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DEPARTMENT OF MECHANICAL ENGINEERING AND MECHANICS
SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

COMPUTATIONS IN TURBULENT FLOWS AND OFF-DESIGN PERFORMANCE PREDICTIONS FOR AIRFRAME-INTEGRATED SCRAMJETS

By

E. Spiegler

G.L. Goglia, Principal Investigator

Final Report

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Under
Research Grant NSG 1348
October 1976 - October 1977
Harry L. Beach, Technical Monitor
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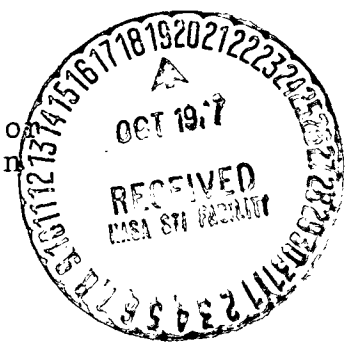

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By

E. Spiegler[1]

INTRODUCTION

The research activity has focused on two main tasks:

1. The further development of the SCRAM program and, in particular, the addition of a procedure for modeling the mechanism of the internal adjustment process of the flow, in response to the imposed thermal load across the combustor.

2. The development of a numerical code for the computation of the variation of concentrations throughout a turbulent field, where finite-rate reactions occur. The code also includes an estimation of the effect of the phenomenon called "unmixedness" (refs. 1, 2).

At this time both tasks can be considered practically completed. Some minor changes or additions might still be necessary, but the programs are debugged and have been operated in test computations. Since both tasks have been carried out in collaboration with Hypersonic Propulsion Branch specialists in their respective fields, the operation and further development of the resulting computer programs should not represent any problem.

THE INTERNAL ADJUSTMENT MODEL FOR SCRAM

Following a survey and critical assessment of some published models for the behavior of supersonic combustors (refs. 3 to 6), Billig's model, developed and extensively used at the Applied

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Physics Laboratory at Johns Hopkins University (refs. 6, 7), has been selected as the most adequate for the SCRAM program. The reasons for this choice are that (1) the mode has been confirmed experimentally (although mostly for axisymmetric configurations having a single fuel-injection station), and (2) it can be used not only to interpret measurements, but also to predict them.

Billig has postulated that:

1. a diverging supersonic combustor has a built-in internal adjustment capability,

2. the adjustment process starts long before critical conditions are reached within the combustor,

3. the mechanism of the adjustment process consists of either a system of separated flow and oblique shock waves, or of a normal shock, located, in both cases, in the region where the fuel is injected, and

4. the adjustment process is spontaneous and dependent on the imposed thermal load and on the flow properties at the entrance to the combustor.

The conservation equations system is closed by using Crocco's assumption (ref. 8) concerning the static pressure dependency on the local cross section (i.e., $P_w A^{\varepsilon/(\varepsilon-1)} = \text{const.}$, ε being a constant). Experiments seem to indicate that, among the many possible mathematical solutions for a given set of data (combustor geometry, initial flow properties, and the overall total temperature ratio), the one chosen by the flow is that which exhibits isentropic behavior in the exit region of the combustor, i.e., for which

$$\left(\frac{dP_w}{dA}\right)_{exit} = \left(\frac{dP}{dA}\right)_{isentr} .$$

It comes out that this solution also yields the highest total pressure recovery across the combustor (ref. 6). It has been

found, however, that some of Billig's assumptions--especially the Crocco relationship--were needlessly restrictive. Also, the criterion by which the "physical" solution is selected among the "mathematical" ones implies a variation of the combustion efficiency, η_c, along the combustor, that cannot be accepted as generally valid.

In order to overcome these shortcomings, the following modifications have been introduced in Billig's original model:

1. An η_c versus A experimental correlation is used, instead of Crocco's assumption, to close the conservation equation system.

2. The combustion efficiency rate of change $(d\eta_c/dA)$ is assumed to increase with the shock system strength, as expressed by the static pressure ratio across the shock, P_s/P_a. Thus, P_s/P_a and $\eta_c = f(A)$ are interrelated. The local values of η_c are, however, bounded by the experimentally determined local mixing efficiency.

3. Among all the possible mathematical solutions (one for each assumed value of P_s/P_a), the flow will prefer the one giving the highest overall total pressure recovery, while still satisfying entropy increase compatibility conditions in the shock system influence region.

4. When the fuel is injected at two stations, the flow may adjust twice, upstream of each injection station. The strength of each shock system is determined by the flow properties at the entrance to, and by the overall thermal load imposed on, the respective section of the combustor (section 1: between the first and second injection points; section 2: between the second injection point and the combustor exit). According to this model there is no "upstream" interaction between the two sections, the only link between them being the flow properties at the exit of the first section, which is also the entrance to the second section.

5. If thermal choking is predicted in the combustor for all physically possible values of P_s/P_a [1], then the engine will become subcritical. In this version of SCRAM, it is assumed that shock waves cannot appear in the combustor when the engine is subcritical.

A subprogram based on Billig's modified model was developed and inserted into a previous version of SCRAM (ref. 9). The resulting new version, SCRAM 4, is capable of estimating the performance of the Langley SCRAMJET Module in both the subcritical and the supercritical mode; this last case includes the internal adjustment model described above.

SCRAM 4 has been carefully checked and debugged, and several test cases have been computed. The results obtained so far and their trends are reasonable and within the expected range. Full instructions for operating the program, as well as an updated card deck and the program listing, have been prepared for and provided to the Components Group.

Even though some of the SCRAM 4 main assumptions have yet to be verified experimentally, it is believed that no major modification of the basic procedure will be necessary.

FINITE-RATE REACTIONS IN TURBULENT FLOWS

Among all the input data needed for the computation of a scramjet performance, the variation of the combustion efficiency along the combustor is of capital importance. Theoretical estimations of this variation are needed not only in the preliminary design stage, but also as a guiding tool during the combustor hardware development.

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[1] $P_s/P_a = 1$; $(P_2/P_1)_{sep} \leq P_s/P_a \leq (P_2/P_1)_{det}$; $P_s/P_a = (P_2/P_1)_{NS}$

where 1 = before shock, 2 = after the shock, sep = minimum for separation (ref. 10), det = maximum before oblique shock detachment (ref. 11), NS = normal shock value (ref. 11).

In order to obtain such an estimation, the Navier-Stokes equations, as well as the conservation equations for the total enthalpy, concentrations, parameters defining the turbulence level, etc., must be solved. For realistic and useful results, the flow field should be at least two-dimensional, and finite-rate chemistry should be used.

Modern computers are capable of handling such complex problems. Numerical codes for solving turbulent parabolic and elliptic non-reactive flows have been developed in the last 12 years and widely used throughout the world (refs. 12, 13). However, when the finite-rate chemistry is also introduced, numerical difficulties arise. Due to the "stiffness" of the concentrations conservation equations system (ref. 14), divergence usually occurs, unless very small computational steps (or a very fine grid in the case of elliptic flows) are used.

Recently, a procedure for overcoming the stiffness problem has been developed by this author and coworkers (ref. 15). Instead of the conventional, constant-rate-of-change assumption, a family of functions, called "the decay functions," is defined and used to express the local variation of the concentrations during a computational step (or an iteration) between initial and equilibrium values. The decay function family satisfies initial and boundary conditions, overall and chemical elements conservation, and all physical limitations. It has been proved that the use of this procedure eliminates the size of the computation step (or of the grid element) as a factor of numerical divergence (ref. 15).

The theoretical predictions of the concentrations profiles in a reacting field are much improved if the effect of the phenomenon called "unmixedness" (ref. 1) on the reaction rates is taken into account. The unmixedness slows down the reaction rate, as a result of the fact that, due to local fluctuation of the concentrations in a turbulent field, the reactants involved are not always present in the same place at the same time (ref. 2). A procedure to quantify this effect has been developed recently and proved quite satisfactory (ref. 16).

After considering the amount of work involved and the time available, it was decided last April to initiate the development of a general code for the computation of the concentration rate-of-change in a turbulent field, where finite-rate reactions occur. Unmixedness effects were to be accounted for. First priority was given to the insertion of this code in an existing parabolic program (ref. 17), while a secondary effort was directed toward the development of a separate program for elliptic flows, starting with an available listing of such a program (ref. 18). J.S. Evans and C.J. Schexnayder of the Combustion Group were actively involved in this activity.

Approximately five months after the beginning of this task, the following achievements can be summarized:

1. A code including finite-rate chemistry and unmixedness, but without using the decay function model, has been developed and introduced in the parabolic program. A first comparative computation has given results which are in satisfactory agreement with experimental data obtained by H.L. Beach and coworkers (ref. 19). The penalty in computer time was large but not prohibitive.

2. Cards for the elliptic program have been punched, and that part of the program that deals with mixing flow only has been debugged and operated in two test cases, one of them with recirculating flow (refs. 20, 21). It has been found that, when the boundary conditions are properly defined, satisfactory agreement is obtained with experimental data.

3. A procedure including the decay function concept has been developed and introduced into the parabolic program. Debugging and test computations are under way.

4. The reaction part of the elliptic program is presently being debugged, and comparative computations are planned.

Considering the relatively short amount of time during which this amount of work has been done, the results can be considered as very satisfactory and the whole effort definitely worthwhile.

CONCLUSION

It is hoped that the results of the activity summarized in this report will represent a positive contribution to the theoretical capability of the Hypersonic Propulsion Branch. In the author's opinion it will be beneficial to both parties for information on results obtained from, or on modifications and further developments of, the computer programs described in this report to be exchanged in the future.

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