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Computer Modeling in Ramjet Combustors

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Abstract

PROBLEMS and progress in the simulation and solution of complex turbulent reacting flows for ramjet combustor applications are surveyed. The full paper reviews the difficulties, discusses developments, and demonstrates that useful predictions are already being made to aid designers. Areas in which further detailed numerical prediction research will be most useful include (for the nonreacting case) recirculation zone characterization, turbulence simulation in swirling recirculation flow, irregular boundary representation (via analytical or numerical transformation techniques or finite element methods), and further complexities and parameter influences; and (for the reacting case) the simulation of complex chemistry, the turbulence/chemistry/spray interaction problem, and application to realistic three-dimensional problems.

Contents

The basic ramjet combustor configuration is the so-called sudden expansion dump combustor. In this type of combustor, liquid fuel is sprayed into the ram air upstream of the dump station, although it may also be injected directly into the chamber via side-wall inlets. Primary flame stabilization is provided by the flow recirculation regions, which may be supplemented, at the expense of total pressure loss, with mechanical flameholding devices at the air inlet/combustor interface and/or the presence of inlet air swirl, obtained by the use of tangential injection or swirl vanes. The flow throughout is multiphase, subsonic, turbulent, and involves large-scale corner recirculation zones. With strong swirl in the inlet flow a central toroidal recirculation zone (a recirculation bubble in the middle of the chamber near the inlet) also presents itself. Even gross features of the flow are not known quantitatively with certainty: for example, factors affecting the existence, size, and shape of the recirculation zones.[1]

The designer has a formidable problem in aerothermochemistry, and the modeling task is to provide a route which leads to the accomplishment of design objectives more quickly and less expensively than current practice permits. Some combustor modeling problems are 1) physical processes: turbulence, radiation, combustion, and multiphase effects; 2) computer programs: 0-, 1-, 2-, and 3-D approaches in steady-state and transient cases; 3) unresolved problems: irregular boundary representation, effect of swirl, recirculation, and wall proximity on turbulence, turbulence—reaction interaction, multiphase simulation.

Current combustor design and development problems, the needs of the combustion engineer in practice, and proposed research tasks which will assist in the attainment of design objectives are becoming clear. Improvements and new developments (both experimental and theoretical) can and should be made, theoretical modeling being aided by specific carefully chosen experiments being performed.

Mathematical models of steadily increasing realism and refinement are being developed, both in the dimensionality of the model (together with the computational procedures) and in problems associated with the simulation of the physical processes occurring. In the modeling and prediction of swirl flow combustion, one is involved with simulating the problem via simultaneous nonlinear partial differential equations. These may be parabolic (boundary layer type) but are more often elliptic (recirculating type) and the solution scheme differs according to the category.

Because application of the general partial differential equations is complex, time-consuming, and in a development stage, simplified approaches to the problem are extremely popular. The most common models include perfectly stirred reactors (PSRs), well-stirred reactors (WSRs), and plug flow reactors (PFRs). Models differ in how these are interrelated to simulate various aspects of the mixing/reaction taking place. An important problem in finite rate chemistry is choosing an appropriate level of complexity, in view of the large number of species and chemical reactions taking place. One solution to this problem is the use of the quasiglobal rection scheme whose key element is a unidirectional subglobal oxidation step. Coupled with this are a number of intermediate reversible reactions. The model affords a useful computer time saving as compared to a full finite-rate chemical kinetics formulation. Well-known models are categorized as integral, modular, or hybrid. Modular[2,3] methods give useful qualitative trend predictions and, when amalgamated with finite difference flowfield predictions via 2-D axisymmetric[4] or fully 3-D approaches,[5] excellent results are available.

Most combustion systems exhibit recirculation, and full flowfield prediction requires iterative solution techniques. Axisymmetric simulations give rise to 2-D elliptic problems and involve 2-D storage, stream function-vorticity ψ-ω or primitive pressure-velocity p-u-v formulation, and Gauss-Seidel point-by-point iteration or line-by-line SIMPLE (semi-implicit method for pressure linked equations) iteration procedures, the line methods involving the TDMA (tridiagonal matrix algorithm). The essential differences between the various available computer codes include the following: the complexity of the equation set for the simulation of the physical processes, the storage requirements, the location of variables in the grid space system, the method of deriving the finite-difference equations that are incorporated, and the solution technique. In primitive pressure-velocity variable formulations a staggered grid system is normally used, as recommended by Los Alamos for its special attributes. In computational fluid dynamics the "best" representation of the convection and diffusion terms is essential to the accuracy and convergence of the iteration scheme. At high cell Reynolds numbers a certain degree of "upstream differencing" is essential, using, for example, these techniques: upwind differencing, a hybrid formulation or the Los Alamos zip, donor cell, etc. Sample recent numerical prediction studies include Refs. 6 and 7 for the ψ-ω approach and Refs. 8 and 9 for the p-u-v approach. Excellent trade-off between code complexity and quality of flowfield

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patterns is available via the axisymmetric approach. For example, in Ref. 9 computational results show the interesting effects of several combustor design parameters, such as degree of swirl, performance of a recirculation zone amplifier ("trip"), and effect of laterally induced secondary air supply on subsequent flowfield development and combustor performance (for example, velocity, temperature, and composition distributions, the occurrence of recirculation zones, and flame size, shape, and combustion intensity).

Practical ramjet combustor designs exhibit many nonaxisymmetric features mainly because of air and fuel inlets at discrete circumferential locations. The requirement to predict a fully 3-D flowfield arises. Recent significant contributions to 3-D combustor flowfield prediction are exemplified in Refs. 5 and 10-13, where application has been to the furnace and gas turbine fields. Computationally, the techniques are very similar, except handling very high combustion intensities in the latter case causes additional problems. Implicit techniques for 3-D flows with recirculation have the advantage of efficiency and stability in their computations. All the work cited is implicit in character and solves directly for pressure and velocities; a staggered mesh system is used and some degree of upstream differencing is used for the convection terms at high cell Reynolds numbers. Perhaps Ref. 5 is the most ambitious in being a hybrid technique. The finite difference solution of some 30 partial differential equations on a $27 \times 18 \times 7$ grid system provides input to a modular approach which handles realistic chemical kinetics, with presently 13 species undergoing 18 reactions. Encouraging results are portrayed for a variety of flow types.

In deciding and justifying the use of a particular procedure, one has some deliberation. One of the objectives of the present full paper was to clarify the choice and give appropriate advice, emphasizing computer application where appropriate. For example, at the present time the usefulness of a fully 3-D computer code in practice is not clear. Again, recent discussions have doubted the industrial value of this, especially when current practice and many problem areas involve use of 0-D and 1-D models, as successful application of modular and hybrid schemes reveal. The 2-D and 3-D approaches do possess the possibility of being eventually capable of a higher degree of realism, but model accuracy is in doubt, time and cost requirements are large and, more specifically, many current needs do not demand them.

Model experiments designed to highlight specific subproblems and their interactions (and not complex combustor flows) should receive attention for model development and validation. Computational results show some of the interesting effects of combustor design parameters on subsequent flowfield development and combustor performance. Computational experiments can be, should be, and have been performed which complement test cell data describing the internal flowfield characteristics. Theoretically, it is in the area of parameter influences that computer programs show their supremacy in terms of time and cost savings as compared with experimental work. Progress will lead to more realistic and cost-effective practical combustor modeling. This, and continued development on the accuracy of the simulation of the physical processes involved, should elevate computer modeling to an established place in practical combustor design and development programs.

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