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New Trends in Combustion Research for Gas Turbine Engines

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NEW TRENDS IN COMBUSTION RESEARCH FOR GAS TURBINE ENGINES

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Abstract

Research on combustion is being conducted at Lewis Research Center to provide improved analytical models of the complex flow and chemical reaction processes which occur in the combustor of gas turbine engines, in order to enable engine manufacturers to reduce the development time of new concepts and to increase the durability of these concepts. The elements of the Combustion Fundamentals Program is briefly discussed with examples of research projects described more fully. Combustion research will continue to emphasize the development of analytical models and the support of these models with fundamental flow experiments to assess the models' accuracy and shortcomings.

Introduction

The economic pressures that face all of us today are also having a dramatic affect on the aircraft industry and their customers: the commercial airlines and the military. In the area of propulsion, the development costs to evolve a new engine for the next generation aircraft are becoming staggering. With the push for fuel economy new engines are operating at higher pressures and temperatures, resulting in a marked increase in operating and maintenance costs. These growing problems are especially true for the combustor of the gas turbine engine. Let us look at the combustor in some detail. No two engines have exactly the same combustor design. And the flowfields of combustors can vary significantly, affected by the types of compressor and turbines of the engine as well as engine shaft considerations. But all combustors have basic standard features. Figure 1 is a cutaway view of a fictious combustor which illustrates several of these features. Air which has been compressed exits at high Mach number from the compressor passing through a diffuser where it is brought to a relatively low velocity with a minimum of pressure loss. The air then enters into a cavity in which the combustor is contained. This cavity allows the air to be distributed to all parts of the combustor. The combustor itself can be divided into three major processes: (1) the fuel/air mixing process where fuel is sprayed into the air and intense mixing and fuel evaporation takes place. This mixing is usually enhanced with air swirlers which provide highly turbulent recirculation zones. (2) The combustion process is initiated in this recirculation zone and continues further downstream where fresh air dilution jets mix with the hot products of reaction. (3) The dilution process continues downstream with further rows of dilution jets to reduce the hot combustion products from stoichiometric temperatures down to temperature levels acceptable to the turbine nozzle and turbine blades. The role of this dilution process is to create a prescribed steady temperature profile with minimum circumferential variation at the turbine inlet station. In addition to these major processes, a significant amount of the air from the compressor is needed to provide adequate cooling of the combustor liners. This cooling is conventionally accomplished by several film cooling air slots although other wall cooling techniques are also considered.

Understanding all of these processes could reduce the time required to design and develop new combustor concepts, and could also lead to more optimized designs resulting in improved component durability. The resultant combustor system would exhibit intimate mixing of fuel and air, complete chemical reaction, uniform heat release, controlled temperature profile, and minimum pollution. It is for these benefits that the National Aeronautics and Space Administration, Lewis Research Center (LeRC) is engaged in combustion research. The objective of the research is to obtain a better understanding of these physical processes and to develop analytical models which can accurately describe these processes. Results of these research efforts are passed on to industry so that they can be used to effectively counter the above problems.

This research program is coordinated with other U. S. Government laboratory programs, such as those from the Department of Energy Sandia Laboratory and the Department of Defense Laboratories. It is the intent of this paper to present an overview of the LeRC combustion fundamentals activities and to highlight several examples as a means of further coordinating this research program with other research organizations.

NASA LeRC Combustion Research Program

The emphasis for research in combustion in the 1970's was to reduce the gaseous and solid pollutant emissions from aircraft engines, reference 1. More recently fuel flexibility has been emphasized. A balanced program has been identified which emphasizes improved combustion systems, high performance with reduced levels of emissions, and fuel-flexible combustors, reference 2. Today, the combustion research program emphasizes even more the far-term fundamental research focusing on improved hardware durability, with continuing interest on low pollutant emissions and fuel flexible combustor concepts.

The current combustion program at LeRC is organized into two categories: combustion

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fundamentals research and applied combustion research, figure 2. The thrusts under the combustion fundamentals area include: (1) combustion modeling - analytically characterize the physical phenomena associated with turbulent reactive flows; (2) model verification experiments - provide benchmark data with well-specified boundary conditions to assess the accuracy of the analytical models; (3) fundamental experiments - achieve a more complete understanding of the fundamental processes occurring in reacting flows; and (4) advanced numerics - develop improved numeric techniques which can be applied to highly turbulent, recirculating, reacting flowfields. The thrusts under the applied combustion research category include: (1) model verification - assess the overall combustor code which uses improved submodels by predicting combustor internal aerothermodynamic performance and combustor exit conditions and compare with full scale combustor data; (2) component research - identify and evaluate subcomponent/component level technology for inlet air diffusion and modulation, fuel injection and fuel-air preparation, liner cooling, primary zone stoichiometry control and exit condition tailoring; and (3) advanced concept research - explore new combustor concepts which have potential for improved performance and capability for durable high pressure and high temperature operation. The remainder of this paper will confine itself to describing the combustion fundamentals portion of the program.

Research activities under the combustion fundamentals category are classified under the subject areas of model assessment, sprays, mixing, radiation - chemistry, and combustion dynamics. In each of these subject areas there are in-house research projects, university grant activities, and contracts with industry, Table I. Each of these subject areas have research activities to develop and improve analytical models and to perform experiments to better understand the physical processes and provide data for the modelers. Time does not permit a review of each research activity at this time. A Combustion Fundamentals Research Conference was held last October 1982, which provided a review of the complete combustion fundamentals program, reference 3. Instead, three programs have been selected for discussion because they best typify the kind of research now being supported at LeRC. These are examples of the new trends in combustion research that will continue to be supported in the future.

Computer Simulation of Turbulent Combusting Flows

With the ever increasing speed of modern computers detailed computations of complex flowfields are now becoming possible. There is no more obvious example of how computational fluid mechanics has impacted aerothermodynamics than in the modeling of combustion. If the reacting flowfield and mixing process of a combustor could be accurately simulated with a computer code, significant savings could be realized in future combustor developments by minimizing build-up and experimental testing of prototype combustor hardware. The development of accurate, reliable analytical models is a complex and difficult task, however. The flowfields in a combustor are highly three dimensional with high turbulence levels and large recirculation zones. Fuels are usually distillate liquid sprays which undergo vaporization and combustion in a very short time span. The approach at LeRC is to develop analytical models that accurately predict a more simplified flowfield and then build-up the model capability to handle more complex flows. There are several current activities that address the analytical modeling of the fluid dynamic and chemical reaction processes.

One project which is producing very promising results is the development of a computer code for two-dimensional, unsteady, turbulent combustion. The model used for the analysis is based on the random vortex method to compute the turbulent flowfield. The method is grid-free and devoid of numerical diffusion; therefore, it is suitable for modeling the intrinsic physical properties of flows at large Reynolds numbers. It is capable of analyzing large gradients produced by the small eddies of turbulent motion, while it allows perturbations to grow into possible instabilities without damping or undue dissipation. The combustion of premixed gases is idealized by the propagation of a flame interface, located between reactants and products, due to convection and self propagation. The expansion of the flow across the flame due to the exothermicity of the reaction is taken into account using a distribution of volumetric sources within the burning zone.

The analytical model is described schematically by the diagram shown in figure 3. The diagram is constructed of two loops that are linked together by the total velocity vector. The loop on the left hand side shows the way vortex dynamics is applied to solve the turbulent field using the random vortex method, reference 4. The key element in this loop is the vorticity which is treated as a set of discrete elements that are transported by convection due to the total velocity field, and by diffusion expressed in terms of random walk. Vorticity is generated on solid boundaries to satisfy the no-slip conditions, and produces the solenoidal part of the velocity field.

The loop on the right hand side illustrates how flame propagation is incorporated into the model. The flame front is treated locally as an interface between two incompressible media, the reactants and the products. The front is advected by the total velocity field and is further displaced by the corresponding burning speed of a laminar flame. The changes in the local volumetric fraction of burned gas due to combustion are employed to evaluate the volume expansion, the key element of the combustion algorithm loop, reference 5. These volume expansions produce the irrotational part of the velocity field.

The computational method can be applied to a number of two-dimensional geometries. Of particular interest is channel flow with a rearward facing step. Figure 4 is a computed progression of the front based on calculated results of references 6 and 7. Comparisons have been made of visual observations of real combustion in such a geometry to computational graphics of the combustion process. Figure 5 compares the result of the calculation at a given instant of time with a frame of a high-speed schlieren movie from a combustion tunnel. The similiarities in the comparative structure of the turbulence are encouraging. Extending such an approach to a more complex three-dimensional flowfield poses both an opportunity and a challenge for the future.

Detailed Fuel Spray Diagnostics

Laser diagnostics is another rapidly advancing field. The use of lasers oftentimes enables the experimentalist to study deep inside complex flows without disturbing the surrounding flowfield. Liquid fuel sprays is a subject area in which laser diagnostics appear particularly attractive. The two most significant parameters which characterize fuel spray combustion are the droplet size distribution and the droplet velocities. Since the basic interactions between fluid mechanics and the combustion process are not well understood, a great deal of research, both experimental and theoretical, has addressed itself to the problem of spray combustion. Turbulent fuel and air motions influence the chemical reactions by increasing the oxygen supply to the fuel. The relative velocities between the fuel's gas phase and liquid droplets affect the evaporation, burning rate, and the pollutant formation. Thus, it is necessary to measure the size and velocity distributions of the spray droplets and the evolution of these distributions with the flow. Such measurements will enable researchers to get a better picture of spray combustion and in turn help in both fuel nozzle research and developing theoretical models of spray combustion.

Several laser measurement methods provide the above required capabilities in principal, reference 8. Particle sizing interferometry, which utilizes the measurement of the visibility (or relative amplitude modulation) of a dual-beam laser velocimeter signal, has shown promise to be very successful in producing droplet size and velocity and size-velocity correlation measurements under a variety of spray conditions. By using off-axis large angle light scatter detection, reference 9, the measurement region has been substantially reduced and spatial resolution was significantly improved.

A Droplet Sizing Interferometer (DSI) has been built under contract and is now in-house undergoing evaluation. Although the measurement technique is similar to particle sizing interferometry, for sufficiently large off-axis collection angles the scattered light is primarily due to refraction and reflection, allowing measurements in more dense sprays, reference 10. The major components of the system are shown in the diagram of figure 6. The current capability of the instrument results in a minimum and maximum detectable droplet size of 3 micron and 300 micron, respectively. And for a given fringe spacing, the usable range of droplets extend over about one decade in size. This system has the additional capability of simultaneously measuring the droplet size distribution and velocities in two orthogonal directions by using two pairs of laser beams. In addition, measurements can be made in flows with recirculation zones by incorporating a Bragg cell inside the transmitter in each beam to distinguish directionality. The receivers are oriented approximately 30° off the forward scattering axis to reduce the probe volume to approximately 1 mm^3. This collection angle also enhances signal to noise ratio and enables measurement of sprays with relatively high number density. A photograph of the DSI system is shown in figure 7. A major consideration with laser diagnostics instruments is analysis of the data. The DSI includes a Data Management System (DMS) which includes a microcomputer and a visibility processor for each droplet size-velocity component. The DMS and visibility processor packages provide data reduction and analysis capability. An example of the data is shown in histogram form in figure 8. The upper histograms are simultaneous measurements of the droplet size distribution for each pair of laser beams. The bottom histograms are axial velocity on the left, and radial velocity on the right, of the droplets in the fuel spray.

the forward scattering axis to reduce the probe

Using water as a fuel substitute, several fuel nozzles are being selected for measurements of droplet size and velocity at representative test conditions, reference 3. In addition, the turbulent interactions between flowing air streams and simulated fuel sprays will be studied. Later experiments will investigate simple flow fields using small particles for air flow seeding to track the air flow characteristics as well.

It is recognized that although the present DSI system has promising capability, there are limitations to the current configuration. For this reason, a continuing development effort is being supported for further improvements to the instrument system and the data analysis. Contract and grant activities are underway which have promise to extend the size range capability, reduce beam alignment difficulties, and reduce the system sensitivity to laser beam quality and differences in the relative intensity of the beams. The goal of this research is to make detailed measurements in confined two phase reacting flow systems where optical access is limited. It is these measurements which eventually must be made for analytical model verification.

Mass and Momentum Transfer

Another diagnostic technique is undergoing rapid development which utilizes the characteristics of laser light to non-intrusively probe inside reacting and non-reacting flowfields. It is called laser induced fluorescence, and the principle is simply that a laser beam of a specific frequency when irradiating certain atoms or molecules cause orbital electrons to be momentarily excited. The subsequent electron relaxation results in radiation or fluorescence of the atom. This phenomena is being applied to flow diagnostics in two ways: to determine minor species concentrations (such as OH and NO) and temperature fields of chemically reacting flow, references 11 and 12; and to obtain detailed flowfield velocity and mass transfer measurements, references 3 and 13. Programs are currently being supported in both of these experiment areas; simultaneous measurements of species concentrations and other flow properties in combustion flowfields are needed to test analytical models which describe the interactions between the chemistry and fluid mechanics of combustion phenomena. Again, rather simple flows are being studied to provide data to assess the models. More complex flows will be dealt with as confidence with the models is obtained.

An example of an experiment using laser fluorescence is the measurement of mass and momentum transfer in jet shear flow. An experimental study of mixing downstream of co-axial jets discharging in an expanded duct is being conducted to obtain data for the evaluation and improvement of turbulent transport models currently used in a variety of computational procedures for combustor flow modeling, reference 3 and 13. As shown in figure 9, four major shear regions are identified; a wake region immediately downstream of the inner jet inlet duct, a shear region further downstream between the inner and annular jets, a recirculation zone, and a reattachment zone. A water tunnel with clear glass walls is being used to conduct the experiment, figure 10. The study uses laser velocimeter (LV) and laser induced fluorescence (LIF) techniques to measure velocities and concentration, and flow visualization techniques to qualitatively determine the time dependent characteristics of the flow and the scale of the turbulent structure.

A dye used as a trace material is injected into the inner jet. Flow visualization studies are conducted with high-speed motion pictures to record the dye patterns in selected r-z and r-θ planes. The optical arrangement for obtaining r-θ plane measurements is shown in figure 10. An example of the resulting flow is shown in figure 11. A similar optical arrangement obtains r-z plane measurements as also shown in figure 11.

In addition to the flow visualization studies, pointwise measurements are being obtained to produce a detailed map of the velocity, concentration, mass transport rate and momentum transport rate distribution, providing data for the evaluation of turbulent transport models. Data sets of two velocity components pairs are obtained simultaneously to determine momentum transport rate and velocities. Data sets of velocity and concentration pairs are obtained simultaneously to determine mass transport rate, concentration, and velocity. Mean quantities, second central moments, skewness, and kurtosis are calculated to characterize each data set. An example of the data being obtained is shown in figure 12. In the upper portion of the figure, the mean and the fluctuating centerline axial velocities are plotted as a function of axial distance from the jet exit plane. The lower portion of the figure displays the mean and the fluctuating inner stream concentration as a function of axial distance. The inner stream concentration falls off for larger values of axial distance as a result of the mass transfer of the streams. Also in figure 12 are results of calculations of the same flow, using finite difference, two dimensional, elliptic transport equations using the two-equation turbulence model, reference 14. The qualitative agreement between the model and the experimental results are encouraging, but sizable quantitative discrepancies which are evident in the figure still need to be accounted for with model improvements.

The data of figure 12 are taken from reference 13 which confined itself to non-swirling flow. The addition of swirl adds a needed complexity to the experiment to better simulate combustor flowfields. Experiments in swirling flows are now being conducted.

Concluding Remarks

Research on combustion is being conducted at Lewis Research Center to provide improved analytical models of the complex flow and chemical reaction processes which occur in the combustor of gas turbine engines, in order to enable engine manufacturers to reduce the development time of new concepts and to increase the durability of these concepts. The elements of the Combustion Fundamentals Program were briefly discussed as a blend of in-house, grant, and contract activities, with examples of research projects described more fully. Recent efforts in combustor modeling now permit us to compute and study the effect of large vortex structures in turbulent flames. From such efforts we are progressing in the predictions of combustor flows and the effects of combustor geometry on the flowfield. Other efforts are providing insight into the mechanism of the formation of fuel sprays. Detailed studies of the fluid dynamics of mixing are providing insight into the structure of turbulence and its effects on transport rates. Combustion research will continue to emphasize the development of analytical models and the support of these models with fundamental flow experiments to assess the models' accuracy and shortcomings.

Acknowledgements

The author wishes to recognize the assistance of the members of the Combustion Fundamentals Section of the Combustion Branch of NASA Lewis Research Center in the preparation of this paper. The continued support of the Propulsion Laboratory, U. S. Army Research and Technologies Laboratories (AVRADCOM), at Lewis Research Center is also recognized.

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COMBUSTION FUNDAMENTALS

	ANALYTICAL MODELS	MODEL VERIFICATION EXPERIMENTS	FUNDAMENTAL COMBUSTION EXPERIMENTS	ADVANCED NUMERICS
MODEL ASSESSMENT	I-H C	I-H		
SPRAYS	I-H C	I-H GRANT C	I-H GRANT	
MIXING	GRANT	I-H GRANT C		I-H GRANT C
RADIATION, CHEMISTRY	I-H GRANT C	I-H GRANT	I-H GRANT	GRANT
COMBUSTION	I-H GRANT		I-H GRANT	

Table I. - Matrix of current Combustion Fundamental Program showing areas of in-house research (I-H), grant activities with universities (GRANT) and contract efforts (C).

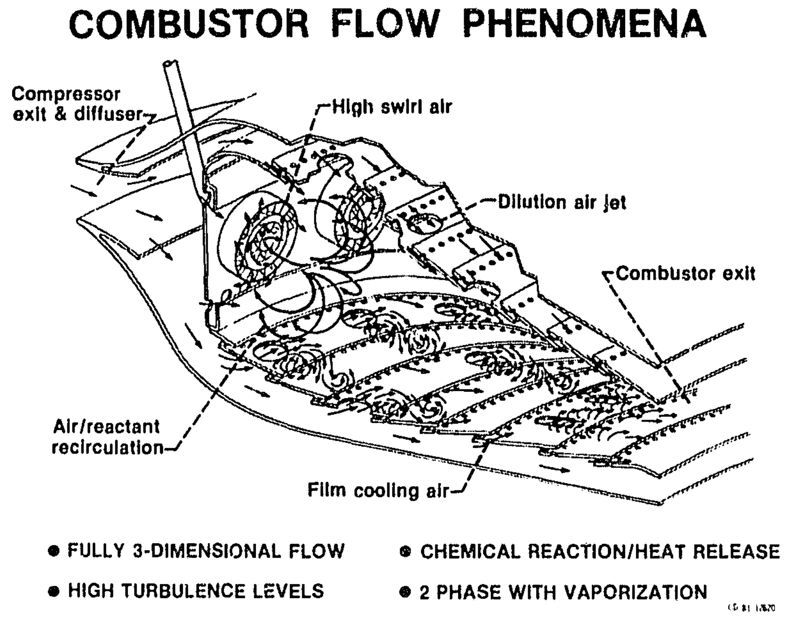


Figure 1. - Cutaway illustration of a portion of a full annular combustor system, with major features highlighted.

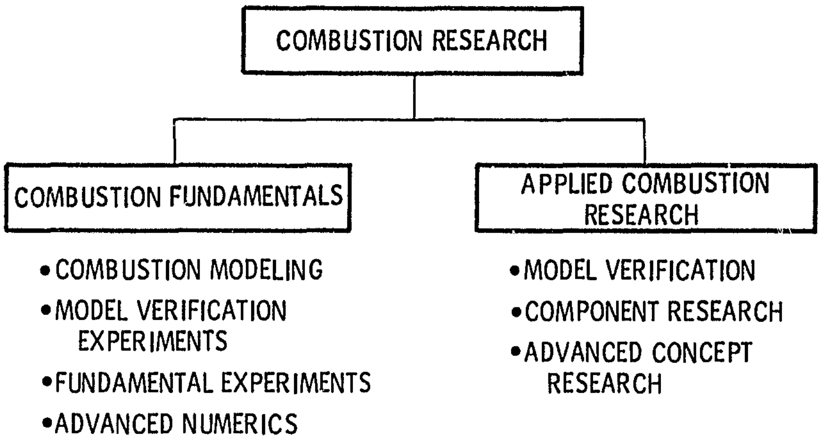


Figure 2. - NASA Lewis Research Center Combustion Research Program Structure.

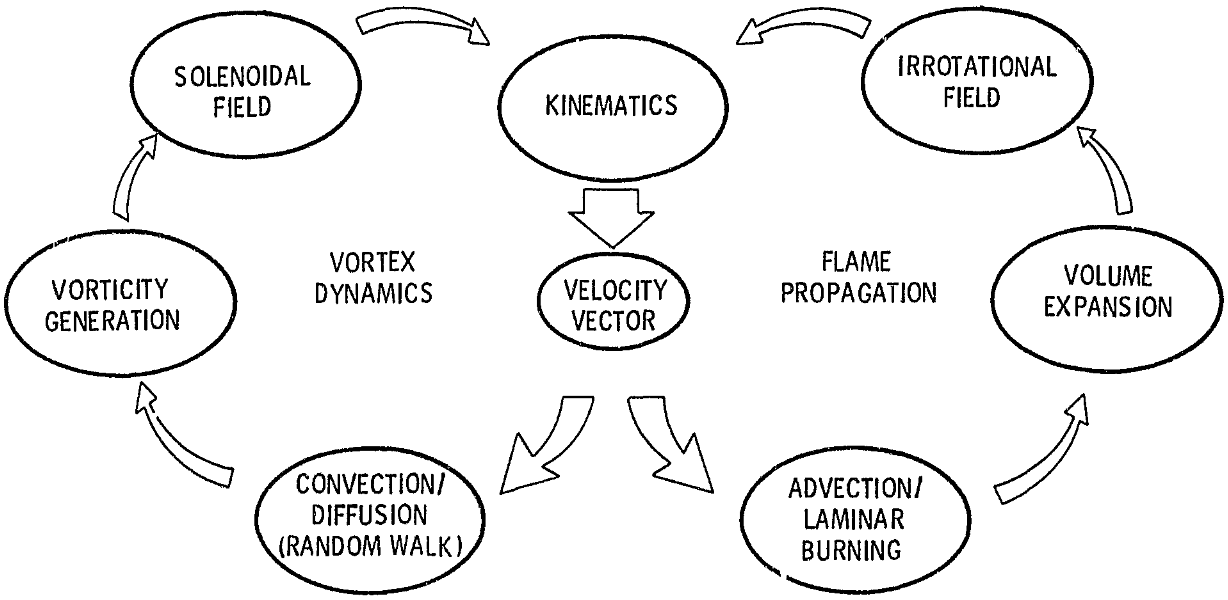


Figure 3. - Diagram showing relationship between the vortex dynamics and flame propagation in the modeling of two-dimensional, unsteady turbulent combustion using the Random Vortex Method.

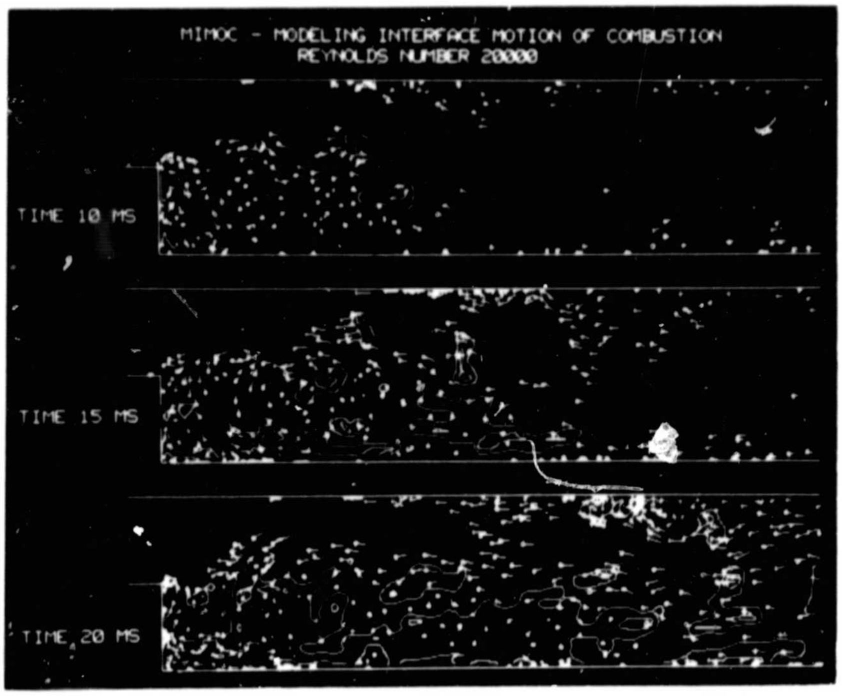
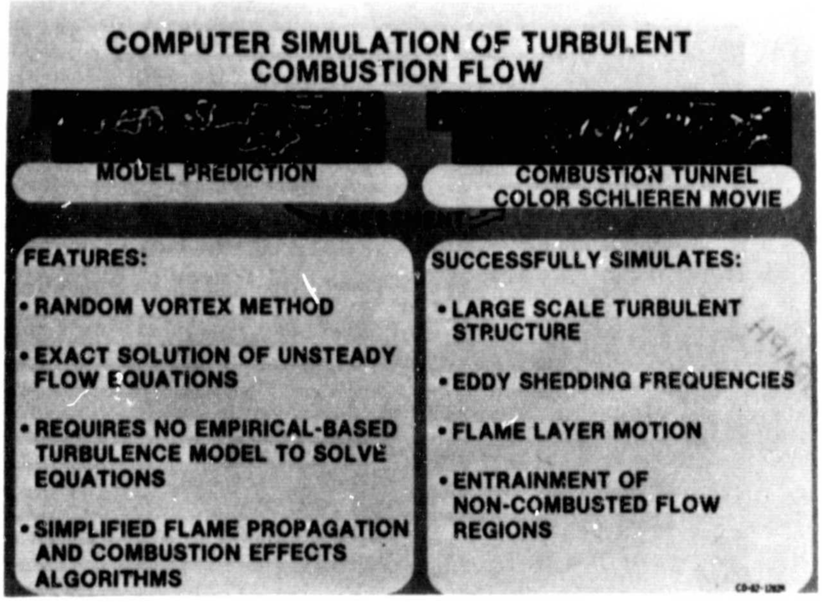


Figure 4. - Example of calculation of two-dimensional, unsteady combustion: channel flow with a rearward facing step, premixed fuel and air. Flagged dots are velocity vectors at different points in the flow. Ignition was initiated at the lower left corner at time = 0; pockets of reacted gases are defined with a solid boundary.



COMPUTER SIMULATION OF TURBULENT COMBUSTION FLOW

MODEL PREDICTION

COMBUSTION TUNNEL COLOR SCHLIEREN MOVIE

FEATURES:

- RANDOM VORTEX METHOD
- EXACT SOLUTION OF UNSTEADY FLOW EQUATIONS
- REQUIRES NO EMPIRICAL-BASED TURBULENCE MODEL TO SOLVE EQUATIONS
- SIMPLIFIED FLAME PROPAGATION AND COMBUSTION EFFECTS ALGORITHMS

SUCCESSFULLY SIMULATES:

- LARGE SCALE TURBULENT STRUCTURE
- EDDY SHEDDING FREQUENCIES
- FLAME LAYER MOTION
- ENTRAINMENT OF NON-COMBUSTED FLOW REGIONS

Figure 5. - Results of calculation of two-dimensional unsteady turbulent combustion over a rearward facing step and comparison with experimental results from a combustion tunnel using color schlieren.

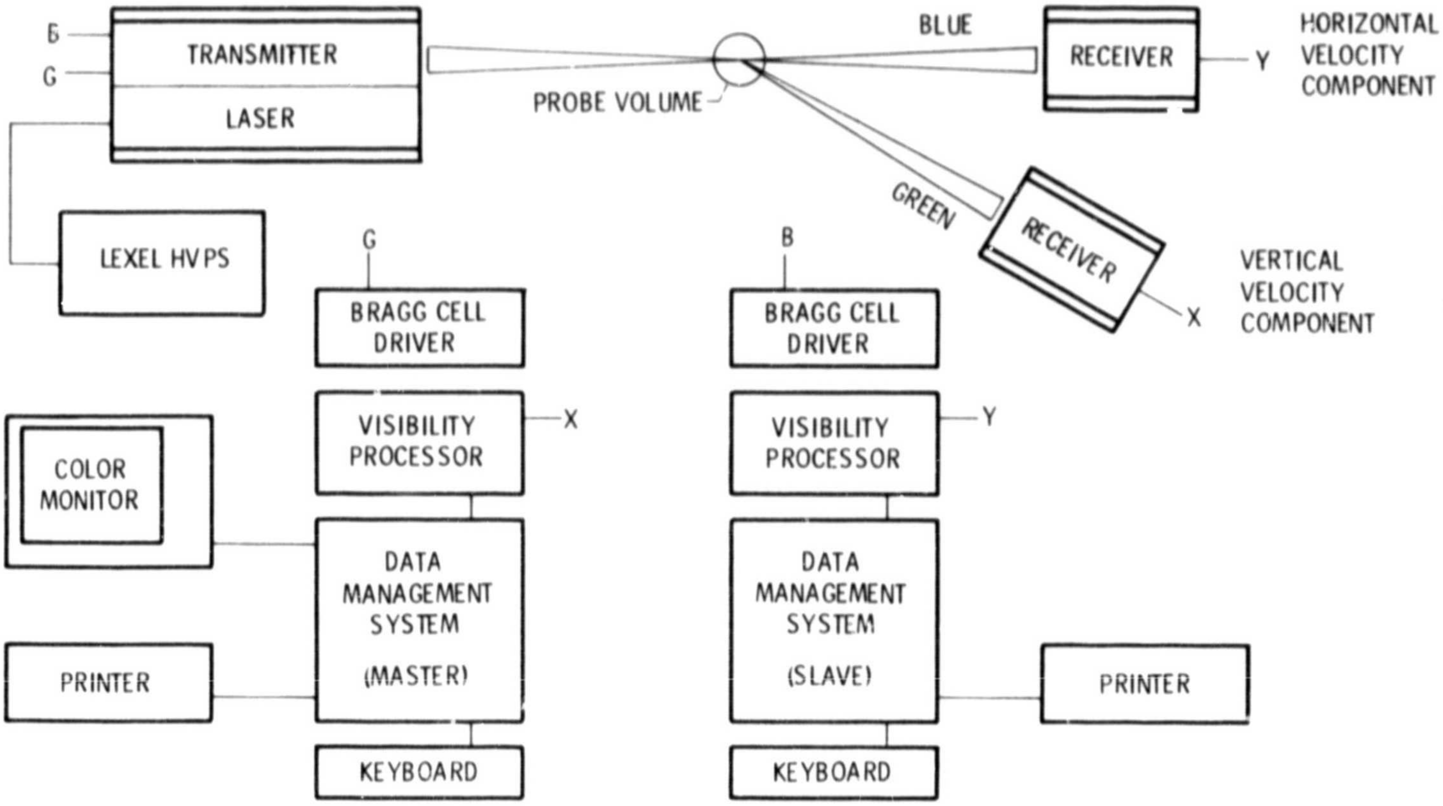


Figure 6. - System diagram for Droplet Sizing Interferometer instrument for obtaining spatially resolved data on fuel sprays.

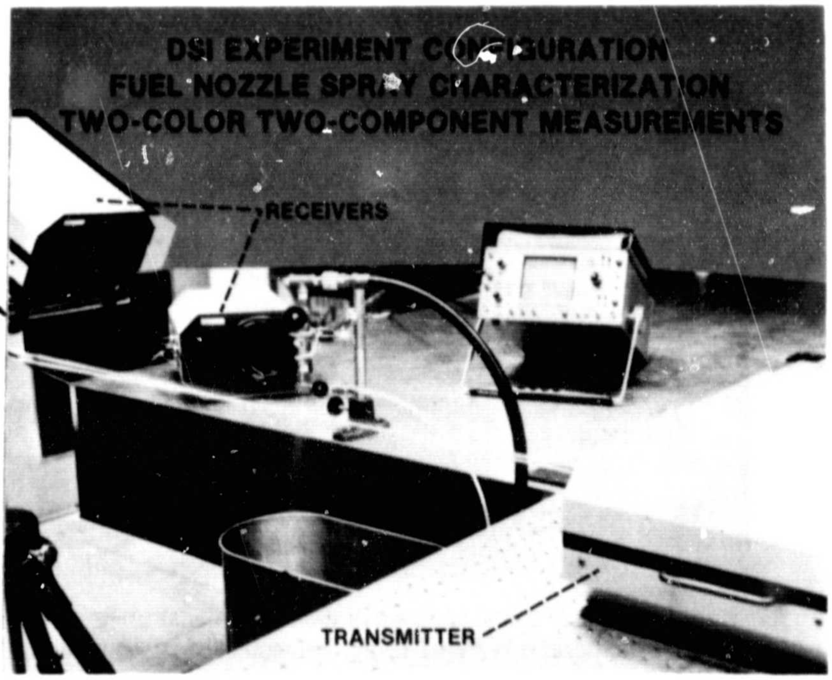
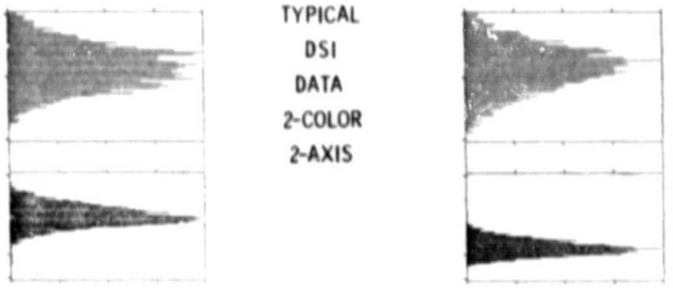


Figure 7. - Photograph of components of Droplet Sizing Interferometer instrument with test fuel nozzle in place.



PLOT LABELS
- DIA AT 100% VISIBILITY: 11 μm
- DIA AT 50% VISIBILITY: 64 μm
- DIA AT 15% VISIBILITY: 117 μm
- LOW VELOCITY: 8.64 m/s
- MID VELOCITY: 17.79 m/s
- HIGH VELOCITY: 26.89 m/s

PLOT LABELS
- DIA AT 100% VISIBILITY: 10 μm
- DIA AT 50% VISIBILITY: 56 μm
- DIA AT 15% VISIBILITY: 101 μm
- LOW VELOCITY: 3.84 m/s
- MID VELOCITY: 7.91 m/s
- HIGH VELOCITY: 12 m/s

Figure 8. - Sample data from Droplet Sizing Interferometer instrument; data includes simultaneous droplet size distribution (above) and 2 components of velocity distribution (lower plots) at a point in spray.

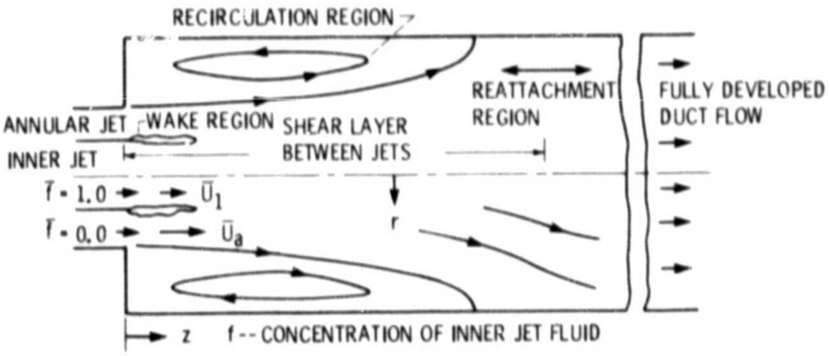
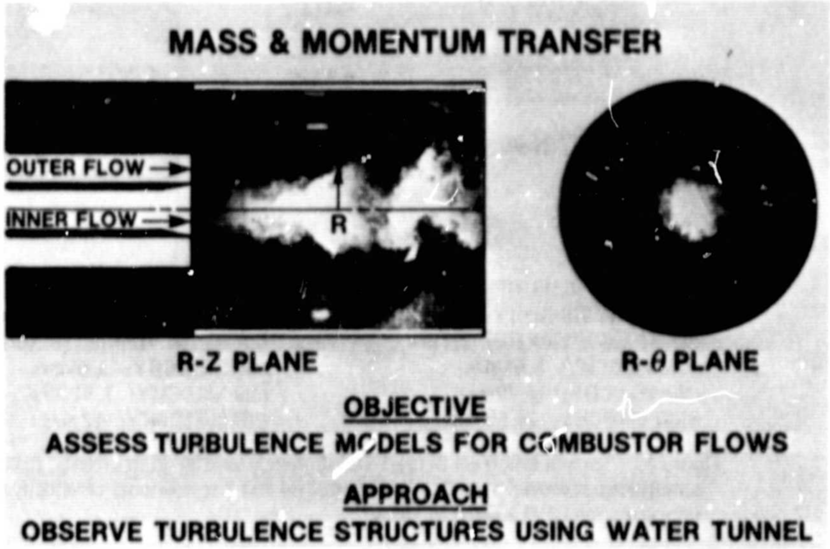


Figure 9. - Illustration identifying fluid shear layers of interest in a co-axial jet flow entering a confined enlarged duct.

Figure 10. - Description of experimental apparatus for studying the mass and momentum transfer of co-axial jets entering a confined enlarged duct; also shown is optical arrangement for photographing mixing of jets in r - θ plane using fluorescence technique.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

ORIGINAL PAGE
~~COLOR PHOTOGRAPH~~
OF POOR QUALITY



MASS & MOMENTUM TRANSFER

R-Z PLANE

R-θ PLANE

OBJECTIVE

ASSESS TURBULENCE MODELS FOR COMBUSTOR FLOWS

APPROACH

OBSERVE TURBULENCE STRUCTURES USING WATER TUNNEL

Figure 11. - Mixing of fluids from two co-axial jets entering a confined enlarged duct. Left side is axial plane illuminated with laser light, with light intensity proportional to concentration of inner jet fluid. Right side is a radial plane illumination.

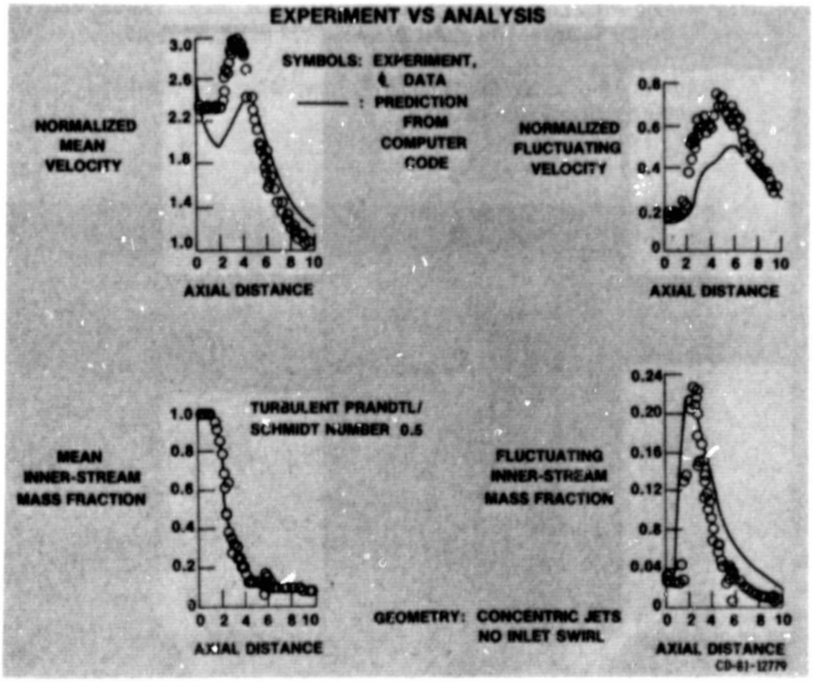


Figure 12. - Comparison of computer calculations and experimental data of the mass and momentum transfer of co-axial jets entering a confined enlarged duct.