processes in conventional combustors and unconventional combustors such as catalytic and surface combustors. Potential applications include stationary, automotive, and aircrafts gas turbines; stirling engines; and rankine engines.

o Boilers and Furnaces

The objective of the Boiler and Furnace effort is to develop advanced burner design technology for (1) operation at low excess air rates and (2) operation with alternate fuels. Effort is directed primarily toward burners for residential and commercial applications using liquid and gaseous fuels.

o <u>Industrial Processes Burners</u>

the objective of the Industrial Process Burner effort is to develop advanced burner design technology for (a) operation with high inlet air temperatures (for waste heat utilization) and (b) operation with alternate fuels. Primary effort is directed toward gas burners and secondary effort toward other industrial burners.

o <u>Alternative Fuel Technology</u>

The objective of the Alternate Fuel effort is to develop technology for utilizing alternate fuels and methods of characterizing fuels to assist in combustion equipment design.

The R&D efforts in each end-use technology project area include activities classified as applied research and technology development. The applied research efort is directed toward improved design methods for combustion components, and the emphasis in this effort is on utilization of fundamental analysis techniques. The technology development effort is directed toward new combustion component design concepts and provides opportunities for screening and evaluation of new ideas and applications.

<u>Combustion Research Program of the Devision of Materials and Exploratory Research</u>

The combustion program in MER consists of exploratory research efforts on clean, environmentally acceptable combustion of coal and coal-derived synthetic fuels. This program includes research oriented toward:

- o Solving the problems of ash-fouling, slagging and corrosion in boilers
- o Prevention of SO_2 emissions (e.g. by fluidized-bed combustion)
- o Combustion modifications for abatement of NO_x
- o Prevention of other emission which are either deleterious to downstream hardware, or environmentally noxious, or both (alkalis, vanadium heavy elements)
- o Better formulation and clean combustion of coal-oil slurries;
- o Stable and efficient combustion of low Btu gases
- o Clean combustion of coal-derived liquids

The MER FY 1977 program plan contains projects, in effect or in planning in most of these technology areas.

EPA Supported Research and Needs in Air-Breathing Combustion

by

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ABSTRACT NOT AVAILABLE

INJECTION, ATOMIZATION, IGNITION, AND COMBUSTION OF LIQUID FUELS IN HIGH SPEED AIRSTREAMS:GRANT NO. 75-2584

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For weapons delivery and defense and for transportation of personnel and materials, advanced subsonic and supersonic combustion air breathing and composite engines are required for aerospace vehicle and missile propulsion. Improvements in the performance of the propulsion system will result in useful improvements in total system performance and efficiency. This research will provide understanding of the detailed physical and chemical processes involved in such combustion systems, in choosing acceptable liquid fuels and in the design and development of practical injector-mixing systems and combustors for these advanced engines. This will result in the formulation of realistic mathematical models to predict these processes.

The approach is based upon detailed experimental observations using primarily optical techniques. Experiments on penetration, breakup and atomization at high subsonic and transonic speeds are underway using a modified version of the VPI&SU 9" x 9" supersonic wind tunnel, and high speed motion pictures, short duration photomicrographs and streak photographs. The observations on ignition are underway using hot supersonic airstreams and kerosene and carbon disulfide as sample liquid fuels. These experiments are conducted in a specially constructed heated air facility, with a combustion fired afterburner to produce temperatures up to 2500°F. Primary observations are in the form of thermographic infrared photographs that show the temperature pattern on the liquid surface films formed near the injection station. The experimental programs are complemented by the development of corresponding mathematical models of the phenomena of interest.

The work currently falls into three related tasks. The first concerns studies of auto-ignition of liquid fuels injected across hot supersonic airstreams. Attention is being focused on the region in the immediate vicinity of the injection port. The most recent experiments indicate that partial pre-atomization of the liquid injectant greatly enhances ignition. Two analytical studies have been completed. A boundary layer computer code was used to predict the detailed state of the boundary layer approaching the injection station. Next, a study of the influence of mass transfer on interface stability was conducted. The second task involves droplet size measurements. A bench facility was constructed for evaluation of optical scattering techniques. We have compared the results with direct observations obtained with nano-second photographs. The results were good. Wind tunnel tests are now beginning. The third main task has just begun. We are examining the influence of a downstream surface step on jet penetration and break-up. An exploratory test series has shown large effects under some conditions. A special test section for a planned comprehensive test program has been designed and constructed and preliminary testing will begin shortly.

MIXING AND COMBUSTION MECHANISMS IN HIGH SPEED AIR FLOWS

AFOSR Contract No: F49620-77-C-0044

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For airborne weapon delivery at high speeds, advanced air-breathing propulsion engines incorporating subsonic and supersonic combustion and capable of operating over wide ranges of flight conditions are needed.

Realization of the performance potential offered by existing and future engine concepts is hampered by insufficient understanding of the basic mechanisms and their mutual interactions. Turbulent mixing and finite rate chemical reactions involving condensed phase fuels are the main processes of interest. Interpretation of data and the development of realistic predictions of performance based on the coupling of the fluid dynamics and chemical kinetics mechanisms are required in order to develop effective systems in an economic and timely manner.

Current emphasis has been on subsonic combustion involving systems of the integral rocket/ramjet type utilizing the sudden expansion (dump) combustor concept. Simplicity is inherent in this concept and high combustion efficiency with wide flame stabilization limits are potentially available as a consequence of the imbedded recirculation zone(s). Consistent and good performance has, however, not been achieved.

Our effort has been directed toward developing an understanding of the parameters controlling the heat release process as it relates to combustion efficiency and flame stabilization. The methodology under current investigation involves a modular approach wherein the reacting flow field is described in terms of domains each of which is characterized by a well defined flow feature. In the sudden expansion burner there are two flow domains; a recirculation zone(s) and a primary, or "directed" flow. The recirculation zone(s) is treated with stirred reactor theory and the primary flow is treated with ducted jet mixing theory. Finite rate chemistry for hydrocarbon oxidation and turbulent kinetic energy (TKE) methods are included in the model. The two flow regions are fully coupled thru the boundary conditions along the dividing streamline separating the non-uniform primary flow from the recirculating flow.

Progress during the past year includes the completion of each separate module and the coupling of these modules. Cold flow calculations of a representative dump combustor geometry have been successfully carried out. In addition, calculations have also been made using a simplified version of our detailed chemical kinetics model in order to investigate the effects of heat release on a representative dump combustor flowfield. This work is being carried out in close coordination with the experimental work under way at the Air Force Aero Propulsion Laboratory at Wright-Patterson Air Force Base and descriptions of various aspects of this work are reported in References 1 thru 4.

Future plans include systematic application of the model to available data. Explanation of the observed performance characteristics and model refinements will be carried out as part of this effort. In addition, multiphase flow processes including liquid fuel injection, spray formation and combustion will be investigated. Delineation of specific experiments to be carried out will continue to play significant role in this effort.

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TURBULENT MIXING AND COMBUSTION IN HIGH SPEED FLOWS/AFOSR-PO-76-0001

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The objective of this research is the development of reliable and physically perceptive analytical models for the turbulent mixing and heat release mechanisms in turbulent combustion systems. The approach taken in this theoretical and experimental study is to develop analytical models for the particular flow processes, then to conduct detailed experiments in order to verify and refine the models. Major emphasis is placed on the development of adequate models for (1) the turbulent transport properties for momentum, energy and mass in a variety of free and confined mixing systems, including flows with chemical reactions and recirculation, and (2) the interaction of heterogeneous turbulent mixing and finite rate chemical reactions.

During FY77, the study concentrated on ducted flows with embedded, reacting, recirculation regions, such as those found in sudden expansion or "dump" combustors. A series of experiments with ducted reactive hydrogen-air flows with recirculation in a duct to nozzle exit diameter ratio 10 configuration was completed. The data were analyzed and reported. The data include radial distributions of hydrogen mass fraction, mean axial velocity, turbulence intensity, and total pressure, as well as axial distributions of wall hydrogen mass fraction and wall static pressure. The report includes a tabulation of the data and a mathematical analysis to confirm the self-consistency of the results. Analysis of the data led to the following conclusions: (1) chemical reaction in the flow field has little effect on the location of the recirculation zone, (2) the gases in the reacting system mix less rapidly than those in a nonreacting system of the same configuration and fuel-air ratio, (3) the turbulence intensity based on the jet mean exit axial velocity has a maximum value of 0.20 in the near field which occurs in the mixing zone at the location of maximum shear stress and (4) the secondary hydrogen stream is diluted in the area of the nozzle exit plane by counterstream turbulent diffusion in the highly turbulent flow field.

A 2.06-in.-diam inner nozzle was installed in the test cell to provide a configuration with a duct to jet nozzle exit diameter ratio of 2.5. A test series using hydrogen-air in the new configuration was initiated.

An evaluation of numerical techniques for use in predicting combustor-type flows was conducted. The analysis revealed that: (1) there are no completely satisfactory general predictive techniques available for combustor-type flows, (2) neither "primitive variable" codes nor "stream function-vorticity" codes are clearly superior in predictive capability and (3) some of the most pertinent problems which must be resolved are (a) the effects of grid spacing, (b) the boundary condition for vorticity at a sharp flow separation corner in the "stream function-vorticity" codes, and (c) turbulence transport and turbulence-chemistry interaction modeling. A stream function-vorticity code using coordinate transformations in conjunction with a reformulation of the vorticity conservation equation is being developed at the AEDC under another project for application to combustor type flows in order to address the grid spacing problem.

The Rhodes turbulence-chemistry interaction model (TCI) is being incorporated into the AEDC integral analysis for ducted mixing flows with recirculation. Check out has been delayed because of modifications to the integral analysis. However, the modification has been accomplished and check out is in progress.

During FY78, hydrogen-air experiments with a duct to jet nozzle diameter ratio of 2.5 configuration will be completed. Both the reactive and nonreactive flow field at one stoichiometry will be defined with laser velocimeter, pressure and composition measurements. After the laser velocimeter measurements are completed, the ducted mixing apparatus will be modified to permit the use of an existing laser-Raman system for determining temperatures and species number densities in the flow field. If successful, the laser-Raman measurements will be repeated in the duct-jet diameter ratio 10 apparatus.

The results of the experimental phases will be compared with the TCI version of the integral mixing theory for ducted flows. The comparisons will aid in the interpretation of the ducted mixing process and indicate if refinements in the TCI analysis are necessary.

RAMJET COMBUSTORS

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Dump combustors have become the basis for modern volume limited ramjet missile designs. Since the combustor must contain the rocket boost propellant, can combustors must not be used and combustion piloting must depend to a large extent on the recirculation zone formed by the sudden area change formed in going from the inlet to the combustor. Although several such combustors have been successfully built and tested in recent years, the specific nature of these prior designs have precluded obtaining a sound technical data base or detailed flowfield data necessary for combustor modeling. The objective of the in-house programs being conducted by the Ramjet Engine Division of the Air Force Aero Propulsion Laboratory is to provide such a data base to assist the combustor modelers and to also provide a data base for making a better first cut at a new engine design.

In the effort being conducted on our thrust rig, a parametric study of overall combustor performance is being conducted on 6", 8", and 12" diameter combustors while maintaining "pressure scaling" criteria. The parameters include flameholder blockage, combustor length-to-diameter (L/D), inlet-to-combustor area (A_2/A_3), nozzle area ratio (A_*/A_3), fuel injector location, inlet air temperature, and air mass flow. Combustor efficiency, combustor pressure drop, and some lean and rich blowout limits are being obtained for JP-4 fuel.

Previous tests with 25% A_2/A_3 indicated that P_3D_3 scaling could be applied to dump combustors without flameholders, but initial results with inlet-to-combustor area ratios of 35% and 45% indicate that pressure scaling does not apply when the recirculation zone volume is smaller than some critical value.

In addition, some tests have been made on the effect of inlet flow non-uniformities on dump combustor efficiency as well as the effect of fuel injector depth and vitiated air heater efficiency.

Experiments being set up to obtain detailed flowfield data include a laser anemometer system and a water tunnel for flow visualization.

RAMJET FLUID DYNAMICS +

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A comprehensive series of cold flow experiments has been performed with an axisymmetric sudden-expansion dump combustor and various annular flame-holding elements. This research effort is an extension of work previously reported on the overall characterization of sudden-expansion dump combustor flowfields. The annular flameholders, which were supported at the dump station by four small struts, had two basic cross-sections and two basic diameters. Both cross-sections were sharp-edged wedges with either a full-wedge configuration (◁) or a half-wedge configuration (◿). The inlet area blockage was held constant at 25% for all of the flameholders.

Pure argon was injected through eight circumferential wall orifices in the air inlet upstream of the annular flameholding elements. Detailed mixing profiles of argon concentration were measured at four axial locations in the dump combustor using an on-line mass spectrometer. Gas sampling results from tests using the smaller diameter annular flameholders showed significantly enhanced mixing as compared to previous results obtained with conventional strut-type flameholders. Complete mixing was obtained in an axial distance of less than two combustor duct diameters downstream of the dump station. In addition to gas sampling, measurements of total pressure profiles and wall static pressure were also obtained for the various flame-holder configurations.

Using results from the present effort, as well as those from the work previously reported, a general correlation has been made between cold flow mixing data and measurements of combustion efficiency from direct-connect dump combustor burn tests as a function of combustor L/D. Correlations have been made for test cases both with and without flameholding devices. The validity of the cold flow mixing data as a good indicator of combustor performance is clearly established.

+ In-house basic research program (Task No. 2308/S2).

TURBULENT VORTEX FLAME STABILIZATION AND SPREADING WITH GAS JETS AND SPRAY CONTROL

Contract Nos. AFOSR-72-2400 and AFOSR-76-2876

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This work is directly applicable to the design of advanced air-breathing engines, airborne weapon delivery and defense, reconnaissance, and transport. There is at present an insufficient understanding of the basic mechanisms and processes involved in advanced air-breathing combustors and lack of realistic guidelines for predicting propulsion system performance and designing combustors with improved reliability and efficiency and acceptable pollutant emissions. The objective of this work is to understand and develop accurate theoretical and mathematical models describing the mechanisms and processes of gas jet-flame interactions involving vortices induced by flow separation and gas jets associated with turbulent reacting flow fields encountered in advanced air-breathing combustors, e.g., dump burners. This research will provide additional understanding and realistic analytical modeling of turbulent reactive flow not now available, will contribute to evaluation of practicability of utilization of aerodynamically created vortex induced combustion and stabilization and guide design and development of advanced combustors using this concept with improved reliability, combustion efficiency, and acceptable exhaust gas emissions.

Study will be made of mechanisms and processes of gas jet-flame interactions including investigation of gas jets used as fluid amplifiers to promote and stabilize vortex combustion, reduce combustion instability and combustion-driven noise. Experiments will be conducted in several quasi -2 and 3-D burners of different characteristic diameters. Cross jets will be introduced at the combustor periphery upstream of the flameholder to create vortices in the main fuel-air stream. The degree of amplification of the recirculation zone in a cylindrical burner with cross jets will be determined to ascertain optimum location and total flow rate of jets. Burner characteristics with air jets performing the dual role of fluid amplifier and swirl generator will be critically examined. Particular emphasis will be placed on the causes of rough burning, spectral character of the pressure fluctuations, and fuel stratification in a volume-limited cylindrical burner.

The behavior of fuel droplets in the highly amplified, swirling, recirculation zone will be studied in an effort to control fuel stratification by providing an optimum residence time for a given fuel spray. Schlieren, high speed photography, gas chromatography, pressure transducers, and noise analyzers will be used to characterize the observed phenomena.

During this period, the following configurations were studied. 1) A 2-D 3" x 1" burner with two steps and a double jet system. 2) A 3" axisymmetric burner with a 2" inlet. Both normal cross jets and swirl jets were investigated. The flow field characteristics with the normal cross jets under cold flow conditions have been studied by means of a hot wire anemometer. 3) Tests are continuing on a 2-D 8" x 1" burner with a total of four sets of cross jets and four steps. Conclusions are: a) In spite of geometric differences, all burners have similar flame blow off characteristics. b) A jet to main stream momentum flux ratio of about 40 produces an optimum result. c) Additional amplification of the recirculation zone caused by the swirl jet system makes it the best configuration. d) In a burner of small radius, due to interference the jet penetration is not as large as that of the 2-D system.

The effect of fuel type, surface character, surface tension, and surface temperature on the lifetime of a drop exposed to a surface has been determined. Fuel drops deposited on a hot surface evaporate in four basic modes: contact, vaporization, maximum evaporation rate, and spheroidal. The occurrence of a mode is dependent upon both fuel and surface properties. The surface temperature range within which the maximum evaporation rate occurs can be expanded to produce more rapid combustion by reducing surface tension, increasing surface roughness and surface deposits. The drop lifetime in all modes of evaporation is significantly reduced when a rough surface or surface covered with carbon deposits is exposed to the drop.

In the spheroidal mode, an instability is observed in which the drop location with respect to the surface and the evaporation rate change in an oscillatory manner. The frequency and amplitude are functions of drop mass and this instability may couple with pressure oscillations within the combustor.

The apparatus to examine homogeneous ignition of fuel-air explosions has been constructed and will be calibrated.

It has also been noted that the evaporation time changes as liquid phase cracking produces high molecular weight decomposition products (precursors of carbon) in the liquid phase. The viscous small drops produced evaporate slowly and may account for a major fraction of combustion inefficiency.

Flow Flame Interactions and Transient Flame Phenomena

by

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ABSTRACT NOT AVAILABLE

COMBUSTION STUDIES OF FAST-FLOW REACTIVE SYSTEMS

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In past reports we have described the ongoing programme of research being carried out at Cranfield and have indicated the two areas of interest upon which we have concentrated our efforts, namely (a) the process of heat release within a ducted supersonic stream and (b) the ignition process with particular reference to hydrocarbon fuels.

In the main, for our heat release studies, we have employed hydrogen as a fuel burning in a duct with inlet Mach numbers from 2 to 3. A full description of the Mach 2 experiments has been included in a paper submitted to Acta Astronautica which has been accepted subject to revision. With the aid of a stagnation temperature booster, which takes the form of a hydrogen/oxygen burner, we are now conducting a series of experiments at inlet Mach number of 2.5. A typical plot of static pressure versus combustor length is shown in Figure 1. In our analytical work we solved the appropriate aerothermodynamic equations by establishing a further equation which is based upon the condition that ignition does occur. In simple terms this equation is a boundary condition or lower bound, which compares the combustor length with the length appropriate to the ignition delay. Utilising this equation we were able to solve the equations by the standard 4th order Runge-Kutta technique. This process indicated that there were four possible solutions in terms of the duct characteristics. These four solutions covered the static pressure ratio, stagnation pressure ratio, static temperature and stagnation temperature. The static pressure form is, of course, the Crocco expression.

Based upon the argument that the critical mach number must always by unity we arrived at the conclusion that the stagnation temperature ratio thus,

$$To/Toi = (A/A_i)^{R_{T_O}}$$

is the most appropriate form for this 'engineering' type approach. As a check the exponent R_{T_O} is calculated at different points along the duct and the resulting stagnation temperature ratio plotted. Figure 2 indicates that this plot is a straight line hence

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helping to justify the assumption that the stagnation temperature ratio is the correct form to use in this situation.

In our ignition tests we have been able to stabilize both liquid and gaseous hydrocarbon flames, in conditions under which they would not normally exist, by the simple expedient of adding a small amount of hydrogen to the flow (see references 1 and 2). This process has developed into a technique by which we are able to determine the effectiveness of various stabilizing devices, based upon the assumption that one configuration, which requires more hydrogen for the initiation of combustion than another, is a less efficient stabilizing process. In this way we have been able to compare the stabilizing properties of aerodynamic blockage with that provided by a physical flameholder.

Currently, we are studying the stabilizing properties of a rearward facing step with kerosene and methane as the main fuels. The test section currently being used in these tests is shown in Figure 3. We believe that this will be the first time that such tests have been carried out with hydrocarbon fuels, although references 3 and 4 report research based upon hydrogen and pyrophoric fuels. It will be possible to vary the step depth and the fuel injection point, and also as an added process to inject oxygen into the fuel rich zone behind the step.

As a further outcome of our ignition experiments we have observed a similarity between the flame stabilization process in subsonic and supersonic flows. This worked is reported in reference 5.

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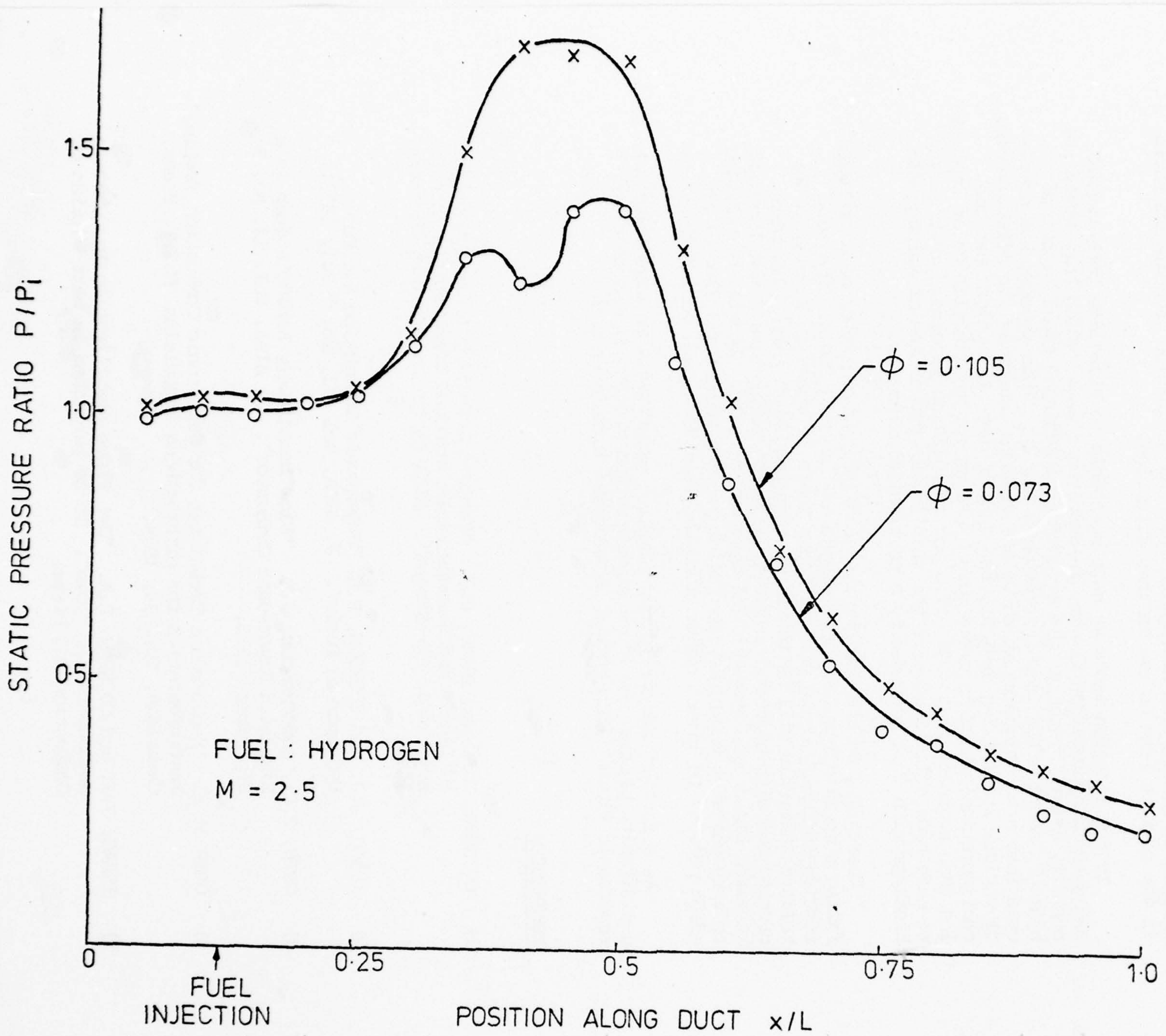


STATIC PRESSURE RATIO P/P$_i$
1·5
1·0
0·5
0
0·25
0·5
0·75
1·0
ϕ = 0·105
ϕ = 0·073
FUEL : HYDROGEN
M = 2·5
FUEL
INJECTION
POSITION ALONG DUCT x/L

FIG 1

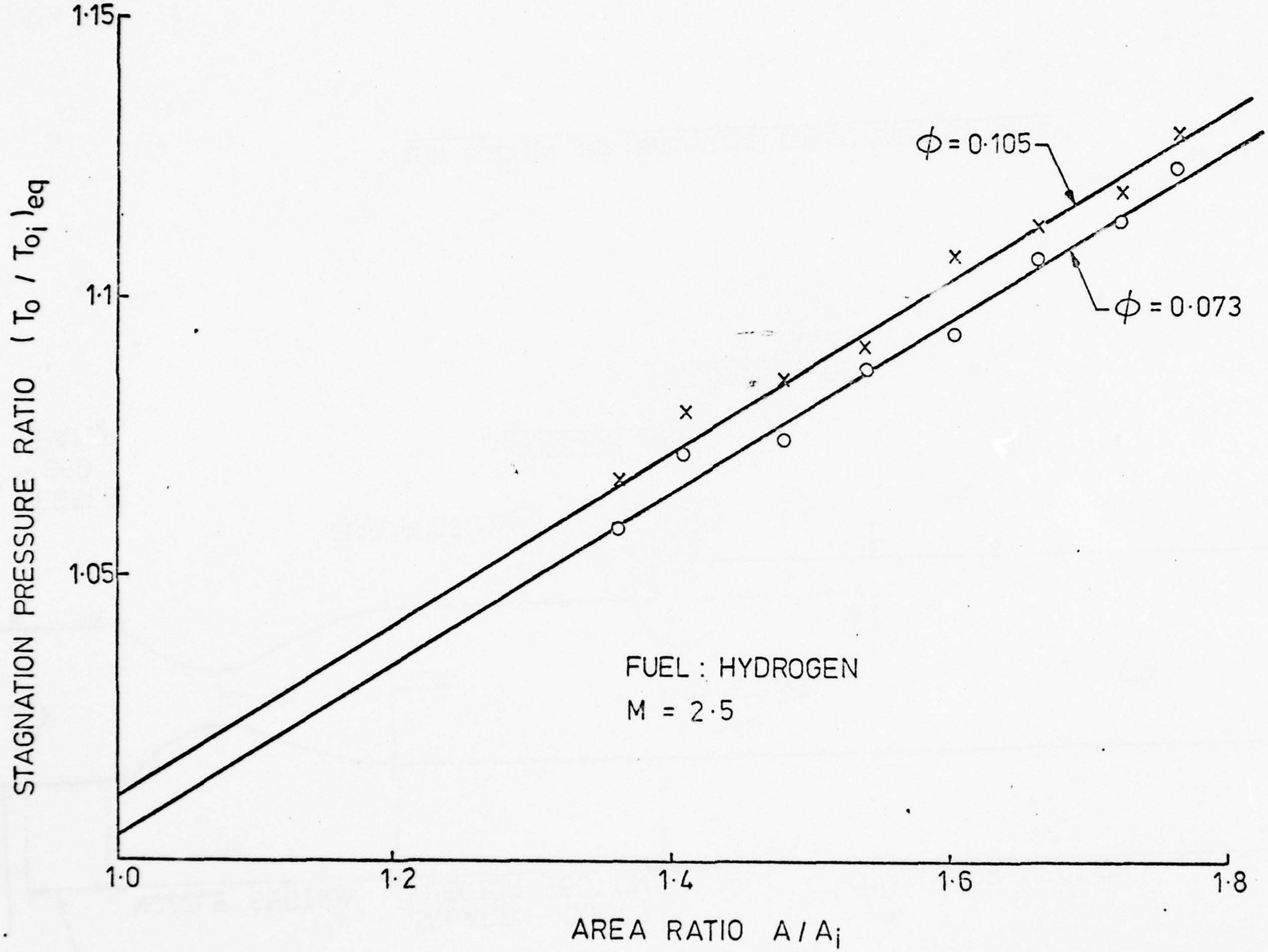
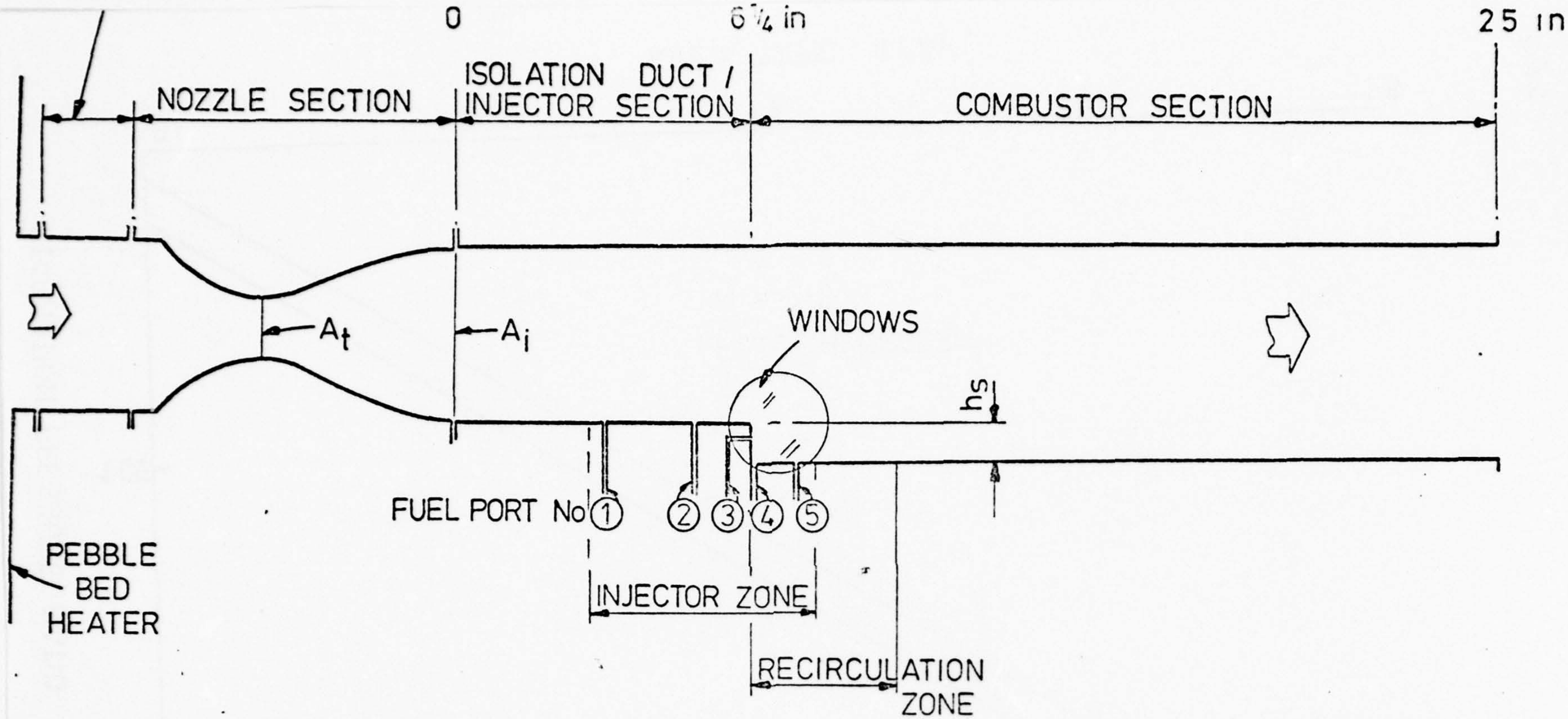

1·15
1·1
1·05
1·0
1·2
1·4
1·6
1·8
ϕ = 0·105
ϕ = 0·073
FUEL : HYDROGEN
M = 2·5
STAGNATION PRESSURE RATIO $(T_o / T_{oi})_{eq}$
AREA RATIO A / A_i

FIG 2

26c



TEST SECTION FOR EVALUATING EFFECTIVENESS OF STEP

FIG 3

22d

Research on Mechanisms of Supersonic Combustion and
External Burning Relevant to
US Navy and Air Force Requirements

by

Drs R.C. Orth, P.J. Waltrup,
F. Billig, R.T. Cusick and J.A. Schetz
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ABSTRACT NOT AVAILABLE

Summary of External and Base Burning JANNAF Workshop

by

Dr C.E. Peters
AEDC (ARO)

ABSTRACT NOT AVAILABLE

AIRBREATHING PROPULSION COMBUSTION

Outlooks in Gas Turbine Combustion Technology

Within the Aero Propulsion Laboratory, there are two groups which deal with turbine engine combustion technology, the Combustion Technology Area, under the Turbine Components Branch of the Turbine Engine Division; and the Fuels Technology Area, under the Fuels and Lubrications Division. The principle difference between the two groups is which end of practical aspects of a combustion system is approached. The Combustion Technology groups deals with hardware influences of the combustion system while the Fuels Technology group deals with the influence of fuel composition and characteristics on combustion processes. The combustion technology program that will be dealt with here is that of the Combustion Technology group; although the basic combustion technology needs of both groups are nearly the same.

The Combustion Technology Area of the Air Force Aero Propulsion Laboratory is responsible for development of new technology and hardware systems which meet the gas turbine combustion needs of the Air Force. The primary combustion technology needs of the Air Force encompass the main combustor and augmentor systems of gas turbine engines.

The areas of technology required to meet the Air Force combustion systems technology needs cover a broad spectrum of scientific disciplines. Combustion, thermodynamics gas dynamics, heat transfer, structures and materials are major disciplines required to carry out the Air Force's program of advanced development. These technical disciplines are directed at major development facets such as concept definition, modeling, stability, and emissions/efficiency to produce advanced technology combustion systems which can be engine demonstrated.

The current program of the Combustion Technology group addresses design, performance and phenomena understanding of both main and augmentor combustion systems. Programs which are currently underway are: the High Mach Turbopropulsion Combustor program, the Shingle Combustor, Augmentor Rumble Stability, Low-Pressure, High-Temperature Augmentor, and Combustor Design Optimization. These five programs address new technology of high payoff and areas of concern.

The "High Mach" contract is a hardware program to design and test an integrated Diffuser/Combustor system capable of utilizing inlet flow at $M_3 > .5$ with very low losses. The diffusion system utilizes a bleed vortex-controlled diffuser and has shown that performance far in excess of past standards can readily be achieved.

The Shingle Combustor program is an engine simulation, cyclic rig demonstration of the Shingle Combustor design durability limits. The Shingle Combustor is a double-walled construction design which isolates thermal and structural loads of the combustor.

Augmentor Rumble Stability is currently being addressed under three contracts. The contracts utilize analytical/empirical modeling of flameholder combustion and full-scale experimentation to investigate rumble-inducing conditions. NASA is supporting the Air Force in this area by providing engine tests of hardware from these programs.

The Low-Pressure, High-Temperature Augmentor contract is a program to design, fabricate and test augmentation hardware capable of efficient operation in fan airstreams.

The Combustor Design Optimization is an effort at Purdue University under the Senior Investigator program to analyze combustion/combustor flow models. This program is to discover areas of weakness and to design experiments needed to provide data to resolve found deficiencies.

These current programs address areas of technology which are expected to have the greatest payoff or are problem areas.

In the coming year, two new programs will be added to address the same basic engine technology areas as the current High Mach Combustor, and Shingle Combustor programs. The programs to be added are the Swirl Flow Combustor and Advanced Material Segmented Combustor programs. The Swirl Flow Combustor program is investigating high velocity burning as an alternate approach to diffusion to achieve effective combustor utilization of high subsonic Mach number flow. The Advanced Material Segmented Combustor will be a program to design a combustor system for very high temperature, very long life which utilizes advanced materials; i.e., ceramics.

The current and coming programs point out the Air Force's near-term interests in advanced aerodynamics and high durability combustor designs. Improvements in all of the basic technology disciplines mentioned above are needed if the Air Force is to reach its goals. Specific basic research needs of the Combustion Technology group include reaction kinetics, turbulence/mixing, heat transfer (convection/radiation), combustion instability, and diffusion. Basic research in areas such as stress predictions, material properties, is of interest, but in a less direct way. Advances in areas such as material properties must be in a highly refined state, such as a new material which has been through manufacturing technology development. To the Combustion Technology group, the most important and useful of basic research is advancements in understanding of combustion, aerodynamics (turbulence, diffusion, droplet/two-phase flow, etc.), and heat transfer phenomena. Such advancements can be directly applied to developing new combustor designs without secondary development of the new technology.

Progress in Modelling Combustors

P.G. Felton, J. Swithenbank and A. Turan

Abstract

Analytical models are required for the design and development of combustors whose applications range from gas turbine engines to industrial boilers. Recent advances in the solution of the problem of predicting the performance of combustors have been based on finite difference and stirred reactor methods.

Three-dimensional finite difference methods were pioneered by Professor Spalding and co-workers and these techniques have been successfully applied to the prediction of gas turbine combustor flow patterns. Due to the limitations of present computers these methods cannot be extended to completely include fuel spray dynamics and realistic chemical kinetics. This difficulty is overcome by using the computed flow patterns to define a network of interconnected stirred and plug-flow reactors. The detailed kinetic scheme presently consists of 13 species undergoing 18 reactions to represent the combustion of hydrocarbon fuels such as kerosine. A model of fuel evaporation is incorporated which assumes the fuel spray to be composed of 21 x 12 μm size ranges, evaporation is calculated using a forced convection model. The mixing of fuel vapour and air is modelled using a micro-mixing parameter, τ_{SD}, based on turbulence dissipation rates. The overall method thus combines 3-D fluid dynamics, turbulent mixing, evaporation and chemical kinetics.

The model has been verified by experiments which show that flow velocity profiles, chemical species (CO, NO etc.) can be successfully computed.

LOW FREQUENCY COMBUSTION INSTABILITY IN GAS TURBINE ENGINE AUGMENTORS

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While the phenomenon of combustion instability has plagued all types of high heat release combustors, the problem has been most severe in flight propulsion systems where weight considerations require highly efficient structures. In turbojets, ramjets, and rockets, the pressure, vibration and heat loads resulting from combustion instability, superimposed on the normal loading, are usually destructive.

In the early 1950's high frequency combustion instability (screech) presented problems in airbreathing engines. Engineers sought solutions through mathematical modeling and analytical studies, but unfortunately the computer technology and analytical techniques of twenty years ago proved inadequate. Engine manufacturers turned to "cut-and-try" empirical approaches involving changes in flameholders, combustion chamber shape, fuel injection, velocity profiles, and flame piloting. They tested fuel additives and combustion chamber baffles. Although some of these approaches, notably baffles, produced marginal improvement, the problem was not solved until damping devices in the form of acoustical absorbers (screech liners) were introduced. Screech liners are used routinely and high frequency instability is no longer regarded as a serious problem.

With the advent of the mixed-flow afterburner in turbofan engines, a type of low frequency instability known as rumble or chugging became a serious problem. Rumble is a periodic afterburning combustion instability (pressure oscillations fed by the combustion process) occurring usually at high fuel/air ratios at flight Mach numbers and altitudes when low duct inlet air temperatures and pressures exist. This instability usually leads to afterburner blowout and/or fan surge and engine stall. The frequency of oscillation usually lies between 30 and 200 Hz. This occurrence of instability at lower frequencies makes use of screech liners of conventional design inappropriate. For adequate damping the absorbing devices are designed so that the resonant frequency corresponds to the expected frequencies of pressure oscillations. Since the required cavity volume for the liner is inversely proportional to the square of the resonant frequency, the liners of large cavity volumes required for low frequencies would necessitate an unacceptable increase in engine weight.

Data from engine programs and early rumble investigations suggest several possible mechanisms which regulate or cause low frequency combustion instability in afterburners. They can be summarized under the following categories:

1) Longitudinal system dynamics.
2) Pressure disturbances at the fuel injector.
3) Combustion efficiency oscillations.
4) Insufficient and/or non-uniform fuel vaporization.
5) Low recirculation wake energy.
6) Turbulence upstream of the flameholder.

Even subtle changes in flameholder designs have altered the rumble characteistics of a turbofan engine. With some experience at hand, the design engineer has successfully produced "fixes" for unstable conditions. Redistribution of the fuel-to-air mixture ratio has worked, and deriching the fan duct has lessened rumble problems in the past. However, complete understanding of this combustion/dymamics problem has been inadequate to design rumble-free mixed flow afterburners with confidence.

The purpose of this research project is to devise a reliable empirical and analytical model that will aid afterburner designers. The approach used began by isolating mechanisms thought to contribute to rumble. As the major mechanisms were being investigated, a mathematical model that could predict unstable conditions and that could be extended to innovative designs was carefully developed. For the tools to be practical, the mathematics must be rigorous enough to model the physics accurately, yet simple enough to be used by engineers other than the originator. For this reason, and because of the current state of the art, we pursued a linear analysis of this combustion problem.

The mathematical model of the augmentor system was developed using linearized continuity, momentum, and energy equations for one-dimensional time variant flow. Laplace transform techniques were used to obtain a distributed parameter solution in the frequency domain relating pressures, temperatures, and velocities at the fan exit, flameholder, and nozzle exit plane to the heat release rate and location within the augmentor. The system stability was assessed using standard control theory techniques. In this method of stability assessment, the linearized heat addition rate is forced to vary sinusoidally at an amplitude and frequency. The linearized system equations are simultaneously solved for pressure, temperature, and velocity perturbations throughout the system. System instability is predicted whenever the forced heat release and the predicted heat release are in phase, and in addition, the amplitude of predicted heat release is equal to or greater than forced heat release. Physically, this means the system becomes unstable when a perturbation in flameholding conditions produces a heat release perturbation in phase with and equal to or greater than the initial disturbance.

The experiments were conducted in a combustion tunnel in which the pressures, temperatures, and gas flows of an augmentor were simulated. The circular cross-sectional rig was designed so that various configuration changes, including flameholders, spraybars, and distances between reflective points, could be made easily. The math model underwent continued refinement as test results from the rig became available. Mathematical descriptions were based on physical reality and their ability to track test data. Comparisons between test and analysis were good, but adjustments in the math have improved the model's capability of simulating experiment.

Rig test results generally show a rising rumble amplitude as fuel-air ratio increases above stoichometric. Model predictions display a rapid movement from the stable to the unstable operating region as fuel-air ratio increases. The model also predicts rumble as fuel-air ratio is lowered, but in this test case lean blowout usually occurs with little rumble amplitude.

The model also indicates that, in addition to fuel-air ratio management, rumble can be controlled by damping oscillations in the spray-bar-to-flameholder region. A turbulence screen with a low pressure drop (5% $\Delta P/P$) was placed 40 inches upstream of the flameholder. There was no dramatic reduction in rumble amplitudes, although some runs showed some reduction.

An estimate of the influence of the temperature gradient on airflow dynamics was made by modeling the gradient as two step changes, one at the beginning and the other at the end of the combustion zone. The spacing between the two steps had limited the checkout to frequencies up to about 60 Hz. A system resonance at 30 Hz, which the model previously failed to predict, was now predicted. Also, a resonance at 70 Hz was now predicted to be lower in amplitude at a fuel-air ratio of .10 and higher in amplitude at a fuel-air ratio of 0.06. Airflow dynamics were affected enough to necessitate an accounting of temperature gradient.

In general, the results of the test rig data agree well with the analytical mode. The brief discussion typifies the kind of analysis that has helped modify the model to improve its prediction capability.

Several general concluding comments can be made. Experimental rig test data identify airflow dynamics and fuel distribution as rumble contributors. Increased wake heat addition, decreased wake fuel-air ratio through flameholder geometry, increased turbulence level, and increased fuel vaporization help reduce rumble. The distance between the fuel injectors and flameholders should be short. The system model predicts rumble conditions well, but will be improved with the addition of an improved flameholder/combustion section that currently is being developed.

RADIATION AUGMENTED COMBUSTION
CONTRACT F49620-77-C-0085

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Aircraft operating limitations due to combustion associated phenomena such as flammability, flame propagation, ignition and stable combustion are becoming increasingly important in advanced military aircraft. These limitations originate in part from system design factors rather than inherent combustion phenomena. Techniques are being uncovered in various laboratories for extending current limits by providing for non-conventional combustion augmentation. These techniques involve combustion augmentation by creating unique effects which are brought about by massive heat exchange, centrifugal force, catalysis, plasma torch exposure, improved spark discharge, laser irradiation, and vacuum ultraviolet or ultraviolet irradiation.

There are potential payoff advantages available when using a combustion augmentation technique because of the basic difference by which a stable combustion wave is created compared to the thermal energy effect generated by the standard spark igniter. For example, military turbine engines usually are required to have relight capability at high altitudes and low combustor inlet pressures and temperatures. The initial reactions created by augmentation, such as irradiating a combustible mixture with ultraviolet light, are not governed by the usual thermal reaction kinetics parameters, and thus it may be possible to initiate self-sustaining reactions in environments of inlet pressure and temperature that are lower than required with a thermal spark system. The relight capability should be limited only by the blow-out limit of the combustor configuration. Further, the ultraviolet light irradiation method, in particular, does not have an upper pressure limit where the igniter becomes inoperative. This is a consequence of the radiation source electrodes being protected from the combustor environmental pressure. Therefore, a photochemical ignition system should have wider ignition capabilities in terms of the combustor inlet air parameters of pressure, temperature, and velocity.

New aircraft engines manufactured after 1979 will have to meet stringent emission standards. Combustors designed to meet these standards could have difficulty achieving ignition and relight capability with the standard spark igniter because of the igniter sensitivity to local fuel-air ratios. The augmentation techniques proposed are considerably less sensitive to local fuel-air ratio at light-off, and therefore may provide a practical method of maintaining more acceptable ignition and relight capabilities with the emission-controlled engines of the 1980's.

The impact of the novel augmentation techniques on combustor operating characteristics will be delineated in the proposed effort. Demonstration of feasibility and the development of realistic design criteria for the most effective augmentation approaches will be the major goals of the study.

The program direction is to demonstrate and characterize dynamic augmentation of combustion initiation, reaction kinetics and propagation rate in practical fuel-air mixtures at reactant conditions encountered in aircraft engine combustors. Although the primary technique to be investigated involves vacuum ultraviolet and ultraviolet irradiation from plasma short arc devices, other approaches such as laser irradiation, conventional spark modification and plasma torch utilization will also be considered. Passive approaches such as catalytic combustion are not included except to the extent of being used in combination with one of the techniques of interest. Particular attention will be given to those aspects of combustion such as flammability limits which represent limiting conditions on combustor operation.

In order to provide the Air Force with the desired results quickly and economically, an overlapping multiple Task program which involves comprehensive experimental and analytical assessment of the most effective augmentation techniques is being followed. Suitable vacuum ultraviolet (VUV) and ultraviolet (UV) sources will be acquired from light source manufacturing specialists and fully characterized using spectroscopic and combustion diagnostic techniques. Additional basic combustion tests will be performed to delineate source-reactant mixture interaction. Characterization of photochemical ignition at aircraft combustor conditions will be explored experimentally using a flow combustor both in a simple premixed flow mode and in a cannular combustor mode using gaseous and liquid fuels. Experimental tests of augmentation techniques other than photochemical will also be scheduled during the program. Computation techniques will be utilized to predict operational parameters in aircraft type systems.

Specific program tasks which have been identified include:

- Source Acquisition (pulsed VUV and continuous UV sources)
- Source Characterization (spectral and optical nature)
- Source/Combustion Characteristics (interaction of photon flux with reactant mixture)
- Combustor Ignition Experiments (simulated flow combustor operation)
- Alternate Techniques
- Technical and Feasibility Analysis
- Engine Test Plan

In particular, the presentation will include comments related to vacuum ultraviolet and ultraviolet source needs of the program and present an analysis which provides verification of combustion enhancement effects based on past results. These past results will also be briefly reviewed. Meeting participants who are familiar with this previous work in the photochemical area are invited to submit questions or discussion topics prior to the meeting.

COMBUSTION DYNAMIC PROCESSES ASSOCIATED WITH CHEMICAL ADVANCED LASING SYSTEMS: THE LAMINAR MIXING LAYER FOR THE COMBUSTION OF CS_2/O_2

AFOSR CONTRACT AFOSR-74-2694

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This program is concerned with several problems arising in CW chemical lasers generally, the CS_2/O_2 system being used as the particular example. Because fresh reagents must be introduced, and combustion products removed, there must necessarily be an average flow in a continuously operating chemical laser. We are studying principally those features which are implied by the term "combustion dynamics," encompassing the various macroscopic and microscopic rate processes taking place in a chemically-reactive flow system. The potential applications are primarily to high power continuously operating lasers.

The first phase of this program, spanning somewhat more than two years, was devoted to questions of chemical kinetics and combustion problems of pre-mixed flames. In addition to establishing the chemical kinetic mechanism, the work produced computations and measurements of flame speed. The results form the basis for present and future work on reacting mixing layers. To date only the low Reynolds number laminar case has been examined. It appears that many striking features may be due to the fact that the combustion processes are founded on a branching chain mechanism. The H/F_2 and H_2/F systems, for example, react according to a chain mechanism which is not intrinsically branching.

As for the hydrogen/fluorine systems, a product of combustion, in the present case carbon monoxide, is generated by a sufficiently exothermic reaction to be initially excited in vibrational/rotational states. Observations of the spontaneous emission from vibrational/rotational transitions is a relatively direct means of determining many characteristics of the mixing layer. In particular, emission spectra, which fall in the infra-red, have been used to infer the temperature field in the mixing layer; and spacial distributions of relative populations in the vibrational levels of carbon monoxide. Over much of the field, a substantial total inversion exists between the twelfth and thirteenth levels; this occurs one or two levels below the region in which a non-equilibrium distribution (but not a total inversion) was found in pre-mixed flames. Although the population inversion is unquestionably produced, our apparatus in present form is such that the associated gain is insufficient to overcome the losses, and stimulated emission in the form of laser output has not yet been observed.

The apparatus which has been used to obtain the data reported here consists of an injector containing two parallel slits, each 20 cm x 2 cm, separated by a thin splitter plate. One stream contains CS_2 and diluent; the other contains O_2 and diluent. Helium, argon and nitrogen have been used as inert diluents, giving qualitatively the same results. A few tests have been performed with O_2 added to the CS_2 and stream, or CS_2 added to the O_2 stream. The optical path is of course parallel to the face of the slits, so that the flow field examined is essentially two-dimensional.

Visual observation, and photographs, show that chemical reactions are not simply confined to a region near the plane of the splitter plate, and the visible emission exhibits very obvious asymmetries in planes normal to the axis. When the CS_2 and O_2 are initially introduced in separate streams, a tongue of bright yellowish emission extends downstream from a position near the splitter plate, but progressing into the CS_2 stream. The emission may be due to the reaction $CS+S \rightarrow CS_2$, the CS_2 being formed electronically excited. In the region within the O_2 stream, the blue emission characteristic of electronically excited SO_2 appears spread out. The region on the other side of the yellow emission is dark.

On the other band, measurements of temperature, both with thermocouples and from the emission spectra, show a field which is more nearly symmetrical about the axis. The region of maximum temperature, $2600^{o}K$-$2700^{o}K$ for the condition existing in our tests, occurs close to the plane of the splitter plate, roughly 3-5 cm downstream from the face of the injector.

The injector is mounted on a moveable table, the whole contained within a large aluminum chamber. The table can be moved vertically up and down the translated parallel to the axis. In this way the flow field may be translated while the optical axis is fixed, and spacial distributions of the emission spectra are obtained. Presently the spacial resolution is approximately 15 mm.

Owing to the relatively low signal/noise ratio, it is very difficult to measure the fundamental emission spectra. Thus, as others have done, we work with the first overtone spectra, using a lead sulfide detector placed at the exit slit of a McPherson Model 2051 monochrometer (1 meter). The data are taken on a strip chart recorder but must be processed in two important respects. First, the calibration of the optical system is applied. This accounts for the response of the optical components, the influence of the slit width, and the effects of absorption, primarily by water vapor (the first overtone spectra lie in the range 2.2-3.1 microns). Second, the spectra contain emission from both R-branch and P-branch transitions, and the overlapping of the spectra produced by the various vibrational/rotational transitions. Moreover, the fact that the R-branch exhibits a bandhead, while the P-branch does not, must be taken into account. The processing is performed by a computer program.

With the processed data the temperature is obtained from the shape of a single vibrational/rotational band, usually that for the 2-0 transition. In practice, this is found simultaneously with values of the relative populations in the vibrational levels. Thus, although the raw data show the presence of a population inversion, considerable reduction is required to verify that this is indeed the case.

Due to limitations set by our pumping facility, we have been forced to work at pressures less than 20 torr, and with flow speeds less than 6 meters/sec. The Reynolds numbers are below those required for turbulent flow.

IONIC MECHANISMS OF CARBON FORMATION IN FLAMES

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Problems associated with soot formation in jet engines will increase as "new fuels," i.e., coal, tar sand, and shale oil derived fuels, come into use. These new fuels will have higher molecular weight, will contain more aromatics, and will have a greater C/H ratio than do currently used petroleum derived fuels. These properties all increase the smoking, or soot producing tendencies of combustion systems. There is presently insufficient understanding of the basic mechanisms and processes associated with soot formation in air-breathing engines to make realistic predictions of the effect of soot formation on engine performance, heat transfer, plume structure and pollutant formation. Thus it is impossible to predict the effect of "new fuels" on Air Force missions.

It is the objective of this program, which was initiated in January, to determine the mechanism(s) of soot formation in air-breathing engines so that the effect of "new fuels" on the Air Force's mission can be predicted.

A nonequilibrium process is involved because soot is produced at a much lower equivalence ratio or carbon to hydrogen ratio, than would be expected for thermodynamically balanced reactants and products. Thermodynamics predict that all of the oxygen would be consumed in producing CO before carbon is formed. This is not the case. While numerous mechanisms have been proposed to explain the formation of carbon in flames and jet engines, the evidence for an ionic mechanism has persuaded us to pursue this idea further. This will be done by determining the effect of fuel type, pressure, flame temperature and chemical additives on both carbon and ion formation in both premixed and diffusion laboratory flames. The principal experimental tool will be a special mass spectrometer with which the ion content will be observed as the flame approaches sooting.

The critical stoichiometry at which soot is produced is a function of flame geometry and flow rate. Meker and flat flames become cellular as gas flow is decreased and soot sets in at the tip of each of the individual cells. For initial studies, an annular Meker burner is being used in which the mixture of interest is fed to the inner burner and a near stoichiometric C_3H_8/air flame is fed to the annulus surrounding the test flame to shroud it from cool ambient air and provide an ever-present ignition source.

The effect of unburned gas flow rate on the minimum fuel/air ratio for soot formation has been measured for C_2H_2, C_6H_{14} (n-hexane), C_6H_{12} (cyclo-hexane), C_6H_6 (benzene), C_7H_8 (toluene), and C_9H_{12} (isopropyl benzene) at 1 atm and, in addition, for C_2H_2, C_6H_6, and C_9H_{12} at pressures of 300, 150, and 75 Torr. Different gas velocities give rise to various peculiar flame shapes which must alter the rate of heat transfer from the flame to the burner. The actual flame temperature under any given set of conditions may very well differ significantly from that for any other condition and flame temperatures are known to have a pronounced influence (other things being presumably equal) on soot formation. Cooling due to these effects can reasonably be expected to be greatest at lower gas velocities. This may explain why lower equivalence ratios are often required at low gas velocities, i.e., the temperature in the soot nucleation zone is lowered, chain reactions are slowed and polymerization is enhanced.

In general, at the higher flow rates, the flames are better behaved in that either a single rounded cone or the familiar multi-cone Meker configuration is obtained; fluttering cellular flames are often observed at low flows. As the flames become better defined and more stable, the point at which soot is observed becomes essentially independent of total gas flow. Because this occurs over a range of high flows, it appears that under these conditions heat transfer to the burner becomes negligible and the flame temperatures attained are constant and probably approach the adiabatic value.

The critical equivalence ratio for soot formation changes very little with pressure. This is in substantial agreement with the results of McFarlane et al at pressures above 1 atm. This point will be checked in future work as an adjunct to our continuing mass spectrometric experiments.

The flames examined to date by mass spectrometry have been 200 Torr C_2H_2 and C_6H_6 air flames held at a stoichiometry just short of the onset of soot formation. Flames heavily laden with soot will inevitably clog the mass spectrometer sampling orifice but it is anticipated that a system now being built will facilitate investigation of flame zones well past the point of nucleation and into the particle growth stage. For the present, however, we have to be content with an examination of the very early stages of nucleation or ion clustering, i.e., the sampling of flames at equivalence ratios just short of that required for sooting.

The ion spectra of fuel-rich C_2H_2/air flames display a wide variety of species, many of which have not been previously observed. As the equivalence ratio is increased toward soot formation the predominant ions are at masses 39, 53, and 63 corresponding to $C_3H_3^+$, $C_4H_5^+$, and $C_5H_3^+$, respectively. These three ions remain abundant as the fuel content is further increased but higher molecular weight species become rapidly more prevalent. The heavier ions (above mass 63) appear to be separated by an average of 13 amu and the more massive the ion, the greater is its sensitivity to fuel concentration. In the richest of the flames examined, i.e., at an equivalence ratio of 2.1, just on the verge of sooting, the ion spectrum is dominated by masses 39, 53, 89, 127, and 165. Masses 39 and 53, the ions $C_3H_3^+$ and $C_3H_5^+$, are commonly observed species in a great many hydrocarbon combustion flames. Under the conditions prevalent in these experiments, mass 63 is almost certainly $C_5H_3^+$ and the ion at 165 amu is most likely $C_{13}H_9^+$.

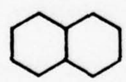
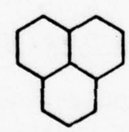
Notwithstanding the present uncertainties in ion identification at higher masses--which are being corrected by modifications to the mass spectrometer--it appears quite reasonable to postulate that the reaction

$$C_3H_3^+ + C_2H_2 \rightarrow C_5H_3^+ + H_2$$

is responsible for the formation of the ion with mass 63, and that mass 89 results from

$$C_5H_3^+ + C_2H_2 \rightarrow C_7H_5^+$$

Masses 127 and 165 (and all the other heavier masses, as well) offer more possibilities for speculation. It is interesting to note, for example, that naphthalenic and phenalenic structures, viz.,

 and ,

correspond closely to mass numbers 127 and 165 and both are characterized by electronic configurations capable of great delocalization of charge and thus the possibility of producing extremely stable ions.

The experiments are continuing.

MECHANISMS OF EXHAUST POLLUTANT AND PLUME FORMATION IN CONTINUOUS COMBUSTION (NA74-012-N)

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INTRODUCTION

The UCI investigation of exhaust pollutant and plume formation in continuous combustion is a combined analytical and experimental study of turbulent, backmixed combustion. The objectives of the UCI program are directed to clarifying the relative influence of those mechanisms responsible for pollutant production in continuous combustion.

APPROACH

The AFOSR UCI Combustion Laboratory program includes both experimental and analytical studies in a task organization structure of four elements:

- Element A: Limits of Combustion

  The evalation of backmixed zone behavior (size, velocity distribution, turbulent intensity) and emission that accompany flame instability at blowout.

- Element B: Mechanisms of Pollutant/Plume Formation

  The conduct of parametric studies (analytical and experimental) to identify the relative contribution of the chemical reactions, transport processes (heat and mass diffusion, fluid mechanics, and recirculation behavior), and system parameters (e.g. geometry, flow rates) to pollutant formation.

- Element C: Model Development and Evaluation

  The evaluation and refinement of numerical procedures and models or turbulennce by judicious comparison of numerically predicted profiles of velocity, turbulence energy, temperature, and tracer concentration to experimentally determined profiles (cold, heated, and hot flow).

  The evaluation and refinement of numerical procedures and the coupled models of turbulence and chemical kinetics by a judicious comparison of numerically predicted profiles of velocity, turbulence energy, temperature, tracer concentration, and mass fractions of hydrocarbons, nitric oxide, carbon monoxide, oxygen, and carbon dioxide to experimentally determined profiles (hot flow).

o Element D: Supplemental Studies

The conduct of studies that support the investigations of combustion stability, pollutant formation, and numerical methods, and address specialized questions current to practical backmixed combustion systems.

Lean Combustion. The evaluation of the emission characteristics of the opposed jet combustor (OJC) and the potential of utilizing the OJC in stabilizing lean combustion.

Particulate Formation/Luminosity. The investigation of (1) particulate formation in reacting flows with recirculation with special emphasis on alternative fuels, and (2) luminous flame radiation in reacting flows with recirculation with special attention to alternative fuels and impact on combustion linear degradation.

NO Probe. The exploration of chemical transformation of nitrogen oxides in sample probes and sample lines while sampling combustion products.

An opposed-reacting-jet combustor (OJC) is adapted for the present study because of the similarity to practical continuous combustion devices and the experimental versatility of the OJC. The OJC utilized a high velocity jet stream opposing the main flow as an aerodynamic flame holder. The option of a nonpremixed system is currently being installed.

The numerical procedures used to solve the governing equations for the OJC flowfield are based on an extended version of the Imperial College 3-dmensional program dubbed TEACH. In cooperation with the Environmental Protection Agency (EPA), the CRISTY method is being adapted to the UCI OJC configuration as well.

RESEARCH STATUS

During this period theoretical descriptions were applied to the opposed jet combustor (OJC). In addition to the predictive method of TEACH, the CHAMPION code was made operational and adaptation to the CHRISTY code to the OJC configuration was continued in cooperation with the EPA. Predicted profiles of chemical composition and turbulence properties were compared to experimentally determined values with emphasis on inlet and boundary condition specification and grid sensitivity. In addition, lean stabilized data were recorded to further assess the potential application of the OJC in practical combustion systems and to initiate the exploration of pollutant formation in backmixed flows. Chemical transformations that may occur in probes and lines used to sample and transport nitrogen oxides were investigated in the presence of oxygen, carbon monoxide and hydrocarbons. Pressure, residence time, and probe history are presently being addressed. Results were reported in three publications, and five technical papers.

FUNDAMENTAL COMBUSTION STUDIES RELATED TO AIR-BREATHING PROPULSION

by

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Research results will be presented on the combustion of carbonaceous particles and on theory of structures and propagation speeds of premixed turbulent flames. These studies are motivated by questions concerning combustion efficiencies and smoke emissions in airbreathing propulsion systems. The work represents a continuation of investigations reported at the previous meeting on air-breathing combustion dynamics.

Materials and apparatus described at the previous meeting were employed in studying the combustion of carbonaceous particles. Emphasis was placed on ascertaining how the hydrogen content and differing consistency cause the combustion to differ from that of pure carbon studied earlier. Experimental techniques employed involved laser ignition, high-speed cinemicrography, two-color optical pyrometry, scanning electron micrography and attempts to collect and analyze self-extinguished particles. Burning was studied in oxygen-nitrogen mixtures, usually pure oxygen, at pressures from 0.5 to 2 atmospheres and at room temperature.

The cinemicrography suggested a burning mechanism similar to that of carbon, with the exception that there appeared to be a possible tendency for gas-phase combustion to occur in addition to surface combustion. Both increases and decreases in the size of the image on the film were observed, but it was unclear whether swelling or displacement of the particle caused the increases.

The two-color optical pyrometry gave burning temperatures in the range of 2000 ^{o}K to 3000 ^{o}K, similar to the range obtained for carbon. However, the intensity-time history was less regular than that of carbon, there being typically two peaks in intensity and a linear decrease in intensity only near the end of burning. This behavior is consistent with swelling of the particle during combustion and with the occurrence of some emissions from gas-phase reactions. A filter pair in the 4000 and 5000 Å range gave lower temperatures than a pair in the 5000 and 6000 Å range, but the difference was less than the estimated error in the measurement; these results thus neither prove nor disprove that radiant emissions occur from gas-phase reactions.

Burning times were obtained from both the cinemicrographic and optical pyrometric measurements. Results were consistent with the diameter-squared law. Burning-rate constants obtained from these results were somewhat larger than burning-rate constants calculated from simplified theory for carbon particles. If corrections are made for swelling, gas-phase reactions, variable properties and particle motion, then agreement between experimental and theoretical burning times can be obtained.

Scanning electron micrographs of partially burnt material revealed the gradual development of a filament-like structure, similar to that observed for carbon. Thus, it is concluded that in many respects the burning mechanism of carbonaceous particles resembles that for carbon particles. One difference was that it was impossible to collect samples of self-extinguished carbonaceous partilces due to a tendency for the particles to disintegrate and disperse into very fine sub-particles prior to extinguishment. This may be a result of the hydrogen content of the material or merely a structural phenomenon produced by weaker inter-grain adhesion.

The turbulent combustion theory for premixed flames was based on an expansion procedure in which the nondimensional overall activation energy was treated as a large parameter and the ratio of the laminar flame thickness to the turbulence scale was treated as a small parameter. There result formulas for turbulent flame structure and turbulent flame speed in reacting flows having large-scale turbulence. The flame thickness is predicted to increase with increasing turbulence intensity, to first order in the scale ratio. To this same order there is no change in flame speed, but in second order, turbulence increases the flame speed. The formula for the turbulent flame speed v_T, shows that in the absence of upstream concentration fluctuations $v_T = v_L(1 + \delta/2)$, where v_L is the laminar flame speed and δ is the mean-square transverse gradient of the fluctuating displacement (time integral of velocity) of the approaching turbulent flow. This result differs from previously available results and agrees qualitatively with experimental results on large-scale turbulence in some respects. Upstream concentration fluctuations can further increase the flame speed.

Research sponsored under AFOSR Grant 77-3362.

CONSIDERATION OF WIDENED SPECIFICATION JET FUELS

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Since the advent of extensive jet aircraft use, operators have enjoyed the luxury of inexpensive, high quality fuel. However within the last five years, the per gallon cost of jet fuel has quadrupled. Based on current USAF consumption this price increase results in a one-billion dollar per year increase in fuel costs. Additionally, in certain geographic regions, it has been necessary to grant waivers permitting limited use of non-specification fuel. These instances foretell the future. The depleting domestic petroleum reserves, with corresponding increased dependence on imported resources, dictate that alternative sources for the production of jet fuels be developed. Coal, tar sands, and oil shale resources have been considered. In particular, USAF programs are vigorously pursuing the latter because of greater chemical similarity between the derived crude and petroleum.

It must be realized that fuels from alternate sources will not be prevalent until the next century. In the interim, considerations must be made to maximize the use of available petroleum without compromising requisite performance characteristics. Therefore, the emphasis is not on deriving a new fuel specification for a presently undeveloped resource. Rather, current and near-term programs are aimed at the impact of relaxing current fuel specifications. The results of these efforts will also indicate the degree of refining necessary to produce an acceptable fuel from an alternate source.

The overall effort to assess the effect of fuel specification relaxation is quite complex. All components of the fuel system need be considered, including the fuel tanks, pumps, filters, heat exchangers, seals, etc. Changes on combustor performance--main and afterburner--must be quantified. Personnel exposure problems (toxicology, environmental impact) must also be made. These several factors must be married with fuel availability and cost considerations in an optimization study. Note that a minimum fuel cost alone is not the goal. Rather, the minimal life cycle cost of the propulsion system is being sought.

As stated, current combustion systems will have to be assessed in considering changes in fuel properties. Minor modifications may be economically acceptable in an attempt to achieve minimal system costs. However, in the long term, future combustors must be initially designed to be compatible with an evolving fuel. Unfortunately, the understanding to predict the effect of fuel property variations on the combustion characteristics does not exist. Therefore a number of fundamental research topics are vital to effective utilization of widen specification fuels, including:

a. Improved understanding of practical hydrocarbon fuel pyrolysis leading to the ability to include gross fuel chemistry effects in combustor analytical models.

b. Development of particulate formation models which allow variations in fuel chemistry and pyrolysis processes (the results of a) in predictions of combustion zone parameters.

c. Enhanced modeling capability to include prediction of fuel effects on combustor radient loading, smoke emission, ignition and stability.

d. Inclusion of fuel effects in afterburner IR modeling.

e. Characterization of preignition and flashback as potential problems in future prevaporization/premix systems.

f. Evaluation of methods to relate combustion system data to final management information (i.e., combustor liner temperature to life, durability, and cost).

Pyrolysis of Hydrocarbon Fuels

by

Dr. W. Blazowski
Exxon

<u>ABSTRACT NOT AVAILABLE</u>

DESIGN CRITERIA FOR CATALYTIC COMBUSTORS AND OVERVIEW OF THE 2ND EPA CATALYTIC COMBUSTION WORKSHOP EPA CONTRACTS 68-02-2116 AND 68-02-2611

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A thorough understanding of the important physical phenomena occurring in a catalytic combustor is required for proper system design. The PROF-HET catalytic combustor code models all of the important physical phenomena occurring within monolithic catalytic combustors. The formulation and numerical techniques applied in the code are discussed. Code predictions are presented which show the effect of bed geometry, bed material, and initial gas conditions (i.e., preheat temperature and mass flowrate) on monolithic catalytic combustor performance. Based on these predictions, a novel catalytic combustor system design concept is suggested.

Catalytic combustion in a honeycomb monolith is a complex process which involves the interaction of several physical and chemical phenomena. Of primary importance are (1) radial heat and mass transport between the gas and wall, (2) axial heat and mass transport in the gas, (3) axial radiative and conductive wall heat transfer, (4) heterogeneous surface and homogeneous gas phase chemical kinetic reactions. The coupling of these phenomena determines bed performance in terms of maximum throughput, maximum bed temperature and fuel conversion efficiency. An efficient, yet adequate, numerical technique, which includes all of the above-mentioned phenomena, has been developed to establish how bed performance varies with bed operating and design parameters. The technique utilizes matrix procedures to solve the finite difference form of the governing differential equations. The axial distribution of both wall and bulk gas properties and wall temperature are output by the code. The solution procedure is reliable and stable for the range of input parameters utilized to date.

Code predictions indicate that (1) maximum throughput levels increase as channel diameter, bed conductivity and surface reactivity increase, (2) maximum bed temperature decreases as conductivity increases, (3) complete fuel conversion requires the activation of homogeneous gas phase reactions. These observations have significant system design implications.

Based on predictions made during this study a catalytic combustor design is suggested which utilizes a bed front end with large diameter channels and a bed back end with small diameter channels. The large front end channels permit bed operation at large throughputs while the small back end channels prevent breakthrough (i.e., poor fuel conversion efficiency). Through experimental testing, this design has been found to give good performance with methane, propane, indolene, and methanol fuels.

The Second Workshop on Catalytic Combustion was held in Raleigh, North Carolina on June 21 – 22, 1977. Forty-three people, representing various governmental, industrial, and academic organizations attended the U.S. Environmental Protection Agency-sponsored workshop. The purpose of the meeting was to provide an overall summary of the current state-of-the-art of catalytic combustion.

Emphasis was placed on the potential role of catalytic combustion in the control of NO_x emissions. For conventional combustion systems, significant amounts of thermal NO_x are produced at temperatures above 2800°F, and large fuel NO_x emissions are found in lean systems. Analytical and very limited experimental results are beginning to show that catalytic combustion systems may be able to minimize NO_x emissions in systems that operate above 2800°F and use fuels which contain large amounts of bound nitrogen.

Current work has concentrated on the use of catalytic combustors with clean, premixed, prevaporized fuels. Much of this work has focused on the gas turbine application, with other significant work having application to industrial and commercial boilers and ventless home appliances.

CATALYTIC COMBUSTOR MODELING

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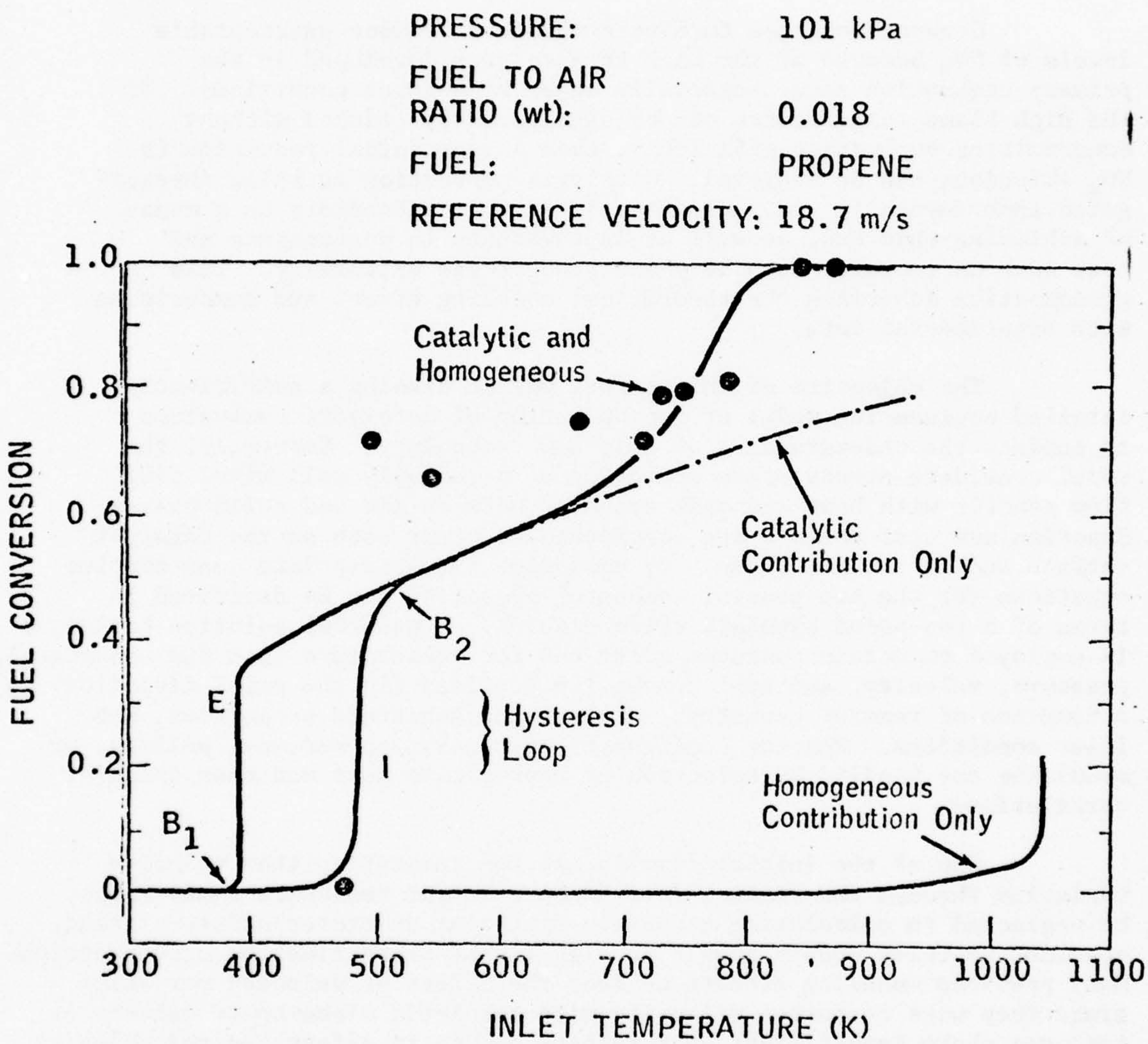
Conventional gas turbine combustors produce unacceptable levels of NO_x because of the high temperatures developed in the primary combustion zone, especially under high-power conditions. If the high flame temperatures can be significantly reduced without compromising combustion efficiency, then a substantial reduction in NO_x emissions can be achieved. Catalytic combustion is being investigated experimentally and theoretically in this laboratory as a means of achieving this end, as well as improvements in performance and cost such as improved stability and product gas uniformity. This presentation describes the theoretical modeling effort and comparisons with experimental data.

The objective of this effort was to develop a sufficiently detailed engineering model of the operation of catalytic combustors to enhance the understanding of this new technology. Currently, the model considers steady state operation of a radially well mixed plug flow reactor with heat and mass transfer between gas and solid phases. Reaction and heat release are considered to occur both on the catalyst surface and in the gas phase. By employing the appropriate conservation equations for the two phases, combustor operation can be described in terms of a two-point boundary value problem. A powerful solution technique is employed to obtain computer solutions for temperature (gas and substrate), pressure, velocity, and fuel conversion profiles (in the axial direction) as a function of reactor geometry, catalyst and substrate properties, and inlet conditions. Reactor configurations containing screens, pellets, or monoliths are handled by selection of appropriate heat and mass transfer correlations.

One of the initial results was the indication that velocity variation through the reactor (and hence reactant residence time) cannot be neglected in calculating combustor operating characteristics. Indeed, constant velocity models result in significant overestimation of conversion. Many previous modeling efforts neglect the effect of velocity variation since they were concerned primarily with catalytic clean-up of exhaust or tail gas where insufficient heat release occurs to affect the gas velocity significantly.

The effectiveness and practicality of the model were demonstrated by excellent agreement between model predictions and experimental catalytic combustion data (see attached figure). Data from catalytic combustor experiments are presented and analyzed using a simplified model indicating the phenomena of catalytic light-off, homogeneous reaction contributions and both catalytic and homogeneous hysteresis effects. Refinement and extension of our current model are in progress to provide for the inclusion of multiple fuel species, two-step reaction schemes, and internal heat removal from the catalytic section.



Experimental Data (•) and Model-Generated Curves Showing the Effect of Inlet Temperature on Conversion

NASA-LeRC Research in the Area of Catalytic Combustion for Air-Breathing Propulsion Systems

Dr. David N. Anderson, NASA-Lewis Research Center

Dr. Edward J. Mularz, NASA-Lewis Directorate, U. S. Army AVRADCOM

Cleveland, Ohio

There are currently two main research programs at Lewis investigating the use of catalysis in air-breathing propulsion systems. One such program is part of the ERDA-supported "Highway Vehicle Gas Turbine Engine Program". The other program is related to aircraft gas turbines and is entitled the "Advanced Low Emissions Catalytic Combustor Program". Each of these programs will briefly be described.

Catalytic Combustion for the HVGT

With catalytic combustion, it is possible to obtain both high combustion efficiency and ultra-low NO_x emissions at the same time. One of the studies at NASA-Lewis is the investigation of catalytic combustion for the ERDA-supported Highway Vehicle Gas Turbine Engine Program. Commercial catalysts are being evaluated to determine which may be able to operate efficiently at conditions representing those of an improved automotive gas turbine engine. Eighteen different 12-cm diameter monolithic catalyst elements have been tested in various combinations to form 26 catalytic reactors. Each reactor was tested with premixed propane fuel at an inlet fuel-air mixture temperature of 800K, and a pressure of 3×10^5 Pa.

NO_x emissions were less than 0.06 g NO_2/kg fuel for all catalysts tested. CO and unburned hydrocarbons emissions were high at low combustion temperatures, but decreased as the adiabatic combustion temperature (fuel air ratio) was raised. Emission index goals of 13.6 g CO/kg fuel and 1.64 g HC/kg fuel were achieved at a value of the adiabatic combustion temperature which depended primarily on the reactor length and the catalyst substrate cell size. This minimum combustion temperature required to achieve the emissions goals varied from 1340K to 1560 K for the 26 reactors at a reference velocity of 15 m/s. The reactor pressure drop ranged from 0.5 percent to 3.5 percent at this same velocity. Those reactors which achieved the emissions goals at low values of the adiabatic combustion temperature tended to have a relatively high pressure drop. On the other hand, reactors with low pressure drop required relatively high adiabatic combustion temperatures. This trade-off between the pressure drop and the required combustion temperature was affected in the same way by either a decrease in substrate cell size or an increase in reactor length. For example, the performance of a reactor with relatively small cells and short length could be matched in pressure drop and performance by a longer reactor with larger cells.

Although the results of steady-state tests have shown that the catalytic combustor has promise for the automotive gas turbine engine, there are a number of areas which remains to be studied. These include the effect of different fuels, and the effect of catalyst aging.

Advanced Low Emissions Catalytic Combustor Program

The purpose of this program is to evaluate the feasibility of employing catalytic combustion technology in the aircraft gas turbine engine field to achieve the control of the emissions of oxides of nitrogen for subsonic, stratospheric cruise aircraft operation. The system performance must be maintained or improved compared with current engines, and practical problems must be avoided such as system endurance and undesirable autoignition and flashback.

The program is a jointly funded effort between NASA and the Air Force and will be performed under contracts in three phases: Phase I is a study to design and analytically evaluate a number of potential combustor candidates; in Phase II, the two most promising combustor designs will undergo a series of designs, tests, design modifications, and retests in a combustor sector rig; further development and testing in either a sector or full-annular combustor rig will take place in Phase III with one or two catalytic combustor designs selected for further refinement toward aircraft application.

In the Phase I study, the following goals are established for the combustor designs: The emission goals include a NO_x emission index less that one at subsonic cruise, and pollutant emissions values sufficiently low over the EPA landing-takeoff cycle to meet the 1979 EPA standards. The performance goals include high combustion efficiency over all operating conditions and a pressure loss for the combustor system of 5% or less. In addition to these goals, combustor durability, reliability, safety considerations and complexity of design will be considered in the combustor evaluations.

Phase I is targeted for an October 1, 1977 start date. This phase will produce a detailed analysis of potential designs for gas turbine combustors using catalytic devices. Results of the studies will include recommendations either for follow-on combustor research or for further work on certain aspects of catalytic combustors before development is practical. Using these Phase I results, a decision by the government will be made whether or not to continue the program into Phases II and III.

AIR FORCE RESEARCH STUDIES AND NEEDS IN CATALYTIC COMBUSTION

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In response to the concern for aircraft gas turbine engine exhaust emissions, AFAPL initiated an investigation of catalytic combustion in 1972. This concept is based upon the alternate reaction paths available to catalyzed reactions. As applied to gas turbine engines, it permits the combustion of fuel/air mixtures leaner than the low flammability limit. Further considerations of the concept have indicated advantages in performance, component life, stability and emissions. Current AFAPL programs are in pursuit of these benefits.

The fundamental concepts motivating the application of catalysts to gas turbine engine main burners and afterburners are explained in AIAA Paper 76-46 presented at the 14th Aerospace Sciences Meeting, January 1976. The requirements of the combustor components were outlined, as were the potential problem areas and the initial data available to address them. The advantages resulting from the application of the concept were shown to be substantial. Although the interested reader would benefit from reviewing the referenced manuscript, the following summary is offered.

Structural considerations of the turbine blades currently limit the maximum turbine inlet temperature to 2500°F which, in turn, places a restriction on the overall fuel/air mixture ratio (f) of approximately $f \leq 0.028$ for JP-4 type fuels. Such compositions, however, are not within the flammability limits. Therefore, the conventional and many future combustor designs employ several zones of combustion. In each reacting zone, the air-flow is throttled to produce a local f greater than the overall value to ensure combustibility. Associated with the more fuel rich regions are higher temperatures, in some cases exceeding 4000°F. Downstream dilution zones mix in the remaining air to reduce the overall temperature to acceptable levels. The thermodynamics and fluid mechanics of such combustors lead to unsteady, skewed combustor exit temperature profiles. As well, the high temperature regions favor the formation of carbon particles, increase the radiant heat transfer to the combustor and turbine components, and produce high NO_x exhaust emissions.

The catalytic main burner, because of high chemical activity of the catalyst, can combust at the overall fuel/air mixture. A maximum combustor temperature of 2500°F occurs at the exit. Additionally, the tubular character removes the large turbulent fluctuations associated with conventional systems. Since each reactor operates independently, the inlet temperature profile is reflected directly in the exit profile. Therefore, optimal turbine inlet temperature profiles could be obtained, with a net effect of an increase in its overall value. Preliminary engine cycle calculations indicate that for a 100°F increase in this temperature, for engines of fixed thrust and size the static SFC reduces by 12%, while for engines of specified SFC the static thrust per air weight-flow increases by 3%. It is noted that due to the presence of the substrate in the reacting flow, the catalytic unit has a heat capacity 500 times greater than a conventional system, enhancing its stability characteristics. As well, the low temperature zones associated with the catalytic combustor decrease the tendency to form carbon particles, reduce the radiative heat transfer by up to 80%, and suppress NO_x exhaust emissions by two orders of magnitude.

Catalytic materials can be used in the afterburner to improve the ignitor and flameholder. The ignitor application is straightforward; the high chemical activity of these materials, if they are located in a locally controlled f, should ensure high reliability. Thus, a separate AB spark system would not be required. The catalytic flameholder acts to promote the axial rate of energy release in the AB. That is, at any given axial position, a greater portion of the chemical energy contained in the reactants has been released. A performance benefit associated with an increase in combustion efficiency ($\Delta\eta_c$) could be attained. Alternatively, because of the asymptotic nature of the energy release, a substantial length reduction would be possible while retaining current performance levels. The option of a combination of these two benefits is also available.

Either of two approaches can be taken to achieve the accelerated rate. First, if catalysts are located to promote the initial processes (fuel reforming, initial oxidation reactions, etc.) then a higher rate could be achieved. Selective catalyst-coating of conventional hardware may achieve this goal. The influence of the catalyst may, however, be confined to the boundary layer over the device. Second, if the size of the sources of the combustion (flameholder width) could be increased without increasing pressure losses, the sources would merge at shorter downstream distances, filling the AB cross-section with reaction. Thus, a greater distance remains before the AB exit to completely consume the fuel and release the energy. The use of an annular ring of honeycomb material would permit increases in flow blockages without prohibitive increases in pressure loss. The device would be coated with catalyst, substituting a catalytic initiation for the traditional fluid mechanical residence time ignition.

While the principle AFAPL programs are pursuing the application aspects of catalytic combustion, a need exists to investigate several related fundamental concerns, including:

a. products of catalyzed reactions, and their role in the total energy release;

b. transfer of the energy release controlling mechanism;

c. processes responsible for chemical, thermal, and physical degredation of catalyst systems;

d. unsteady, catalytic combustor modeling;

e. influence of liquid fuel impingement on catalytic surfaces;

f. flame stabilization in the presence of a catalyst for both bluff and porous bodies.

MECHANISM OF HIGH TEMPERATURE CATALYTIC COMBUSTION

GRANT AFOSR-76-3052

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At present, there is an insufficient understanding of the basic fluid dynamic, surface and chemical processes involved in catalytic combustion and a lack of realistic guidelines for predicting combustor and propulsion system performance, and for the solution of existing combustor difficulties. The objective of this research is to clarify the relative influence of chemical kinetics and transport processes associated with catalytic combustion phenomena encountered in advanced air-breathing combustion engines. This work will provide additional understanding and realistic analytical modeling of the reactive flow field associated with high temperature catalytic combustion, now not available, and contribute to establishing realistic guidelines and techniques for overcoming present difficulties and design criteria for efficient, stable, jet engine catalytic combustors.

Measurements will be taken of velocity, temperature, pressure and composition within a honeycomb catalyst and a boundary layer using both physical and optical techniques and varying the parameters of the experiment over their operating ranges of interest. A two dimensional model with mutiple gas and surface reactions will also be formulated and the computed results will be compared with the measured ones.

During the first year of the program, a steady combustor was designed and built with an appropriate test section. Chromatographic Gas Analysis was implemented and some preliminary data were collected.

Steady Combustor - A steady combustor was constructed and tested. It delivers up to 100 SCFM, at a maximum temperature of 1000°F and a maximum pressure of 10 atm at the test section. It consists of a reciprocating compressor, which includes particulate and oil filters; a first, low temperature, receiving tank to smooth out pressure fluctuations; a bypass valve to control the flow rate to the test section. a flow meter: three heaters in parallel whose energy input can be varied continuously to vary the test section temperature, an automatic high temperature safety shut off system; a high pressure, high temperature settling tank; a converging and fuel addition section; a mixing and turbulence control section; a test section; a water addition cooling section; a downstream valve to control the pressure; and a exhaust system. To assure steady state operation, the compressor is run continuously and excess air is bypassed away from the heaters and the test section.

Test Section - The test section for the catalytic flat plate boundary layer and the catalytic honeycomb experiments was designed and constructed. The test section houses stainless steel grids which are used to inject fuel and to control turbulence; it supports the catalyst while allowing for electrical connections to the catalyst as needed. The modular design of the test section permits changes in physical dimensions to be easily made. Both optical (laser) and physical (gas chromatography, hot wire anemometry, and thermocouples) eccess to the test section are allowed for. The first honeycomb catalyst was selected fitted into the test section and preliminary testing to establish operational procedure for the experiments are in progress. The honeycomb catalyst is pure platinum on a ceramic substrate. It was made available by Engelhard Ind.

Gas Composition Measurements - An expansion quenched, water cooled, stainless steel gas sampling probe was designed and constructed for use with a Hewlett-Packard Model 5830 gas chromatograph. In the honeycomb experiment, the gas temperature and concentration measurements along the length of the honeycomb are made by inserting a thermocouple probe and a gas sampling probe into a drilled out channel (from the back of the honeycomb) of progressively lengthened depth. The channel only covers a small portion of the cross section, thus keeping the bulk of the honeycomb temperature constant. One thus determines the gaseous species produced by the catalyst as a function of the catalyst length (or residence time within the catalyst). The measured composition at the exit plane identifies the extent of the catalytically induced reactions. The downstream, gas phase measurements identify the species by, the mechanism of, and the limit within which catalysts (of various lengths but fixed temperatures) act as an igniter of homogeneous reactions.

CONTRIBUTIONS OF SURFACE CATALYSIS AND GAS PHASE REACTION TO CATALYTIC COMBUSTOR PERFORMANCE

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Catalytic monolith combustors are being considered in the development of advanced air-breathing engines. Currently the stability and efficiency of such combustors are limited by blow-off at high power and extinction at idle. The objective of the research is to assess the relative contributions of surface catalysis and gas phase reaction to catalytic combustor performance by a mathematical model of the reactive flow through a catalytic monolith. The model will assist in optimizing catalyst kinetic properties, catalyst placement in the monolith, and flow geometric factors for extending the operating range of catalytic combustors.

In the first phase of the research, the theoretical temperature distribution on the monolith duct wall has been found from a model that takes account of heat conduction in the wall, heat transfer to the stream, and heat generation and fuel consumption by the catalyzed reaction. For simplicity, the heat transfer is described by uniform parameters, and the two limiting conditions of infinitely fast catalyzed reaction on a heat conducting wall or finite reaction rate on a monconducting wall are analyzed.

In the case of the conducting wall the location and magnitude of the maximum temperature depends on the Lewis and Peclet members. The wall temperature increases monotonically down the duct if the Lewis number is greater than one. The temperature has a maximum that can be nearly the adiabatic catalyzed reaction flame temperature and can be near the duct entry for appropriate values of Peclet number and Lewis member less than one.

The temperatures reached in the case of finite catalyzed reaction rate on a nonconducting wall are determined by the duct entry gas temperature, the Damkohler number, and the activation energy for the wall reaction. The wall temperature is found to increase down the duct in almost all cases. The increase is contINOUS for low entry gas temperatures, but for higher entry temperatures shows jumps from the low values of kinetically controlled catalyzed reaction at the wall to the high values of diffusion controlled reaction.

AFOSR-76-2936

FLAME EFFICIENCY, STABILIZATION AND PERFORMANCE IN PREVAPORIZING/PREMIXING COMBUSTORS

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Advanced combustor concepts involving fuel prevaporization and premixing upstream of the flame stabilization zone are considered. Applications include automotive, catalytic, ramjet, as well as aircraft propulsion systems. However, problems of poor combustion efficiency, upstream flame propagation, lean blowoff and incomplete prevaporization and premixing must be overcome. The Purdue program which is currently in its second year considers these problems using a simplified sudden expansion combustor, a compromise between the disc flameholder, which has been studied extensively by Tuttle et al. (1977) for EPA, and the dump ramjet burner of Stull et al. (1974). Flame stabilization occurs via a bluff body recirculation zone characteristic of ramjet and turbojet afterburners.

During the current grant period, combustion efficiency and lean blowoff limits were measured using five different geometries, two fuels (Jet A and liquid propane) and several fuel injectors over a wide range of burner inlet conditions typical of modern continuous combustion systems. A comparison of the results from these two fuels should identify any important heterogeneous effects since liquid C_3H_8 flash vaporizes under these inlet conditions whereas Jet A is not expected to completely vaporize in the fuel preparation tube.

Conventional correlating parameters (air loading parameters) examined using these data are unable to collapse geometry, equivalence ratio and heterogeneous effects. Therefore, a characteristic time approach (Mellor, 1976a) which has proven successful in correlating and predicting CO and NO_x emissions in both simplified (Tuttle et al., 1977) and conventional combustors (Mellor, 1976 b,c; Hammond, 1976) is considered. The characteristic time model separates the combustion process into three subprocesses involving heterogeneous, chemical and fluid mechanic effects, each characterized by an appropriate time scale. For lean blowoff the important times are: 1) the fuel droplet evaporation time (τ_{eb}), 2) the fuel ignition delay time (τ_{hc}) and 3) the shear layer mixing time (τ_{sl}). τ_{eb} will be important only when complete prevaporization has not been achieved in the fuel preparation tube. The characteristic time correlation for lean blowoff is based on the theory of Zukoski and Marble (1956) but modified to include heterogeneous effects:

$$\tau_{sl} = \tau_{hc} + a\tau_{eb}$$

where

$$\tau_{sl} = L/V$$

$$\tau_{hc} = e^{E/RT}$$

and

L = length scale

V = air velocity

T = adiabatic flame temperature at the blowoff equivalence ratio

R = universal gas constant

τ_{eb} = droplet evaporation time calculated from "d^2" law

a,E = empirically determined constants = .059 msec, 12500 cal /mole respectively.

The model includes pressure, temperature, velocity, fuel and injector variations; however, geometry effects have not been completely determined at the present time (See Fig. 1). The characteristic time model for combustion efficiency also exhibits similar trends.

Three mechanisms of upstream flame stabilization have been identified from a review (Plee and Mellor, 1977) of current literature: 1) classical flashback (Fig. 2A), 2) flame propagation through reversed flow fields (Fig. 2B) and 3) pre-ignition of separated flow regions (Fig. 2C). The latter two resemble classical flashback in appearance; however, closer examination indicates that they are induced by flow disturbances such as steps, diverging sections, surface discontinuities, etc. and even methods of fuel injection. To date classical flashback has not been observed in non-catalytic combustors burning liquid jet fuels or propane. Instead, upstream combustion as a result of mechanisms (2), (3), and autoignition of the main air stream are responsible for much of the reported flashback in the literature. Only catalytic combustors appear capable of experiencing classical flashback because reference velocities are extremely low.

Using the simplified prevaporizing/premixing combustor, an attempt was made to induce classical flashback. Results are consistent with the literature and indicate that classical flashback is not a problem in non-catalytic combustors utilizing straight cylindrical fuel preparation tubes.

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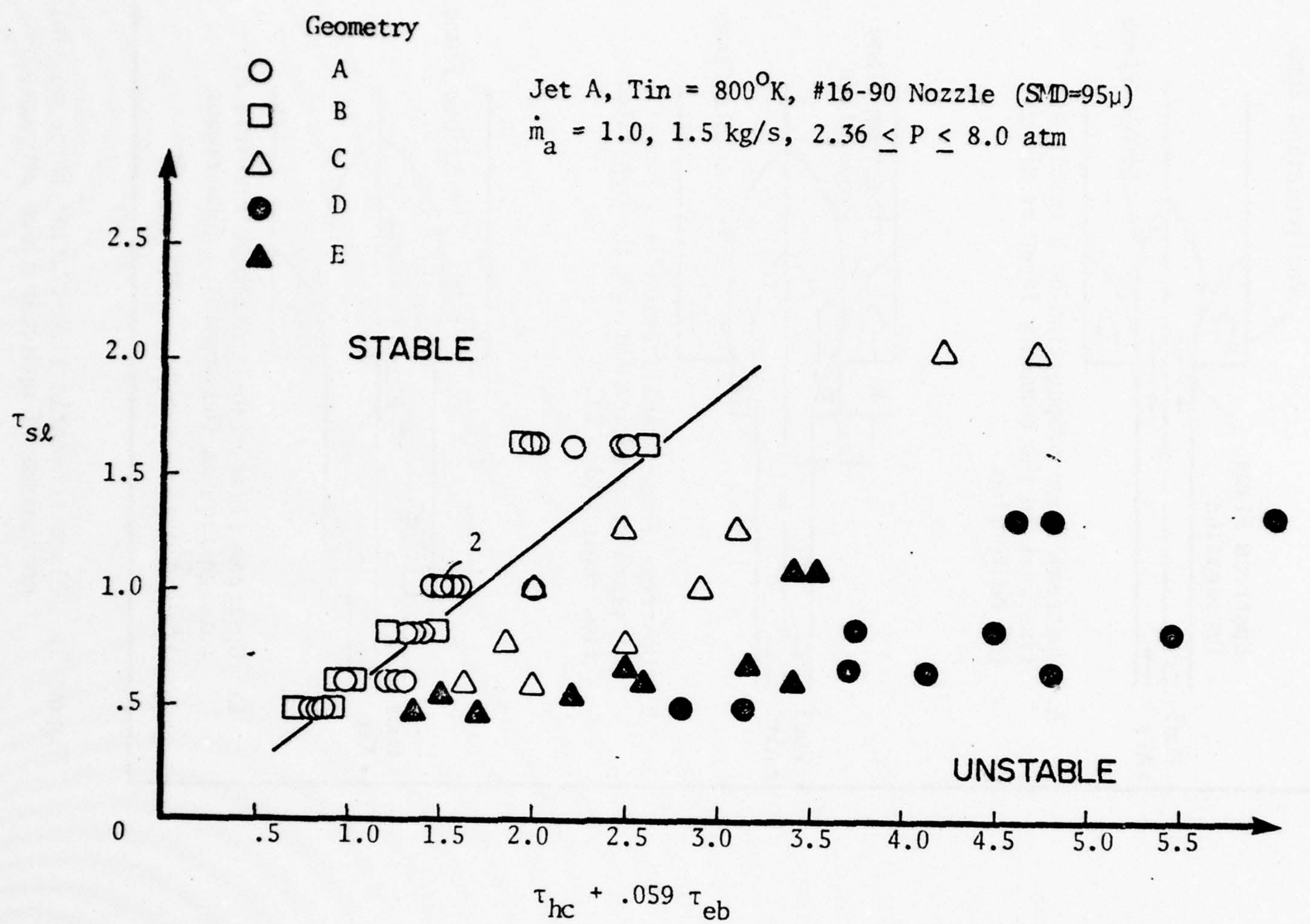
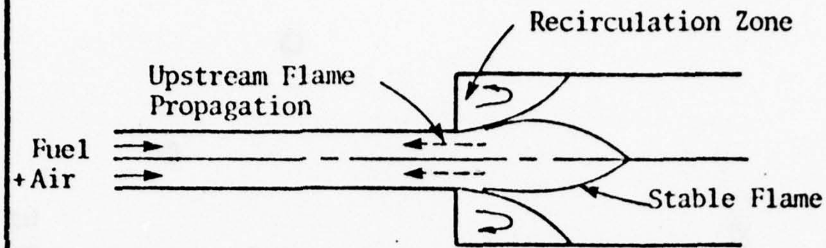
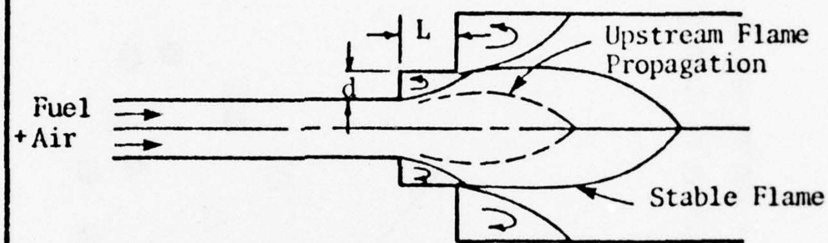


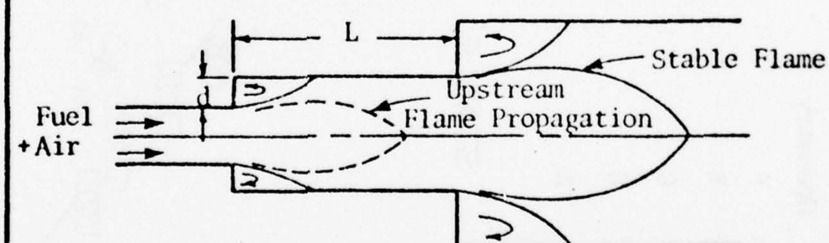
Figure 1. Characteristic time correlation for blowoff (Jet A, all geometry variations).



A. Upstream flame propagation as a result of flashback in the boundary layer or along the centerline.



B. Upstream flame stabilization as a result of flame propagation through the separated flow region (d $\sim$ L).



C. Upstream flame stabilization as a result of autoignition in the separated flow region (d << L).

Figure 2. Flame schematic illustrating three possible mechanisms of upstream flame propagation.

Air Force Supported Research Development Trends and Needs in Aircraft Fire and Explosion

by

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AFAPL (In-House)

ABSTRACT NOT AVAILABLE

AIRCRAFT FIRES IN FLIGHT (AFAPL CONTRACTS)

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Over the past decade, combat experience proved that even the most modern high-performance aircraft were vulnerable to conventional anti-aircraft weapons, and that fuel fires and explosions were prevalent kill mechanisms. The Air Force Aero Propulsion Laboratory (AFAPL/SFH) implemented a series of in-house and contracted programs to: 1) define the problem of combat threat-induced aircraft fuel fires and explosions, and 2) to evaluate various aircraft passive defense measures.

We at Falcon R&D have participated through three contracted efforts. Our initial effort was to develop a computerized aircraft vulnerability analysis program which integrated threat effects and flammability subroutines into tri-service coordinated vulnerability programs. The model was constructed to allow convenient updating as more data became available.

Two particularly important areas where data were lacking were pre-impact flammability of aircraft fuel tank ullage and the mechanisms of fire initiation and sustainment in void spaces adjacent to damaged aircraft fuel tanks. We will present the approach to these two problems and progress to date.

The first program consists of the design, construction and checkout of an aircraft fuel tank simulator for fire and explosion vulnerability assessment. We are supported by a subcontractor, Systems Research Laboratories, Inc., Dayton, Ohio, who is responsible for a major part of the detail design and construction work. We are in the 15th month of a 27-month program. The detail design is virtually complete.

There are several features of this simulator which make it uniquely suited for generating and studying realistic aircraft fuel tank ullage environments. These are:

1. Simultaneous simulation in full-scale and real-time of the effects of mission and aircraft subsystem dynamics on the tank fluids. These include pressure and temperature variation (-40°F to +300°F) of fuel and vent air entering and leaving the tank, independent control of the temperatures of the six walls of the tank, and time rates of change of wall temperature as high as 10°F per minute.

A 20,000 pound capacity simultaneous slosh and vibration table is used to agitate the tank and liquid fuel to simulate the effects of nominal and extreme aircraft vibration and maneuvers. The test tank is 4 by 6 feet in the plan view and is 3 feet high. It is provided with a horizontal baffle which can be relocated to simulate wing fuel tanks of various depths.

2. The capability to ignite the flammable ullage vapors at any time without damage to the explosion-proof test tank. Also, fire extinguishing is provided within the tank, within a bounded region surrounding the tank and in the test bay.

3. The use of five independent, hydraulically-driven, vertically-translating ullage gas sampling probes and an on-line, high-speed quadrupole mass spectrometer to obtain fuel/oxygen ratio readings within the ullage. The design goal is for a maximum sampling/reading rate of 30 or more per minute. Viewing ports are also provided for television and movie cameras. Conventional pressure and temperature transducers are also provided.

4. Automatic, remote simulator operation and data acquisition for the entire system. Supporting computer software is also planned for preparing the operating instructions for the on-line control computer and for reducing the large quantity of data into a readily interpreted format.

This integrated "simulated aircraft fuels environment" (SAFE) system will accurately duplicate the boundary conditions and phenomena for actual or hypothetical aircraft, missions, and fuel system operating conditions.

The second program is a study of the initiation, sustainment, and extinction of fires in void spaces adjacent to a damaged aircraft fuel tank under the influence of the slipstream. Prior test programs consisted of firing projectiles into replica aircraft fuel tanks with airflow directed over the external region of damage. Inconsistent results were often obtained under identical test conditions.

Hence, the approach of this study is to perform fire tests with more precisely controllable conditions and higher resolution instrumentation. By this means, the many variables affecting aircraft void space fires can be isolated and individually investigated.

To obtain test control and a high rate of testing, the following simulations are used:

1. The slipstream boundary layer thickness, its velocity profile, and pressure coefficient (c_p) are simulated full-scale with a closed-circuit duct/blower system.

2. The terminal effects of the U. S. 0.50-caliber Armor-Piercing Incendiary (API) Type M-8 are simulated by an incendiary device developed by AFAPL and by a modified Ballistic Research Laboratories fuel spray simulator which simulates both the fuel spray generated

by a projectile penetrating a fuel tank and the subsequent leaking fuel stream.

3. The void space representing the interior of the aircraft between its skin and the fuel tank wall is simulated full scale and is variable in spacing from 2 to 12 inches. Internal air circulation within the aircraft is simulated by a blower and open duct system.

A crucial aspect of this program is the precise determination of steady-state airflow conditions in the simulated slipstream, the void space, and in the region of the bullet hole in the skin prior to introducing the incendiary material and the fuel. Another important feature has been viewing the combustion phenomena with high-speed movie cameras simultaneously from above and from the side.

The effort to date has consisted of constructing a sustained and flash fire "envelope" for the most significant test variables. A "flash" fire is considered a transient effect which does not normally lead to loss of the aircraft, whereas a "sustained" fire is essentially an aircraft "kill".

This program also includes the parallel development of an "External Fire Model" which will be added as a subroutine to the aircraft vulnerability program previously mentioned. Professor William Sirignano of Princeton University has developed the basic flash fire model and is presently extending it to sustained fire conditions for fuel pools and streams. For his sample problems, he has used input values closely matching the test apparatus and conditions.

The test program has been extended to include simulated damage and thermal effects of an antiaircraft laser weapon in lieu of incendiary bullets. The tests are similar, except that the incendiary and spray simulations of the projectile are replaced by pyrotechnic devices which generate holes and hot edges in the aluminum simulated aircraft skin and the tank wall.

The latter tests will yield a better understanding of sustained fires in aircraft void spaces with laser effects and provide for a direct comparison of laser and projectile-initiated fires.

Both the fuel tank simulator and the study of external fuel fires could greatly benefit from basic research programs. For example, more definitive fuel spray models are needed which relate to bullets or fragments passing through a tank wall or entering or leaving the liquid fuel surface within the tank. The interactions of such sprays with projectile impact flashes also need to be better understood. In situ methods of measuring hydrocarbon vapor/air concentrations within test tank ullage are necessary, as well as methods to monitor the combustion process which are compatible with the fuel simulator and void space fire test apparatus.

MULTIPLE IGNITION, COMBUSTION, AND QUENCHING OF HYDROCARBON FUEL SPRAYS (AFOSR 76-3041)

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Ignition of combustible fuel-air mixtures by burning metal particles presents a fire hazard. Aircraft fires can be started in this way when projectiles penetrate fuel tanks [1]. Fuel spraying through the punctures into the dry bay or splashing into the ullage yields a combustible mixture; the burning metal particles are abraded from the aircraft structure or originate from projectiles with metallized explosives. Similar fire hazards exist in rooms with combustible environments and in mines where electrical equipment or abrasion can supply burning metal particles [2,3]. The physical situation relevant to aircraft involves a cloud of hot and burning metal particles passing through a mixture of fuel vapor, fuel droplets, and air near damaged fuel tanks. This investigation is the first step toward understanding how to minimize the fire hazard for this situation. Metal particles formed by abrasion have little initial oxide coating, so ignition criteria for these particles in air should be determined. Also, the criteria for ignition of combustible gases by hot and burning metal particles should be determined. The important variables governing ignition are particle size and type, fuel/air mixture ratio, pressure, and initial particle temperature. It is planned to determine experimentally the envelope of these variables, in which the combustible gas ignites, and to predict theoretically this envelope.

The objective of the first experiments will be to determine the minimum size of burning aluminum particles needed to ignite CH_4/Air mixtures. (Future experiments will involve other hydrocarbons and other metals.) An aluminum particle, about 100 μm in diameter, will be suspended on a glass filament in a methane/air mixture. The mixture will be in a closed vessel with Plexiglas windows so the metal particle can be ignited by a pulse from a Nd:Glass laser. Measurements will determine the timing and order of events that follow the laser pulse. A Sundstrand Model 601B quartz pressure transducer will be flush-mounted in the wall of the vessel and protected from high temperature by a film of silicone grease. An oscilloscope will be used to record the pressure versus time in the vessel. The record will show if the CH_4/Air mixture is ignited by the aluminum particle. Band emission of radiation from aluminum combustion can probably be recorded to determine when and if the metal particle burns. Experimental variables will be the initial gas pressure, between 7 kPa and 140 kPa, and the CH_4/Air ratio, greater than and less than stoichiometric, initially at room temperature. It is planned to compare these experimental results to theoretical predictions of the minimum initial size of burning aluminum particles needed to ignite CH_4/Air mixtures.

In development of theory, the initial effort involves a constant temperature, inert, sphere surrounded by combustible gas. (Future developments will include the chemical reactions on the metal particle surface and a vapor-phase metal-oxygen diffusion flame around the particle.) A steady-state solution is being sought for temperature and species concentration in the combustible gas. To avoid the problem of a non-zero reaction rate at large distances from the inert sphere, the reaction rate is set to zero for temperatures less than a prescribed "ignition" temperature. The critical sphere temperature (above which ignition occurs) is being sought. It is the maximum temperature for which a steady-state solution still exists and will probably be a function of sphere diameter. This problem is similar to work by Sharma and Sirignano [4] who investigated ignition of a combustible gas by a moving inert projectile. Criteria were derived for the existence of an established flame around the projectile; in the present work, criteria will be derived for ignition around stationary praticles. The energy and species equations that define this problem are:

$$\rho\alpha \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \frac{\partial}{\partial r} \left(\frac{C_p T}{Q}\right)\right] = \dot{m}_{FO} + \rho \frac{\partial}{\partial t} \left(\frac{C_p T}{Q}\right)$$

$$\rho D \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \frac{\partial}{\partial r} (Y_{FO})\right] = -\dot{m}_{FO} + \rho \frac{\partial}{\partial t} (Y_{FO})$$

$$\dot{m}_{FO} = - (\rho\ Y_{FO})^2\ Z \exp(-E/RT)$$

where fuel and oxidizer are in stoichiometric proportion. Y_{FO} is the mass fraction of fuel and oxidizer treated as one. Q is the enthalpy of reaction per unit mass of fuel and oxidizer. For the steady-state problem the derivatives with respect to time are zero, but future developments will include these derivatives in a non-stationary analysis of ignition. These analyses are expected to show that smaller particles must be at higher temperatures to ignite the combustible gas and thus that there is a minimum particle size needed for ignition. They may also show that the total amount of heat supplied by the particle prior to ignition is more important than particle size or temperature. These trends would be in agreement with experimental data of

Bowden and Lewis [2] who found that the minimum particle masses needed for ignition of a CH_4/Air mixture were lower for metals with higher heats of combustion.

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IGNITION OF A LIQUID FUEL UNDER HIGH INTENSITY RADIATION*

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Laser technology has been rapidly advancing in the last two decades. Power outputs of modern lasers increased significantly and these lasers can be used as tactical weapons. A high power laser weapon can ignite aircraft fuel through fuel tank penetration causing fire or explosion of the aircraft. However, there is little basic information available about the ignition of flammable liquids by high intensity radiation. The objective of this study is to obtain a fundamental understanding of physical and chemical mechanisms of the ignition of liquid fuels under high intensity radiation, thus, enabling future improvements in aircraft survivability from fire and explosion threats.

The program consists of an experimental study to clarify the key mechanisms of ignition, and of a theoretical study to predict the qualitative effects of physical and chemical parameters on ignition of flammable liquids under high intensity radiation. Since the radiative ignition mechanism of flammable liquids is hardly known, the theoretical study is deferred until the key ignition process is confirmed from the experimental study.

The program was started in May 1977 and we have some experimental results to report. Auto ignition experiments were conducted using a CO_2 laser and n-decane as the flammable liquid. At present, the laser beam hits the n-decane surface vertically. The effect of the size of a liquid container on ignition delay time was studied. Results indicate that there are no significant effects of diameter and depth of the liquid container on ignition delay time except for extremely shallow or small diameter containers. The effects of incident radiant flux on ignition dealy time have been studied from about 6000 W/cm^2 to below 1000 W/cm^2. Above 4000 W/cm^2, ignition delay time decreases gradually with increase in flux from approximately 70 msec to 50 msec. However, below 2000 W/cm^2, it increases strongly with decrease in flux up to about 1 second.

High speed motion pictures show the onset of flaming in the gas phase far above the decane surface. After ignition, the flame spreads rapidly toward the surface and a narrow column of flame was observed. However, this colum did not stabalize. Its bottom part started to disappear upward. Then, reignition was observed

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near the decane surface and the column of flame started to grow upward. This oscillating flame after ignition can be explained as follows: vaporized decane from the surface is ignited by the absorption of the incident laser beam. Then, the long column of flame absorbs more incident radiation so that the energy into the liquid is reduced. This reduces the amount of vapor and the laser part of the flame column extinguishes due to the consumption of the fuel vapor. The reduction in flame size reduces the absorption of the incident beam and increases energy into the liquid. This increases the amount of decane vapor and again ignition occurs in the gas phase. Apparently, this process repeats and causes flame oscillation as observed by the high speed movie. Therefore, one of the important mechanisms for radiative ignition of decane is interaction of the vapor plume with the incident laser beam.

The future plan of the program is: (a) to measure the absorption coefficient and total surface reflectance of liquid n-decane at the laser wavelength of 10.6 μ. The total surface reflectance will be measured under various incident beam angles to the liquid surface by using the technique of ellipsoidal mirror reflectometer; (b) to find the effects of laser incident beam angles to the liquid surface on ignition delay time under various radiant fluxes; (c) to measure the amount of absorption in the vapor phase during the ignition period; (d) to investigate the relative feasibility of several measurement techniques to determine gas phase temperature and the concentration of vaporized decane during the ignition period; (e) to develop and calculate a one-dimensional ignition model including absorption of the incident beam in the vapor phase.

AFOSR-77-3446

IGNITION OF FUEL SPRAYS BY HOT SURFACES AND STABILIZATION OF AIRCRAFT FIRES

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This new research program is concerned with two general topics related to aircraft fire safety: (1) the ignition of fuel sprays by hot surfaces, and (2) the stabilization of both external and internal aircraft fires. The ignition of fuel sprays by hot surfaces may occur when a combustible liquid spray (fuel or hydraulic fluid, for example) caused by accidental or combat damage comes into contact with hot surfaces such as engine parts or surfaces heated by fires or other sources. The spray is dispersed in an airflow and may occur over a range of spray conditions including various droplet sizes, fraction vaporized, etc., with varying fuel/air mixture conditions, and with a range of airflow properties. It is necessary to obtain a better understanding of such ignition phenomena to enable assessment of aircraft fire hazards under those conditions. The second general topic, that of stabilization of aircraft fires, addresses two types of situations. The first is the stabilization of external fires arising from external fuel leakage caused by accidental or combat damage to fuel tanks, etc. External fires may be stabilized by structural protrusions created by the source of the damage, regions of separated flow on other parts of the airframe, or by jets of fuel penetrating into the airflow from ruptured, pressurized fuel systems. Fires within the airframe may also arise in void spaces as may be present between fuel tanks and the external airframe structure, for example. The occurrence and stabilization of fires in these confined spaces depends on the nature and extent of ventilation of the void spaces both from damage to the external airframe and from the normal internal ventilation of the spaces, and also on the nature and extent of the fuel injection into the void space. Both of these flame stabilization problems must be better understood to assess the vulnerability and survivability of aircraft subject to such hazards.

It is convenient for the purposes of discussion to divide the research into three separate Phases.

Phase I. Ignition of Fuel Sprays by Hot Surfaces

Phase II. Stabilization of External Fires

Phase III. Stabilization of Void Space Fires

Experimental data are to be obtained and appropriate theoretical models are to be developed for the ignition of fuel sprays by hot surfaces in Phase I. The effects of the properties of the fuel spray, the airflow, and the surface on the ignition phenomena will be investigated in that Phase. Phase II is concerned with the extension of experimental [illegible] stabilization data to large-scale flameholders of double- and s[illegible]-vortex types, evaluation of the applicability of existing stability correlations to the larger scale devices, and improvement of theoretical understanding of the phenomena. Both types of flameholding geometries are likely to occur in aircraft fire situations and extension of the data to scales larger than those previously investigated is essential to account for actual sizes of possible flameholding objects present in areas of structural damage, for example. The investigations of Phase II will be extended to other pertinent aspects of flame stabilization such as injection of fuel into the upstream boundary layer on the surface of a solid flameholder, for example. In Phase III, the possible stabilization of void space fires and related external fires under various conditions of ventilation and fuel injection are to be investigated experimentally and theoretical models for the flow conditions and flame stability are to be developed. The three Phases of the proposed research are to be conducted concurrently, with varying topical emphasis from year to year.

Ignition, Combustion, Detonation and Quenching of Combustible Mixtures

by

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ABSTRACT NOT AVAILABLE

BASIC INSTABILITY MECHANISMS IN CHEMICALLY REACTING SUBSONIC AND SUPERSONIC FLOWS

(Grant AFOSR - 74 - 2619)

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ABSTRACT

This research on instability mechanisms involved in the mutual influence among sound, entropy, and vorticity modes in chemically reacting sobsonic and supersonic flows will aid in the design and development of practical combustors for advanced air-breathing and hybrid engines, for MHD generators and chemical lasers. Further, it will also provide the fundamental information needed to solve many practical problems related to noise pollution and unconfined explosions.

The effect of chemical kinetics on high-frequency sound waves has been studied earlier in this program. The propagaiton of acoustic waves in the frequency range 300-900 Hz in a non-equilibrium hydrogen-chlorine reacting mixture was examined in a 5.5 m - long, 8 cm - diameter pyrex tube. The photochemical reaction between hydrogen and chlorine was initiated by ultraviolet radiation incident onto the premixed, homogeneous reactive mixture. The overall reaction was measured by monitoring the quantity of ultraviolet light absorbed by molecular chlorine, and the mean temperature of the gas by means of a tungsten-wire resistance thermometer. The high-frequency sound waves were generated at one end of the tube, by means of a piston-shaker arrangement, in the form of a 2-cycle burst of a given frequency, and monitored by means of several microphones placed along the tube.

In order to account for the effects due to both the frequency of sound and the reaction rate, a parameter Ω has been defined as the ratio of chemical time (the time required to consume the initial chlorine concentration at a constant reaction rate identical to the initial reaction rate) to the characteristic acoustic time (the reciprocal of the acoustic frequency). Hence, the parameter Ω plays the role of a normalized acoustic frequency. At large values of Ω (about 1000), corresponding to high-frequency sound and/or slow reaction rates, the measured amplification rates agree with the theoretical predictions for the quasi-steady regime. In this regime it was found that the instantaneous rate of sound pressure amplification depends on the instantaneous experimental value of the expression

$$\frac{1}{2\gamma T_o(t)} \frac{dT_o(t)}{dt} \left\{ m + \frac{\beta(\gamma-1)}{T_o(t)/T_{o,in}} + \frac{\gamma}{2} \right\}$$

where m and β are the order of reaction and the reduced activation energy,respectively.

The objective of the recent study is to examine the chemical effect at lower values of Ω. For this purpose, the acoustic frequencies were decreased to their lowest accessible values, while the reaction rates were enhanced by using richer mixtures. However, due to the poor performance of the piston-shaker system at low frequencies, it was decided to conduct the experiments, using standing waves rather than sound bursts.

In the new experimental procedure, the piston-shaker is used to establish first a standing wave in the reaction tube with the selected frequency. Once the wave achieves its maximum amplitude, the piston-shaker is turned off, and the reaction initiated. The behavior of the resulting wave is then monitored by microphones and compared with that in a non-reacting mixture.

At high values of Ω, the measured amplification rates agree also with the theoretical predictions for the quasi-steady regime; a result which demonstrates that the acoustic-kinetic coupling is essentially the same for a travelling wave (sound burst) and a standing wave (two oppositely travelling waves) at the same frequency and mixture composition. The measured amplification rates are also found to be independent of the initial sound pressure level of the standing waves, thus confirming the linear approximation employed in the theoretical predictions.

On the other hand, for lower frequencies (Ω = 300), the measured amplification rates are much higher than those predicted and measured for the high-frequency regime. Typical experimental values of the amplification rates at lower frequencies are 4 times as large as those at high frequencies.

In the course of the theoretical study, the full chemical-kinetic scheme for the hydrogen-chlorine-argon-oxygen system has been examined with the objective of verifying the approximation of the reaction rate by an Arrhenius expression. A rate expression, similar but not identical to an Arrhenius expression, is found to be valid beyond the induction period. The stability of this reaction was also examined. Although the scheme does not possess the chain-branching character necessary for chemical explosions, it may undergo thermal explosions where heat plays the role of an autocatalytic product, as was observed during the experimental work.

Currently,the study of nonlinear wave-kinetic interactions is being undertaken. A shock-generating system is being used to produce planer weak shock waves of different strengths and widths at one end of the reaction tube. The travelling waves are to be monitored by sensitive pressure transducers, and the reaction histories by a resistance thermometer and a photomultiplier. The main effort will be devoted to identifying the nonlinear effects by a critical comparison of results obtained in the nonlinear and the linear region. In particular, wave amplification and dispersion are to be examined for shock waves of different initial strengths and widths (time durations), and for reacting mixtures of different compositions and pressures. On the basis of the features identified in the experimental study, a theory will be formulated. Such theoretical analysis would shed light on the detailed features of the nonlinear effects. The findings of this nonlinear study will help in understanding the mechanism of initiation of explosions, and consequently, their suppression.

State-of-the-Art of Combustion Diagnostics and Future Requirements

by

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ABSTRACT NOT AVAILABLE

DIAGNOSTIC ASSESSMENT FOR AIR-BREATHING PROPULSION SYSTEMS

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Diagnostic techniques for the determination of particulate size distribution, particulate mass loading density, gas velocity, gas temperature and species concentration are discussed. The application of these techniques to air-breathing propulsion systems is described with particular emphasis on limitations resulting from burning coal-derived fuels.

REVIEW OF LASER RAMAN AND FLUORESCENCE TECHNIQUES FOR PRACTICAL COMBUSTION DIAGNOSTICS

EPA Contract 68-02-2176

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With the advent of laser light sources, light scattering spectroscopic diagnostic techniques are assuming an ever-increasing role in a broad spectrum of physical investigations. Of particular importance is the potential application of laser spectroscopy to the hostile, yet sensitive, environments characteristic of those in which combustion occurs. These diagnostic techniques should facilitate greatly improved understanding of a variety of combustion processes which, in turn, should lead to enhanced efficiencies and cleanliness in energy, propulsion and waste disposal systems.

Under Contract 68-02-2176 sponsored by the Environmental Protection Agency, the United Technologies Research Center (UTRC) is conducting an analytical and experimental investigation aimed at developing non-perturbing, spatially precise, in-situ diagnostic techniques to measure species concentrations and temperature in practical combustion flames, i.e., luminous, particle-laden, turbulent. Under Task I, a comprehensive review has been conducted, which will be described, of potential, nonintrusive laser light scattering techniques for thermometry and chemical composition measurements in hostile combustion environments such as furnaces. Under Task II, laboratory investigations of the more promising diagnostic techniques will be conducted.

In the Task I review, various laser diagnostic techniques potentially suitable for "point" temperature and species concentration measurements in flames were reviewed. From this list, four techniques were selected for detailed evaluation including: (1) spontaneous Raman scattering, (2) near-resonant Raman scattering, (3) laser fluorescence and (4) coherent anti-Stokes Raman scattering (CARS). The spectroscopy of species of combustion interest was discussed and the applicability of the foregoing techniques to detection of the various species was examined. Practical device considerations were reviewed with emphasis on sources of noise (e.g., luminosity, particulates), medium perturbations, laser and signal transmission, and signal averaging in temporally fluctuating media. Each diagnostic technique was then addressed in some detail in the order previously stated. Basic physics, species sensitivity, thermometry applicability, signal to interference ratios, problem areas, and new variations of the techniques were included in these treatments. Measurement systems approaches were described together with approximate cost estimates, probability of success assessments and risk assignments. An integrated measurement system was described.

On the basis of the foregoing studies, the following general conclusions were drawn:

(1) For most species of combustion interest, at least one of the diagnostic techniques investigated is applicable for point measurements of that constituent. The lone exception is the N atom which would have to be probed using either a lamp source absorption of fluorescence technique. Of course, depending upon which technique is relevant, sensitivity limits may vary widely, e.g., CARS is much less sensitive than saturated laser fluorescence.

(2) Practical combustion devices contain flames which are very hostile from an instrumentation viewpoint. High levels of spurious radiations, either naturally occurring or laser induced, must be overcome by the signal of interest. These effects, rather than shot noise, are generally the major determinants of signal/background ratios. A host of other practical problems, e.g., gas breakdown, window damage, large distances to the measurement location, must also be confronted. Temporal fluctuations may well preclude signal averaging approaches to enhance signal/noise ratios. These effects should be closely examined in each measurement situation <u>before</u> a given measurement approach is adopted.

(3) Spontaneous and near-resonance Raman scattering appear generally incapable of probing practical flames over a <u>broad</u>

range of operating conditions. Application to exhausts and secondary combustion regions may be possible if particulate levels are not too high. For primary zone diagnostics, thermometry and major species concentration measurements appear problematical even with advanced state-of-the-art laser sources. Trace species concentration measurements are definitely precluded. Due to its advanced state-of-development, spontaneous Raman scattering should receive much near term emphasis for fundamental combustion research in specially selected clean flame investigations.

(4) Saturated laser fluorescence has great potential for the measurement of selected species in low concentrations (ppm) in both practical and clean flames. Unfortunately, the number of applicable species is quite small. The fluorescence signals will be independent of gas quenching effects if the absorption resonances can be saturated and if simple two and three level models are applicable. Considerable fundamental and applied research investigations are required to address these questions for this potential to be realized or dispelled.

(5) CARS is ideally suited for thermometry and major species concentration measurements in both practical and clean flame environments. Considerable research is nevertheless still required. Potential nonlinear laser-soot interaction effects and turbulence dephasing effects need to be systematically evaluated. Simplifications in gathering and treating CARS data are highly desirable. Species sensitivity limits in flames need to be clearly established experimentally. Present estimates indicate sensitivity to be relatively poor for most molecules, i.e., on the order of 1000 ppm. CARS variants need to be assessed vis-a-vis their practical utility and capability in regard to lowering detectivity limits.

(6) Laser diagnostic techniques capable of point, in-situ application to practical combustion media are quite expensive and require skilled personnel for their operation. Considerable simplification of any diagnostic approach would be desirable to reduce systems costs and personnel skill requirements.

The Task II experimental investigations will also be outlined and an update of recent activities will be given.

REVIEW OF COMBUSTION DIAGNOSTICS FOR APPLICATION TO ROCKET PROPULSION

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ABSTRACT

The Air Force Rocket Propulsion Laboratory (AFRPL) has recently begun a review of "needs" for combustion flow property measurements over the next several years and an assessment of available techniques to meet those needs. The needs arise from the necessity to obtain improved performance by either increased energy conversion efficiency or new propellant formulations, or from the requirement to characterize plume observables (infrared radiation, ultraviolet radiation, smoke, etc.). Because of the large costs connected with cut-and-try testing analytical modeling has become a principal design tool at AFRPL in recent years. It is the definition of input data to the analytical models and data for verification of the resulting computer codes that is the driving force for measurements of combustion gas properties. The harsh environment of the combustion gas plus the inevitability of disturbance of the process forces attention on the non-obtrusive, in situ techniques that have been introduced recently.

The review of the measurements required for liquid rocket engines resulted in identification of local temperature and the local density of a few species (H_2O, CO_2, N_2, H_2, OH and CO) as being the most important variables. An assessment of the various diagnostic tools available revealed that infrared and ultraviolet emission and absorption methods with inversion, and/or Laser Raman scattered Stokes radiation were adequate in principle to meet most forseeable requirements. However, a considerable amount of instrumentation development (faster data acquisition, improved signal to noise ratio, uncertainty analyses, etc.) is required to facilitate efficient acquisition of reliable test data. A few examples will be presented to support this position.

On the other hand, the review revealed that existing diagnostic technology was not nearly adequate to meet the needs for measurement of the critical variables in the two-phase flows produced in solid propellant combustion. The critical variables for solid propellant combustion effluents include the properties of both solid and gas phases. Local gas temperature and species densities are of course desired, but first priority must be given to particle properties--not just size distribution, but weight or density, velocity, composition, state, and temperature. Laser holography and scattering methods are beginning to be useful in some applica-

tions but the extent of the information obtainable is a size distribution which, when coupled with knowledge gained from sampling and electron microscope analysis leads to some conclusions about the in situ particle properties. What is needed, however, are techniques which can yield more specific data about the particles. The AFRPL has pursued work in holography and in some Mie scattering techniques which push the state-of-the-art and these will be discussed briefly.

The advanced technique being explored by the AFRPL for particle diagnostics is X-ray spectroscopy. The work in progress is aimed at determining the feasibility of several approaches at tieing the spectral absorption and fluorescent yield from an X-ray beam to atomic composition, atomic density, particle weight, and particle velocity. Some techniques have been shown to be feasible (on paper) and the logic leading to this conclusion will be discussed.

The temperature of hot particles can only be revealed through radiative emission or absorption properties. Consideration of the interpretation of spectral radiation from particles in terms of temperature has received some attention in the work at AFRPL over the past few months. The use of the Planck function to describe thermal radiation from particles when the wavelength is of the same order as the particle size is in error and more appropriate expressions have been developed for black particles. The impact of the new expressions on measurements as well as several other areas will be discussed.

Finally, the approach to gas phase diagnostics in the presence of particles will be addressed briefly. First consideration in this area should be the determination of the extent to which proven techniques such as emission and absorption spectroscopy, Raman scattering, and saturated fluorescence can be applied.

AFAPL RESEARCH AND NEEDS IN COMBUSTION DIAGNOSTICS

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Introduction

An improved technology base is necessary to generate new ideas and improved appraoches which will eventually satisfy future turbo-propulsion combustion requirements. This technology base, as in the case of any science, must be established through the strong interaction of experiment and theory. The intent of combustion diagnostics is to provide the tools needed to collect the necessary experimental data. This section presents the background, some research needs, and AFAPL research for developing and applying advanced diagnostic techniques in practical combustion environments.

Background

Jet engine combustor designs are based on past experience and the cut and try approach. As a consequence, combustor development is a long and expensive process which will undoubtedly be greatly extended by future requirements of burning alternate fuels and complying with pollution regulations. To improve combustor development approaches, models are being developed which can calculate the performance characteristics of different combustor designs. Some models are available, however; they have not been adequately evaluated because of the lack of profile data in combustor reaction zones.

Practical combustion environments are both severe and complex. They consist of interactions between fuel vaporization, diffusion and turbulent mixing, chemical kinetics, and various heat transfer processes. To completely characterize these environments requires simultaneous profile measurements of particle size, mass and velocity distributions, as well as gas velocity, temperatures, and specie concentrations. The measurements should be made in the microsecond time frame with spatial resolutions of less than a millimeter. Complete characterization is almost impossible and compromises between requirements and what can be measured will have to be made.

Probes are the state-of-the-art techniques for making combustion measurements. They are routinely used in combustor development programs as well as by the combustion research community. To survive, probes are normally water cooled and are rather large.

Such probes can cause disturbances in flow fields, act as flame holders, redistribute fuel by acting as collectors or atomizers and can be a significant heat sink. Also, samples may not be properly quenched and catalytic or other types of chemical reaction may be induced by the probe or sampling lines. Consequently, the environment described by probe measurements may not be the same as that occurring when probes are not present. On the positive side, probes are inexpensive, available, and easy to use. Because of this, they will remain important diagnostic tools in the future.

The new laser techniques such as laser Doppler velocimetry (LDV), laser Raman scattering (LARS), coherent anti-Stokes Raman scattering (CARS) and fluorescence offer the possibilities of non-interfering, real time, point measurements. These techniques also have inherent limitations as well as limitations imposed by the combustion environment. Unfortunately, their capabilities and limitations are not well established in reactive environments.

Research Needs

The intent of combustion diagnostics is to provide combustion data needed to establish a technology base for future combustor requirements. Hence, most of the diagnostics needs are driven by the combustion technology needs presented by other Air Force speakers and the interested reader should refer to these needs.

Combustion research involving laser diagnostic techniques is just beginning. As in any new technical field, there are numerous research opportunities for imaginative scientists or engineers. Several of the research needs involving combustion diagnostics are presented below:

a. To a certain extent, the capabilities and limitations of probes and the optical techniques have not been established in various combustion environments. These are difficult assessments to make, since their are no standard methods for comparison and no standard combustion sources. One way is to make redundant measurements with the different techniques and use statistics to determine "best values" and error limits. The different diagnostic techniques need to be systematically evaluated for different fuel to air ratios, inlet conditions, fuel types, and levels of turbulence.

b. Active integration of theory and experiment are essential for improving the combustion technology base. Theories of combustion processes are being integrated into jet engine combustor models. These models are in the development stage where data are needed for their evaluation. Programs are needed where laser and probe techniques are used together in well conceived experiments to provide data for evaluating existing models or the different theoretical aspects of models. This is the most important Air Force combustion diagnostic need.

AFAPL Programs

The feasibility of using LARS to measure temperatures in the reactive exhaust of a J85 afterburning engine and a ramjet combustor are being evaluated. LARS temperatures are determined by curve fitting theoretical and experimental N_2 spectra. Very good curve fits were obtained for the spectra collected in the J85 exhaust. Also, the LARS determined temperatures compare favorably with temperatures calculated from gas sampling probe measurements. The results of the ramjet combustor exit measurements were not as good. The LARS measurement volume actually extended beyond the combustor diameter encompassing some cool air. As a result, LARS temperatures were about 200^{o}K lower than expected. The extended measurement volume was the result of a large divergence of the laser beam which made it difficult to focus. In summary, we have encountered no fundamental problems which would prevent N_2 spectra from being obtained in these environments. However, numerous problems have occurred during the tests. They have been mostly instrumentation problems due to the severe test cell environments and are solvable.

CARS is presently being developed as a diagnostic tool for real time and time averaged measurements of temperature and species concentrations in laser and combustion media. The method is based on the generation of two high-power laser beams (one used as a pump and the other as a Stokes component) and the subsequent mixing of the beams in the molecular medium. The anti-Stokes spectrum of the medium can be obtained by tuning the Stokes beam. This method, however, requires excellent frequency stability. A CARS technique employing a broad-band dye laser in conjunction with a single-mode ruby laser allows spatially and temporarily resolved species concentrations and temperature measurements with a single laser pulse. Q-branch spectra are obtained with a grating spectrometer and an optical multi-channel analyzer. In addition, spectra can be scanned with the spectrometer and a photomultiplier or by increasing the slit width, real time integrated Q-branch data can be measured. These experimental methods are frequently being employed to measure species and temperature distributions in laboratory burners and a small rocket plume. The effects of various parameters such as pressure, mixtures, turbine, and beam intensity are also under study. Data generated under this study are presently being used to design and test environmentally hardened CARS system for in situ combustion measurements at AFAPL.

Our future efforts involve: (1) designing the experiments to be conducted in AFAPL's combustion tunnel, (2) making model predictions of temperature, concentration, and velocity profiles for the experiments and (3) comparing model predictions with experimental results. LARS, CARS, LDV, and probes will be used to collect profile data. The various tasks will be performed by contractors working in conjunction with AFAPL.

Laser Holographic Techniques for Particle and Droplet Size Measurements and Analysis in Chemically Reacting Flows

by

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ABSTRACT NOT AVAILABLE

INVESTIGATION OF LASER INDUCED FLUORESCENCE SPECTROSCOPY FOR MAKING IN-SITU SPECIES CONCENTRATION MEASUREMENTS IN TURBULENT COMBUSTION FLOWS

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(AFOSR-77-357)

ABSTRACT

In the study of complex reacting flows there is a need to measure species concentrations with spacial and time resolution. In the present work, the application of Laser Induced Fluorescence Spectroscopy to the measurement of radical species, especially OH, in a flame is being studied. The method consists of illuminating the gas with a laser source tuned to an absorption line of the species of interest. The specie is excited, re-radiating spontaneously. The fluorescence is observed at 90° to the laser beam (Figure 1). One of the major difficulties in applying LIFS has been that due to quenching. Quenching arises because collisional de-excitation in high pressure flames completely dominates radiative de-excitation, causing reduced fluorescence. In the present work, this effect is overcome by using a laser source of sufficient intensity to saturate the exciting transition. Under saturated conditions, the population relations are simplified considerably and the fluorescence signal enhanced(1).

We have completed a set of preliminary experiments using sodium[2] and have established that LIFS is extremely feasible for atomic species. Using simple electronics, a linear curve of growth was obtained for the range 0.888 → 0.2 PPM with spacial resolution of < 1 mm and single laser pulse sampling (Figure 2). The detectability limit was quantum noise limited. The curve of growth becomes non-linear at about 0.2 PPM due to fluorescence trapping.

We have observed OH fluorescence under excitation at a number of different wavelengths. We are in the process of generating curves similar to Figure 2 for OH, for different excitation wavelengths and observing different portions of the fluorescence spectrum.

Turbulence measurements require a suitable data acquisition system. We are currently constructing a gated integrator system which will be interfaced to an LSI-11 microprocessor. This system, which will be ready in September, will allow us to perform real time statistical analysis of our data.

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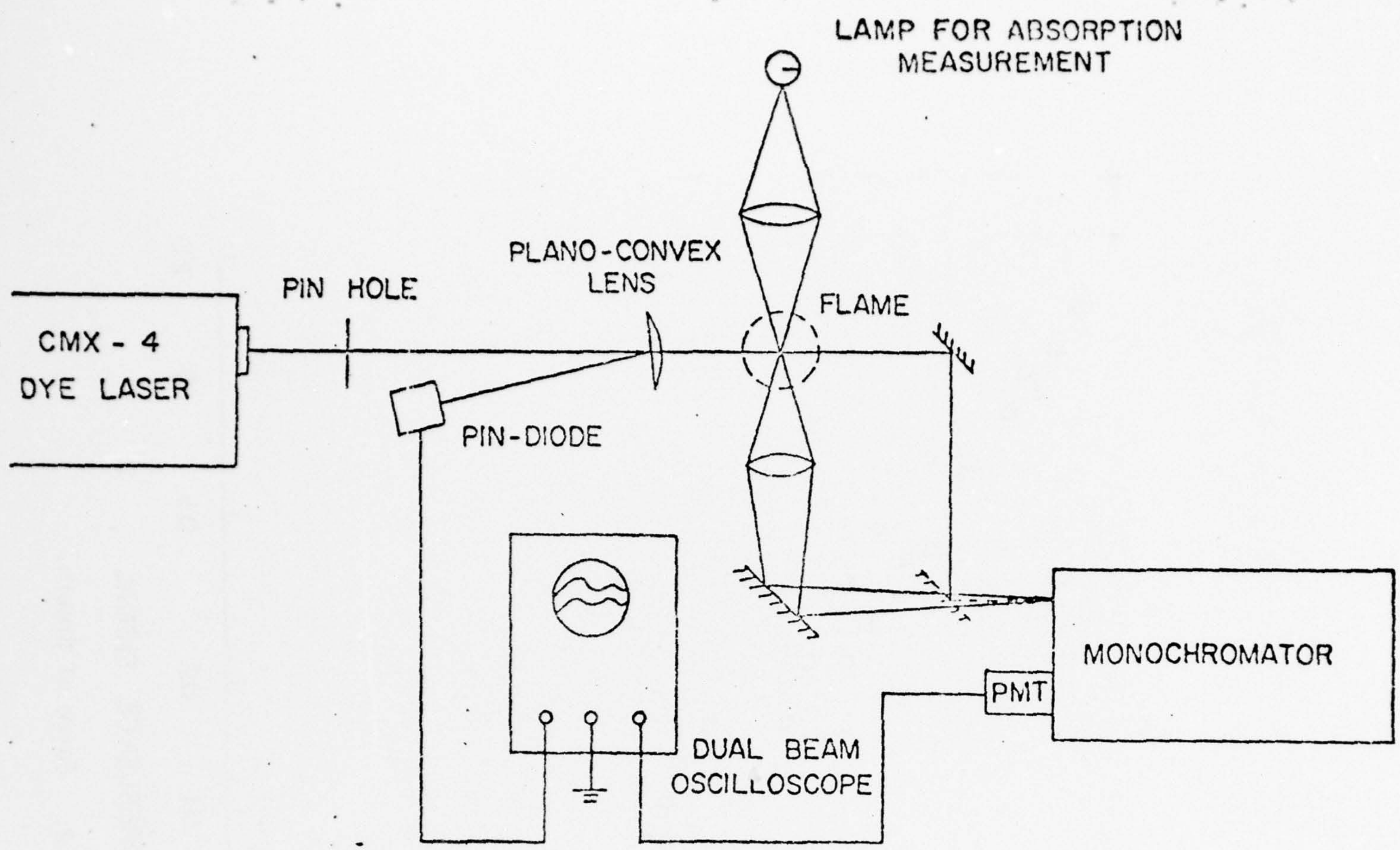

Fig. 1. Experimental Setup.

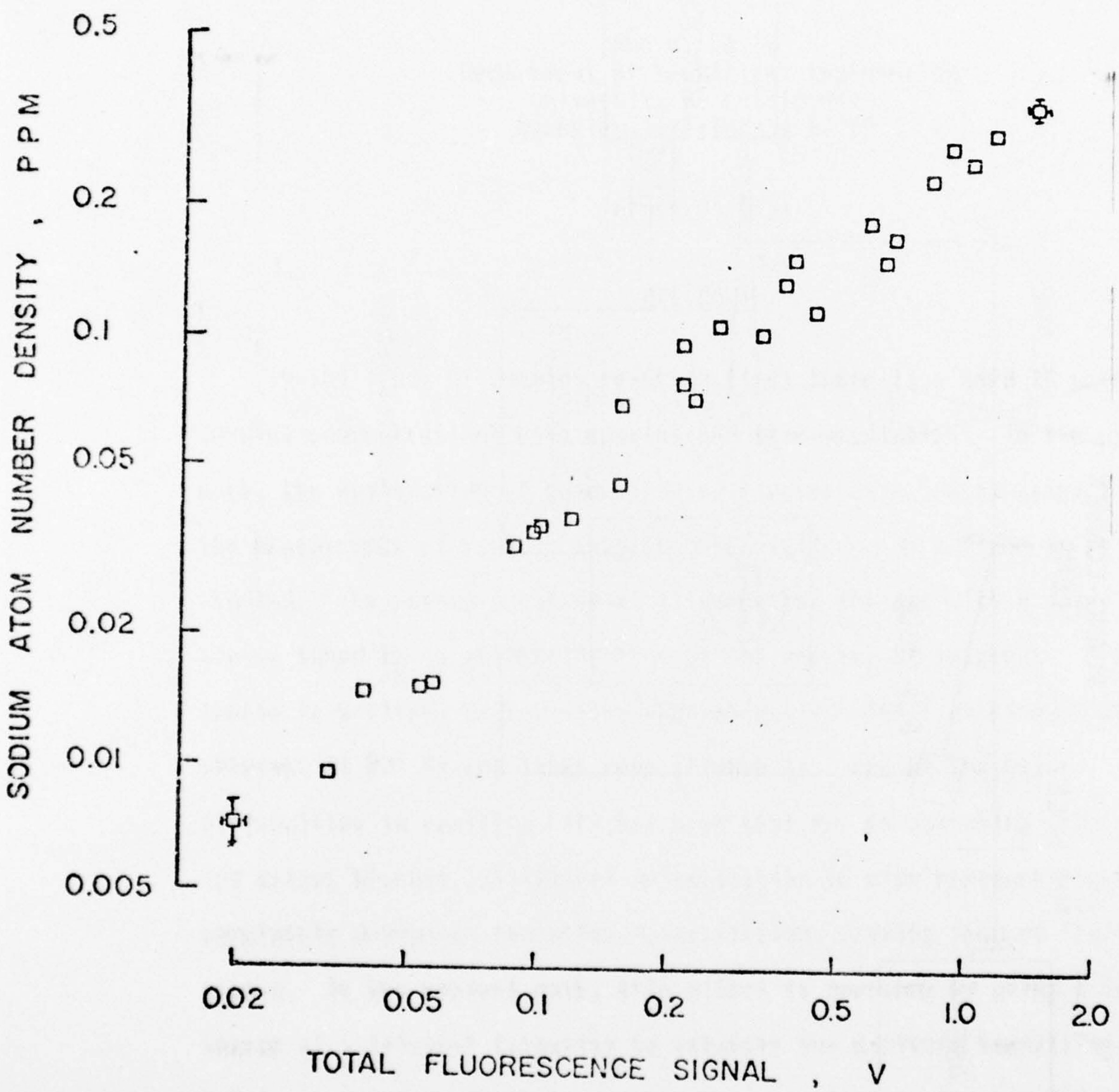

Fig. 2. Curve of Growth.

COMPARISON OF RAMAN SCATTERING METHODS FOR COMBUSTION DYNAMICS MEASUREMENTS

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Experimental environments in combustion dynamics require measurement probes which can survive hostile conditions without producing significant perturbations and still provide the necessary space and time resolved data. Current widely-used probes are not able to satisfy these disparate requirements, and therefore non-immersed sensing devices based upon optical detection techniques have been receiving substantial attention.

Among potential candidates, probes based upon light scattering processes possess particularly attractive attributes for measurements in turbulent, hot, chemically-reacting gases, including submicrosecond time resolution and three-dimensional space resolution with millimeter or less characteristic dimensions. In several different Raman scattering methods, measurements can be made both of temperature and species concentrations, and non-thermal equilibrium conditions can be probed.

However, in considering any specific instance for the application of light scattering spectroscopy to combustion diagnostics, the effect of the particular experimental conditions (such as the level and spatial extent of turbulence) and of the measurement perturbations (such as luminosity and/or fluorescence of various flame components) must be carefully taken into account in choosing the detailed measurement scheme. Here, we are embarking on a program of flame gas temperature measurements of one particular type -- based upon vibrational Raman scattering (VRS) -- in order to compare them with similar measurements made (at the Air Force Aero Propulsion Laboratory) by another method -- coherent anti-Stokes Raman spectroscopy (CARS). These measurements will be made under varying types of experimental conditions, both in laminar and turbulent flow, and with varying degrees of measurement perturbation problems present.

Most fundamentally, VRS is a simpler method to instrument and produces data which are more directly related to the desired experimental parameters than CARS, but it is a far weaker process, which makes it susceptible to measurement perturbations. The strength of CARS should make it a useful probe for many combustion dynamics conditions for which VRS is inapplicable, but its complexity and its potential experimental sensitivity to problems such as turbulent environments will impose limits to its utility. Thus, our goal is to explore the limitations of VRS temperature measurements in carefully controlled combustion experiments, and to critically compare these results with similar CARS data.

The first portion of our effort has been concerned with defining burner configurations and assembling apparatus to obtain VRS temperature measurements on a premixed hydrogen-air flame produced on a porous plug burner. The initial work on the one-inch diameter plug burner has been conducted with a horizontal flame and a Spectra-Physics Model 170 argon ion laser (operating at 488 nm), with a SPEX 1400-II double monochromator used for spectral discrimination. In order to overcome purposely-introduced measurement perturbations, a pulsed laser source will be utilized next. For this purpose, a Phase-R Model Dl-2100B pulsed dye laser currently is being modified for narrow-line operation in the 470 to 490 nm spectral range, with pulse energies of about 1 J and linewidths of about 0.2 nm or less. Each laser pulse will be monitored for both pulse energy and linewidth. Finally, in preparation for tasks which will start at the end of the first contract year, work has begun on determining experimantal problems associated with light scattering measurements for the coaxial combustor to be used in the turbulent diffusion flame studies.

ABSORPTION SPECTROSCOPY OF COMBUSTION GASES USING TUNABLE INFRARED DIODE LASERS

AFOSR F44620-76-C-0024

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1.0 Introduction

Increasing demands on combustion systems (e.g., with regard to efficiency, fuels and emissions) have stimulated new interest in combustion processes and in the development of new laser-based diagnostics for combustion studies. This presentation will describe work recently initiated at Stanford to develop and apply tunable infrared diode lasers for combustion gas measurements. Future research plans, involving application of the diode laser to a study of turbulent combustion, will also be discussed.

Tunable infrared diode lasers are well suited for in situ measurements of species concentrations and temperature in combustion gases. These lasers are also a powerful tool for determining spectroscopic parameters needed to describe the spectral characteristics of radiation from high temperature gases, such as found in engines, exhausts and plumes. The diode laser serves as a source of narrow-linewidth (10^{-5} cm^{-1}) infrared radiation whose wavelength can be rapidly modulated (> 10^{-3} cm^{-1}/microsecond) to perform fast, high-resolution absorption spectroscopy. The complete fully-resolved absorption profile of a single vibration-rotation line can thus be quickly recorded, and from this one can infer the partial pressure of the absorbing species and the lineshape parameters describing the absorption line. Temperature can also be determined by measuring the relative absorption in adjacent lines originating from different vibrational levels. The ability to rapidly modulate the laser suggests that the technique can also be applied to studies of transient combustion phenomena.

Advantages of tunable diode laser absorption spectroscopy are its simplicity, high sensitivity, high spectral resolution (orders of magnitude improvement over conventional ir spectroscopy), and its fast modulation capability. The primary limitation, for some applications, is that it is a line-of-sight method. In our first year of work with the diode laser we have demonstrated the feasibility of diode laser techniques for measuring species concentrations, temperature, and the fundamental spectroscopic parameters of line strength and collision halfwidth in laboratory combustion systems.

2.0 Results

Experiments have been conducted in a flat flame burner and in a shock tube. In the flame experiments, the laser was used to perform high-resolution spectroscopy of CO and NO vibration-rotation transitions (near 5 microns) in the postflame region of a laminar, premixed atmospheric-pressure propane-air flame. Results with CO include fundamental data for line strengths and collision halfwidths as well as determinations of species concentrations and temperature. The measured concentrations agree well with calculated values, and the measured temperatures agree well with thermocouple measurements. In the shock tube experiments, high-resolution absorption spectroscopy of shock-heated CO was performed using the test time available behind an incident shock wave. Both sets of experiments were executed by rapidly varying the diode laser wavelength across the full width of isolated vibration-rotation lines and recording the transmitted laser intensity as a function of time (wavelength) on an oscilloscope.

A typical experimental result for a fully resolved CO absorption line in the flat flame is shown in Figure 1. The experiment was performed by modulating the laser across a single CO line ($v = 2 \leftarrow 1$, P(10) at $\nu = 2077.0\ cm^{-1}$) under fuel-rich ($\phi = 1.36$) conditions where the CO concentration was known. The measured gas temperature was 2066 K. The transmitted laser intensity for a single scan of the laser was normalized and converted to a spectral absorption coefficient using Beer's law. Figure 1 provides a comparison between the measured lineshape and a lineshape calculated assuming a Voigt profile. The data can be used to infer a linestrength [$S(T) = \int \beta d\nu$] and collision halfwidth γ under combustion conditions. The predicted absorption coefficient assuming a Voigt profile and using the inferred values of S and γ agrees well with experiment. Having verified the suitability of Voigt profiles and having determined $S(T)$ and $\gamma(T)$, the same experiment can be performed to measure the CO concentration under conditions where it is not known.

The presentation will include sections on the experimental apparatus and technique, relevant theory of infrared absorption, and recent experimental results.

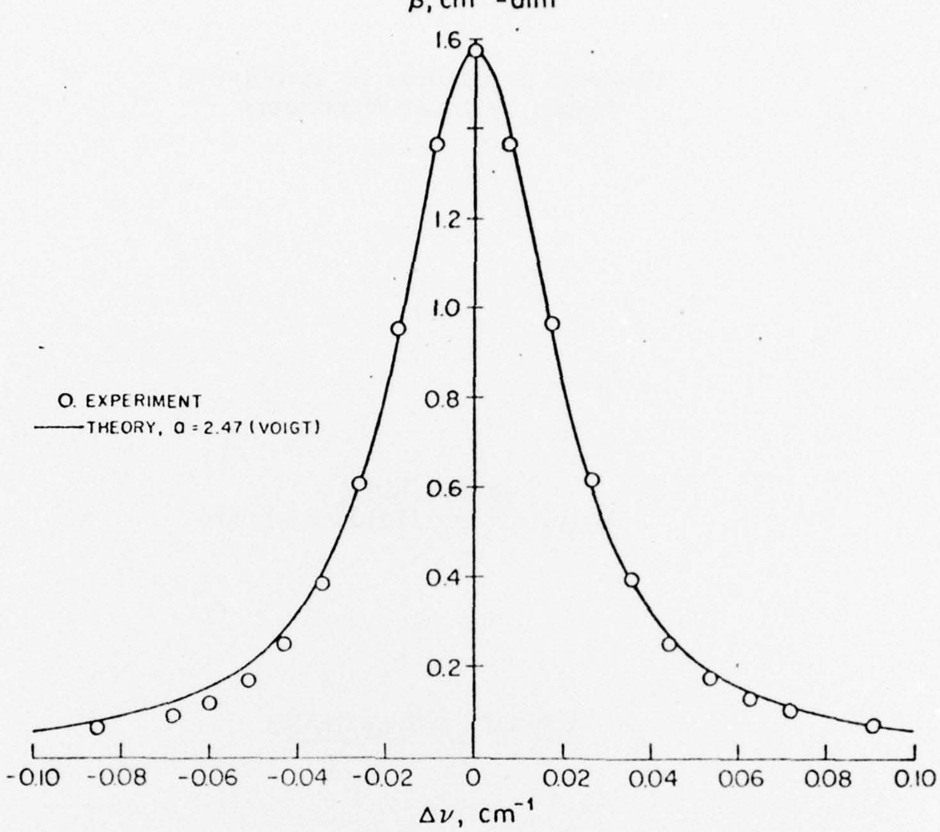

Figure 1. Comparison of calculated and measured spectral absorption coefficients for a single transition of CO ($v = 2 \leftarrow 1$, P(10)) in an atmospheric pressure, propane-air flat flame; T = 2066 K, $\phi = 1.36$. The best fit to the data is based on a Voigt profile with $a = 2.47$.

Coherent Structures in Turbulent Flames by Laser Anemometry

by

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<u>ABSTRACT NOT AVAILABLE</u>

LASER VELOCIMETRY MEASUREMENTS AND ANALYSIS IN TURBULENT AND MIXING FLOWS

AFAPL Contract No: F33615-77-C-2010

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Location: W. Lafayette, IN 47907

The objective of this effort is to experimentally and analytically investigate the biasing of individual realization LDV (Laser Doppler Velocimeter) signals and to investigate the feasibility of the use of fluorescent dye tracers in the study of mixing and turbulence. The contract was initiated about 1 June 1977. The LDV optical system design is for two velocity components using a two color, dual scatter, forward scatter design. Initial hardware and experiments will use only one component. A 5 watt argon laser is used. The optics can be rotated to permit component measurements in the plane perpendicular to the laser beam. Either or both input laser beams can be frequency shifted.

The data processor is a high speed unit designed and built at Purdue. For data recording, a dedicated micro computer facility is being installed with a direct link tp Purdue's main CDC-6500 facility for data processing.

The initial studies will be carried out in a subsonic wind tunnel facility. The flow pattern over a rearward facing step will be probed. Free stream velocities up to about 100 m/sec are possible.

Initial experimental studies will concentrate on identifying and measuring biases arising in individual realization LDV measurements in highly turbulent flows by

a) comparing results with and without frequency shifting;

b) comparing measurements at different angles to the main stream flow,

c) controlling the seeding particle size, distribution and concentration, and

d) using fluorescent dye tracers in the seeding material.

A parallel analytical program is being conducted which consists of developing a turbulence model on the computer to study and compare the effects of the experimentally derived results.

ABSORPTION - EMISSION TECHNIQUES IN 3-DIMENSIONAL DIAGNOSTICS

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AFOSR - 77 - 3439 (New Contract)

It is proposed to develop and test the absorption-emission techniques as three-dimensional combustion diagnostics. It will be shown that by using multiangular scanning, the traditional "onion-peeling" method can be extended from axisymmetrical flows to arbitrary distributions of radicals and pollutants in the flow. Since scattering "point" techniques are limited by their very small cross section, such an extension would be a step improvement in sensitivity, down to low radical concentration.

The following five areas will be investigated:

1. Known profiles of radicals or pollutants [see for instance Klueg and Slusher's test data (1974)] will be used to produce predicted parallel beam absorption data f_θ (r) in 20 x 20 positions (r,θ). This information will be fed to the ACTA computer and profiles will be retrieved in video form. We plan to check the effect of the number of positions (θ,r) and the effect of adding measurement noise. This simulation will be made for several pollutants as well as for the major constituents of the flow.

2. Special attention will be given to fan shaped beams (rather than parallel beams) as they appear best suited for situations where the access to the flame is limited. The steps described in Task 1 will be repeated in this case and an optimum set of viewing points will be determined.

3. On the basis of these first two tasks, an optimized design will be proposed which will enable an accurate measurement of the flow field (including low ppm components). The result would be a proposed scanning device to be built a year from the beginning of the contract and then tested in the laboratory.

4. A study of emission technique, based on a two - or three-fan geometry will be completed. Since the sizing of each cell is already available in the literature, an instantaneous map of the temperature and the major constituents concentrations would be obtained by this procedure (see Part II, Section E).

5. Finally, the field of combustion will be continuously evaluated for new diagnostics and measurement needs (See Part I). The potential of other techniques in obtaining similar data will be carefully assessed, so that the proposed work will concentrate on those aspects for which it is uniquely suited. Similarly, we shall assess the implications of new models or suggested theories in terms of needed diagnostics of critical profile or local measurements.

A TWO LINE ATOMIC FLUORESCENCE FLAME SPECTROMETRIC METHOD FOR MEASUREMENT OF SPATIAL TEMPERATURES OF FLAMES

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Most flame temperature methods, e.g., sodium line reversal, iron two-line emission, two line absorption, etc., do not give local flame temperatures but rather a series of line of sight intensity measurements must be transformed via a mathematical treatment, e.g., Abel inversion. We have applied the two-line atomic fluorescence method (1,2) to the temperature measurement of analytical flames (3-6). This method provides local flame temperatures (ca. 600-3000° K) directly (without any mathematical treatment) owing to the characteristic optical arrangement in atomic fluorescence spectrometry. Also, it may be applicable to the lower or higher temperature via appropriate use of elements. In this paper, the theoretical considerations, experimental setup, application to the temperature profile measurements in the various flames and the "figures of merit" compared to the other methods will be discussed with respect to the two-line atomic fluorescence method.

As a consequence, temperature profiles in various analytical flames obtained by the present method reveal, along with the intensity profiles of atomic fluorescence, the flame structures, the effect of the flame sheath with the inert gas, the atomization processes in flames, the quenching effects of the flame components and so forth. These results and further development in this area will be given in the talk.

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