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# Future Fundamental Combustion Research for Aeropropulsion Systems

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# FUTURE FUNDAMENTAL COMBUSTION RESEARCH FOR AEROPROPULSION SYSTEMS

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## Abstract

The current understanding of the physical fluid mechanics, heat transfer, and chemical kinetic processes which occur in the combustion chamber of aeropropulsion systems is based on many years of empirical research and experimental experience. Successful gas turbine engines and other propulsion systems are the result of many years of research and development on the various engine components, especially the combustor. Now as we enter the age of the computer and the laser, new tools are emerging that show promise in greatly improving this understanding. With the component requirements becoming more severe for future engines, the current design methodology needs these new tools to obtain the "optimum" configuration in a reasonable design and development cycle. Research efforts in the last few years have been encouraging but in order to achieve these benefits much further research is required into the fundamental aerothermodynamic processes of combustion. There is much in combustion science that remains to be researched and understood. Research must continue in the areas of flame stabilization, combustor aerodynamics, heat transfer, multiphase flow and atomization, turbulent reacting flows, and chemical kinetics. Associated with each of these engineering sciences is the need for research into computational methods to accurately describe and predict these complex physical processes. This paper highlights research needs in each of the above areas.

## Introduction

U.S. Aeronautics is a major influence on the long-term economic and military security of the nation. Our world preeminence in this field has narrowed in recent years as foreign competition has increased. In order to establish a clear path for the U.S. to maintain a leadership role in aeronautics, the Office of Science and Technology Policy, directed by G.A. Keyworth, has established National Aeronautical R&D Goals.[1] A committee was established that proposed "three national goals to clarify and focus the direction for U.S. Aeronautical R&D:" Subsonic Goal: to build transcentury efficient and affordable aircraft; Supersonics Goal: to attain long-distance efficient aircraft; and Transatmospheric Goal: pursue research toward capability to routinely cruise and maneuver into and out of the atmosphere. They also clearly stated that "a broad-based national program of basic R&T must be supported and sustained to produce the new concepts and ideas essential to technological advancement. A continuous flow of fundamental knowledge from both public and private research is vital if new advances and breakthroughs are to occur."

In a presentation to the Congressional Advisory Committee on Aeronautics, Dr. R.S. Colladay, Acting Associate Administrator of NASA, endorsed Keyworth's committee recommendations and added that the "R&T base is the lifeblood of NASA's Aeronautics Program: (it) provides technology foundation from which important advances can flow, and sustains the excellence of our institutional capabilities."[2]

In another recent activity, the National Research Council organized a "Workshop on Aeronautical Technology: A Projection to the Year 2000." The workshop was organized into seven technology panels including propulsion. The published report indicated that the benefits to be expected from advanced propulsion technology will provide both economic gains and increased capability.[3] The panel also pointed out that "advanced propulsion systems derived from an enhanced research and technology development program hold the key to successful development of future air vehicles." Their recommendation was to place a renewed emphasis on propulsion R&T in order to enable promising new systems to be realized.

Finally, in the area of fundamental combustion research, last fall a review of the Lewis Research Center combustion research activity was conducted by a group of outside peers from industry, Government, and academia. In addition to an assessment of the technical content and quality of the current program, the peer group identified several key areas where specific research needs exist. They recognized that future high technology programs will not be possible unless an adequate research base is supported to meet the technology needs. The recommendations of this peer review, along with a recent assessment of the state-of-the-art of aerothermal numerical codes by Garrett Turbine Engine Company,[4] General Electric,[5] and Pratt & Whitney Aircraft,[6] are being given serious consideration as we establish the future direction of fundamental combustion research at NASA Lewis Research Center.

At Lewis, combustion research is integrated into activity in internal fluid mechanics. The objectives of the research are to advance the understanding of flow physics, heat transfer and combustion processes which are fundamental to aeropropulsion, and to translate this knowledge into models and numerical codes of aerothermodynamic phenomena. The overall goal is to bring internal computational fluid mechanics to a state of practical application for propulsion systems. These models and numerical codes would then be available to the industry to incorporate into their own engine/component design systems.

The approach at Lewis is to establish an integrated computational-experimental research

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program. The activity consists of research on numerical methods, well-defined experiments for code and model verification, and the demonstration of computational codes for propulsion system components. In the area of combustion, research has been underway for some time in these three areas.[7-10] With a recent reorganization in the Aeronautics Program at Lewis, this research activity has been consolidated with similar research in other components such as compressors, turbines, and transition ducts and is continuing in the internal fluid mechanics research program. Although the amount of work currently being supported in combustion has been decreased in the new organization, the prime research needs in combustion are recognized.

Figure 1 is a cut-away view of a representative combustor which illustrates the complex fluid mechanics and combustion features. The flows are highly three-dimensional with turbulence levels in many cases comparable in magnitude to the bulk velocity. Liquid fuels are injected as a spray which then undergoes vaporization and mixing. Chemical reaction occurs which causes changes in density and fluid mechanics properties and can cause the formation of a solid phase (soot) with its attendant high radiation heat transfer. The understanding of these physical processes is needed before accurate numerical codes can be built and used as a predictive tool in the design process. In this paper, research needs will be highlighted in the areas of flame stabilization, combustion aerodynamics, heat transfer, multiphase flow/atomization, turbulent reacting flow, and chemical kinetics. In addition the numerical methods for three-dimensional flows need improvements in accuracy and efficiency in order to properly simulate the features of these flows. Research needs in computational fluid mechanics for reacting flows will also be discussed.

## Flame Stabilization

A flame is stabilized in a gas stream by creating a local region where the velocity is less than or equal to the turbulent burning velocity of the fuel and oxidant mixture. There are two principal methods of providing the required region of low velocity: a wake created by a bluff-body flameholder and a region of reverse flow created aerodynamically, usually by means of swirl. Often a combination of these two phenomena occur. This involves very complicated flow and chemical interactions that are poorly understood at present. Flame size, shape, stability and combustion intensity are all influenced by the swirling flow.

Fluid dynamics computer codes are being developed for the mathematical simulations of flows in aeropropulsion combustors. It is important that these codes have the ability to accurately and reliably calculate swirling flow, both the time-mean and fluctuating quantities. Failure to make a realistic prediction of basic flame holding and heat release processes will seriously compromise the efficacy of the overall calculations. Our understanding of swirling flows and the generation of recirculation zones is superficial at best and our ability to calculate these flows reflects this understanding. In addition, current computer codes are steady-state: they assume the existence of a stationary condition that may not actually exist in the real flow. Research is needed to fully characterize swirl generators, including the relative roles played by turbulence and nonstationary flow. With the advent of large multiprocessor computers such as the National Aerodynamic Simulator (NAS) opportunities exist to develop innovative time-dependent computer codes to simulate these flows.

A better understanding of the interaction of the chemistry with the fluid mechanics is also needed. Fundamental work on the physical and chemical processes involved in flame extinction and blow-off is necessary to supplement current largely empirical design practices.

## Combustor Aerodynamics

Combustor aerodynamics refers to the study, prediction and control of overall flow patterns inside the liner of an aeropropulsion combustor. These flow patterns play a dominant role in determining conditions in the combustor and have great influence on performance characteristics. Our current knowledge of the flow patterns existing in combustors is imprecise and largely empirical with limited contributions in recent years from numerical flow predictions. Continued demand for efficient, compact, low emission combustors are placing extreme pressure on combustor design which cannot be met without excessive development costs with today's operative but immature design technology. Continued basic research is needed to improve our fundamental understanding of combustor aerodynamics and to help in the development of new sophisticated design tools (computer codes) adequate for present and future needs.

Examples of current, pressing technical problems related to combustor aerodynamics include the following: (1) large localized wall heat flux loads exist associated with power transients and hot streaks. (2) Inadequate control of the temperature distribution at the combustor exit adversely affects turbine heat transfer and blade life. Design goals typically specify <u>mean</u> temperature profiles, but evidence is accumulating that the magnitude of temperature fluctuations about the mean is also of practical importance to blade life. (3) Relight at altitude is a perennial problem in which aerodynamics plays an important role. (4) Air pollutant emissions control will continue to be important as higher performance is achieved. Our current largely empirical knowledge of aerodynamics is not sufficient in breadth and depth to enable the design of cleaner combustors. (5) Overall combustor pressure drop must be kept to a minimum. (6) High noise and vibration levels are sometimes related to aerodynamic factors.

These technical problems require solutions that our current understanding of aerodynamics cannot support. Thus there is a need for fundamental research in aerodynamics and the state of our knowledge and the research tools available suggest that the time is right for addressing many of our problems from a fundamental perspective. The techniques of computational fluid dynamics (CFD) can and are being applied to combustor aerodynamics. A key to applying CFD will be the development of applicable turbulence models. We must also work on better boundary condition specification. Finally, we must improve our general understanding of flow patterns for the types of flow encountered in combustors. Further experimentation is needed in support of this CFD effort, in simple flow systems, bench scale combustors, and more realistic hardware.

## Heat Transfer

In the combustion chamber of aeropropulsion systems the metal liners forming the combustor have to be provided with some form of thermal protection from the high temperatures of the reacting gases contained therein. Thermal stresses, high temperature erosion, high temperature strength characteristics, and crack formation and growth due to thermal cycling are all major factors influencing liner wear and durability. Thus there are obvious gains to be had from improved heat transfer performance in keeping liner temperatures low and uniform. Current developments and design trends, however, make this task difficult. Some factors influencing design include increased radiative heat transfer stemming from higher combustion temperatures and increased soot levels, reduced cooling air flow due to increases in overall combustor equivalence ratio, and increases in demand for dilution air for improved gas temperature distribution. Increasing operating pressure also increases heat transfer loads, due especially to radiation.

Radiant heat transfer from flames is a prime contributor to durability problems of engine components. Unfortunately, this flame radiation is very complex since it is emitted from a turbulent reacting flow. This introduces effects of turbulent fluctuations on radiation as well as soot formation and properties in flames which are just beginning to be understood.

Moreover, problems of flame radiation will become more acute with trends toward higher combustor pressures, loss of fuel quality, and less available cooling air. Advanced liner materials will have greater thermal resistance but reduced ductility; therefore thermal cycle fatigue due to time varying loads will still be a problem. A clear need exists therefore to develop a better understanding of flame radiation at this time. More specifically, work is needed to develop improved models for predicting radiative heat fluxes at the wall properly coupled with aerodynamic models for the overall liner flow patterns. Advances in this area will be contingent on the development of applicable soot formation and oxidation models. There are currently a number of focussed research activities looking at the chemistry involved in the formation of soot. Excellent progress has been made to date and with continued effort quantitative simulation of soot nucleation and growth can be expected.

## Multiphase Flow/Atomization

Spray combustion processes are a central issue in aeropropulsion systems. Current understanding of these processes is very incomplete, however, since they involve multiphase turbulent reacting flow. The view was held that the atomization process in aeropropulsion engines is well understood, using empirically based equations for estimating the Sauter mean drop size produced by fuel atomizers. However, recent work suggests that these equations are inaccurate and are not applicable over a sufficient range of operation.

In addition, both the radial and circumferential fuel distributions of atomizers can exhibit appreciable nonuniformities. These distributions cannot be predicted by the empirical based design techniques, and yet may lead to very serious performance problems with the combustor, such as hot streaking or high soot formation resulting in locally high liner heat transfer.

Work is needed to examine nozzle features that influence the radial and circumferential fuel distributions. More fundamental work is needed on the atomization process itself, to elucidate the basic mechanisms whereby a jet or sheet of liquid is converted into a multiplicity of small drops. More work is needed on spray dynamics, drop trajectories, droplet drag coefficients, etc., for evaporating sprays injected into highly turbulent, swirling air streams. With laser-based diagnostic tools now becoming available, an opportunity exists for significant progress in this field.

The powerful tools of computational fluid dynamics are being applied to fuel sprays, and the potential exists to develop codes that can be used effectively in the industry. Detailed data required for the validation and assessment of these codes does not currently exist, however. Data are needed for a variety of conditions, of increasing complexity, to establish a data base against which numerical codes can be exercised. Based on progress over the last few years, major advancements in this field appear within reach in the near future.

## Turbulent Reacting Flow

A useful discriminant of two limiting regimes of turbulent combustion is the ratio of the thickness of a laminar flame to a suitable length scale of turbulence. If this ratio is small then the turbulent flame consists of wrinkled laminar flames; if it is large then the turbulent combustion occurs in a distributed-reaction zone. Most practical combustors lie more nearly in the regime of wrinkled laminar flames, although small high intensity combustors may fall in the distributed reaction regime. Approaches to modeling turbulent combustion differ for the two regimes, and the relevant experiments also differ. Further research, both experimental and theoretical, is needed for each regime.

Experimental research on flame stabilization in small high-intensity combustors is needed to better characterize the distributed-reaction regime. Influences of variations in design parameters on stability ranges, efficiencies, local heat loadings, etc., should be obtained using modern diagnostic techniques. These same methods should be applied to turbulent flames in the large-scale wrinkled laminar flame regime. In addition, measurements of structures, stability dynamics, and extinction of stretched and curved laminar flames are needed.

Theoretical studies along many different promising lines are needed for improving capabilities of numerically calculating flows with turbulent combustion. Analyses of wrinkled laminar flames are needed in which turbulent dispersion, hydrodynamic instabilities, and modifications of flame-sheet dynamics are accounted for. Two-fluid models with different and separate modeling of burnt and unburnt gas need to be developed. Approaches to closure of PDF evolution techniques must be explored. Sub-grid-scale modeling of reaction effects in numerical simulation techniques must be developed. Ways to account for vorticity generation by heat release should be found for random-vortex methods. This list is by no means complete but simply illustrates kinds of research that could prove fruitful.

## Chemical Kinetics

Chemical kinetics influence the use of alternative fuels, ranges of stability and relight, and the formation of soot and other pollutants. Large computers have made it feasible to model combustion processes using literally hundreds of elementary reactions and, more importantly, sensitivity analysis provides methods of extracting information from these models (i.e., which reactions are most important). Applications of these detailed chemical mechanisms in turbulent fluid mechanic models is not currently feasible and drastically simplified chemical mechanisms are required. The applicability of various simplified mechanisms to various combustion regimes can be assessed by comparing computer calculations using the simplified and the detailed mechanisms. Thus the need for simplified chemistry models does not lessen the need for detailed understanding of chemical kinetic rate constants and mechanisms. Research has been steady in this area for many years and excellent results have been achieved to date. Continued efforts in chemical kinetics is required as new aeropropulsion systems are identified with attendant demands on combustor performance.

Experimental research in this area is also needed. Controlled experiments using a shock tube, flow reactors, or one- or two-dimensional premixed or diffusion flames may be used to probe the chemistry of fuel-air reactions. Emerging diagnostic tools such as highly sensitive mass spectrometers and nonlinear laser spectroscopy enable measurements of minor species to be made. Dedicated minicomputers allow these measurements to be analyzed in a fraction of the time previously required. These tools need to be applied to areas such as the formation and control of soot, ignition and blowout of flames, and high speed combustion. The interplay between the numerical calculations and experimental measurements can be of valuable benefit in unlocking the mysteries of flame.

## Computational Fluid Mechanics for Reacting Flows

In 1983 Lewis Research Center sponsored a program to evaluate the capability of current computational fluid mechanics for use as a design and analysis tool in gas turbine engine combustor development. Three contractors participated in this study: Garrett Turbine Engine Company, General Electric, and Pratt & Whitney Aircraft. The conclusions from these three independent evaluations were quite consistent. Serious difficulties exist with the present generation of computational fluid mechanics codes for application to the combustor. However, the economic and competitive driving forces in the industry that gave rise to the present codes are still real and urgent, and these codes have indeed demonstrated great potential for productivity improvement in addition to improved technical capability. Two-dimensional codes have the capability for use today to establish trends and as a tool in diagnostic studies of relatively simple flows. Complex fully three-dimensional flows cannot be accurately predicted at this time. Computer size and speed limits the grid density in these calculations and numerical diffusion with today's differencing schemes then dominates the calculated results. A hierarchy of physical modeling exists, and the accuracy achieved with a given model depends as much on preceding models in this hierarchy as on the particular model itself. Their recommendations for future research included: (1) improved numerics and solution algorithms; (2) turbulence modeling to account for large scale nonisotropic turbulence and coherent structures; (3) benchmark data for code verification, especially with highly turbulent flows and two-phase flows. Research in turbulence/chemistry interaction, improved chemical kinetics, and flame radiation are also important, but effects of these submodels are currently overwhelmed by numerical error and the turbulence model shortcomings in complex three-dimensional flowfields.

More specifically, research in improved numerical methods is needed. The hybrid finite difference scheme most commonly used has been shown to be unsuitable for turbulence model studies, and to give misleading results when used with grid densities currently affordable for three-dimensional and elliptic flow calculations. Replacing this scheme with anything better is a difficult but necessary task. It also is realized that more forgiving solution algorithms are needed for compatibility with finite difference schemes being evaluated. Clearly, there is a need for work on solution algorithms. Compatibility should result in a much-needed speed-up in convergence rates. Use of computer architecture with multi-processor capability also has high promise for improved calculation efficiency. Finally, work on mesh generation and body fitted coordinate systems also is needed to better describe the flow of interest. Unphysical sharp corners must be eliminated and high gradient regions properly accounted for in the calculations.

In the area of turbulent flow modeling, three basic approaches can be defined: finite-difference solution of the Reynolds-averaged equations of motion, vortex dynamics techniques, and solution of the Navier-Stokes equations for large turbulence scales by pseudo-spectral methods. Reynolds-averaging of the Navier-Stokes equations sacrifices a large amount of turbulence information in exchange for a relatively simple procedure. This exchange reduces the amount of information that can be extracted from the solution, and only time-mean flow pictures are obtained. An alternative approach is to use Monte Carlo methods to solve velocity-scalar transport equations for the joint probability density function. It voids the need for a turbulence model and does not require a grid and is therefore free from numerical diffusion. This method is not extensively developed and as a potential second-generation code should be studied.

A new era in theoretical combustion research is evolving in which the closure problem associated with the Reynolds averaged equations can be bypassed by numerically solving the time-dependent Navier-Stokes equations. Although this approach removes a major impediment, there are new constraints imposed, the most serious being that the computer memory and speed dictate the turbulent scale that can be resolved. Current calculations are restricted to relatively low Reynolds number flows, but projections of computer growth suggest that within a decade computations should be applicable to flows with Reynolds numbers in the tens of thousands. Indeed the future use of direct numerical simulations to study turbulent combusting flows seems very promising, but much work remains to be done on this emerging technique.

Procedures based on the random vortex method also provide solutions of the Navier-Stokes equations. Since the basic, highly nonlinear equations allow it, this approach is sensitive to imposed boundary conditions, and it can become questionable if the time-dependent flow structure development calculated is "real" or is due to the imposed boundary conditions. Nonetheless, it is attractive because there are no closure problems that require modeling and it is a grid-free procedure. This solution method allows the detailed interactions of turbulent eddies at all scales in a rapidly changing field to be reproduced. Results to date have been promising, but much more development work is required before this technique can be used as a development tool for advanced propulsion combustors where the time-dependent solutions are essential.

In summary, the thoughts expressed in this section really must be integrated with what was said in the previous six sections. Much research needs to be done in connection with flows with chemical reactions in order to bring internal computational fluid mechanics to a state of practical application to propulsion systems. The chemistry and combustion effects on the viability of numerics for turbulent flows must receive special attention.

## Concluding Remarks

The national goals in aeronautics established by the Office of Science and Technology Policy will require support in the basic research and technology areas. Enabling research in combustion science is critical to the successful implementation of new advanced propulsion systems in support of these aeronautics goals. Although the research needs cited above appear formidable, the progress achieved in most of these areas in the last few years has been very encouraging. New ideas in computer architecture and numerical methods are materializing at a fast pace and the challenge is to ingeniously apply these computer advances into real problems of chemically reacting fluid mechanics. Diagnostic instruments are now available to obtain fluid mechanics experimental data at a level of detail not before possible. Instruments on the horizon will enable even more complete and detailed measurements to be obtained. Here the challenge is not only to effectively use these instruments in research, but also to apply computer capability to the analysis and tactile display of this enormous amount of experimental data. In short, opportunities exist today in combustion research to make significant breakthroughs in understanding complex areas of physics and chemistry. These breakthroughs will permit advanced aeropropulsion systems to be successfully developed for application into the areas of subsonic transports, supersonic aircraft, and hypersonic vehicles.

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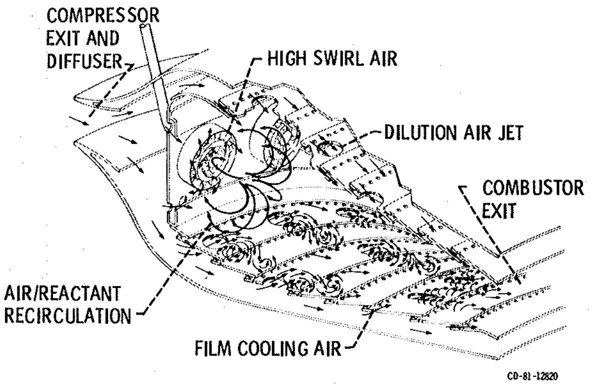


• FULLY 3-DIMENSIONAL FLOW
• CHEMICAL REACTION/HEAT RELEASE
• HIGH TURBULENCE LEVELS
• 2 PHASE WITH VAPORIZATION

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

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