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Technical Notes

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Aerothermodynamic Analysis of Combined-Cycle Propulsion Systems

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Introduction

COMBINED-CYCLE propulsion systems exploiting the advantages of both air-breathing and rocket propulsion subsystems, have been identified as the candidates for propulsion of the future single-stage-to-orbit vehicles.[1-3] This class of propulsion systems has multimode operating capabilities and the flexibility to provide mission-required thrust for both acceleration and cruise while thermodynamically matching a wide range of flight conditions to minimize the fuel consumption. Flexible takeoff and landing capabilities, simpler logistics, and total reusability, are some of the advantages of these propulsion systems. Combined-cycle propulsion systems encompass a wide variety of combinations of conventional and nonconventional propulsion subsystems. Some combinations have been discussed by Esher,[3] Kors,[1] and Ganji et al.[4,5]

This note describes a PC-based computer program called combined-cycle propulsion systems analysis (CCPSA) which has been developed for design-point aerothermodynamic analysis of a series of combined-cycle propulsion systems which can be formed from a combination of ramjet, rocket, turbojet, turbofan, and scramjet propulsion subsystems. Some typical results of the program will also be discussed. The combined-cycles which can be analyzed by CCPSA are 1) turbojet/ramjet, 2) turbojet/rocket, 3) turbojet/ramjet/rocket, 4) turbojet/scramjet, 5) turbojet/scramjet/rocket, 6) turbofan/ramjet, 7) turbofan/rocket, 8) turbofan/ramjet/rocket, 9) turbofan/scramjet, 10) turbofan/scramjet/rocket, 11) rocket/scramjet, and, 12) turbo/air-augmented rocket.

The program, while using hydrogen and hydrocarbons as the fuel for propulsion subsystems, is capable of producing specific impulse (Isp), thrust-specific fuel consumption (TSFC), and air-specific thrust (AST) for various operational conditions of the components, subsystems, and combined cycles from takeoff to hypersonic flight conditions. Design and operational parameters including flight conditions, component efficiencies and losses, combustion chamber(s) temperature, nozzle(s), and diffuser(s) area ratios are inputs to the program. For details the reader is requested to consult the report by Ganji, et al.[5]

Mathematical Models

Mathematical models for the steady-state design-point operation of the components, subsystems, and the combined-cycles, were developed using the basic physical principles as outlined by Hill and Peterson.[6] For analysis of the scramjet, the methodology developed by Waltrup, et al.[7] was followed. Table 1 lists the components and subsystems for which the models have been developed.

In the combined-cycle configurations considered in this work, the subsystems operate as individual propulsion systems integrated into one engine structure. The air-breathing subsystems (with the exception of the scramjet) in one engine may have either mixed or separate nozzles. With this premise, we can look at the performance of individual subsystems and also investigate the overall performance of a combined-cycle when all or some of the subsystems are in operation. For the combined-cycles considered, the relevant performance parameters are developed below.

Thrust, F

$$F = \sum_j [m_{e,j}U_{e,j} - m_{a,j}U_{a,j} + (P_{e,j} - P_a)A_{e,j}] \qquad (1)$$

Specific Thrust, SPT

$$\text{SPT} = F/m_p = F\Big/\sum_j m_{P,j} \qquad (2)$$

Air Specific Thrust

$$\text{ASP} = F/m_a = F\Big/\Big(\sum_j m_{a,j}\Big) \qquad (3)$$

Thrust Specific Fuel Consumption

$$\text{TSFC} = m_f/F = \Big(\sum_j m_{f,j}\Big)\Big/F \qquad (4)$$

Specific Impulse

$$\text{Isp} = F\Big/\Big[\Big(\sum_j m_{p,j} - \sum_j m_{a,j}\Big)g_0\Big] \qquad (5)$$

The summation is on all subsystems of the engine as they operate in the integrated system. It has been assumed that the performance of each subsystem in the integrated engine is independent from the rest of the subsystems. The symbols a, ab, A, e, f, i, m, p, and P refer to ambient air, air-breathing, area, exhaust, fuel, inlet, mass flow rate, products, and pressure, respectively.

For calculation of the above performance parameters (in addition to the internal and performance parameters of individual components and subsystems) it is essential to know the ratio of the exhaust mass flow rates of the subsystems. For the case of air breathers (ab) this ratio is

$$m_{e,\text{ab1}}/m_{e,\text{ab2}} = (A_{i,\text{ab1}}/A_{i,\text{ab2}})[(1 + \text{FAR}_1)/(1 + \text{FAR}_2)] \qquad (6)$$

where FAR is fuel-air ratio. For this case, the relative size of the engines (as determined by their effective inlet area ratios)

Table 1 List of components and subsystems

Components	combustor/afterburner/duct-burner, compressor/fan, diffuser (inlet), mixer, nozzle, turbine$_{\parallel}$, thru-duct
Subsystems	ramjet, rocket, turbofan, turbojet, scramjet

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will be an independent parameter. For the case of combination of air-breathers and rocket r engines, the ratio of propellant mass flow rates is directly proportional to their nozzle throat (th) area ratio as shown below:

$$m_{e,r}/m_{e,\mathrm{ab}} = (Q_{\mathrm{th}}A_{\mathrm{th}})_r/(Q_{\mathrm{th}}A_{\mathrm{th}})_{\mathrm{ab}} \qquad (7)$$

where

$$Q_{\mathrm{th}} = (k_{\mathrm{th}}R_{\mathrm{th}}T_{\mathrm{th}})^{1/2}\, P_{\mathrm{th}}/R_{\mathrm{th}}T_{\mathrm{th}}$$

In Eq. (7) all parameters except $A_{\mathrm{th},r}/A_{\mathrm{th,ab}}$ are calculated in the analysis of the subsystems and are independent from $A_{\mathrm{th},r}/A_{\mathrm{th,ab}}$ which represents the relative size of the two subsystems. In the present analysis, the rocket engine never acts as an ejector for the air breathers, and always have a separate nozzle to avoid excessive expansion in the mixer. Some of the other options incorporated in the program are complete and equilibrium combustion, and frozen and equilibrium nozzle expansion.

Sample Results and Discussion

The performance of turbojets and ramjets produced by the current computer program have been compared with the data of Hill and Peterson.[6] ASP produced by the current program is up to 15% higher than those of the above reference. The results of Hill and Peterson are based on the assumption of constant specific heat gases and heat transfer (instead of fuel addition) in the combustor, whereas in the present calculations these assumptions have been waived. Figure 1 compares the Isp for hydrocarbon fueled (except scramjet) air-breathing engines and a typical rocket along a trajectory of 1000-psf constant dynamic pressure. This figure shows the clear advantage of the air-breathers over rocket engines. This is especially the case for scramjets at hypersonic flight conditions. Figure 2 shows the performance of a typical scramjet along the above trajectory for two cases of constant-exit stagnation temperature, and constant-temperature rise in the combustor. This figure shows that if the stagnation temperature at the exit of the combustor is held constant, scramjet performance will sharply drop at high Mach numbers. To sustain high performance at hypersonic Mach numbers, the temperature rise should remain approximately constant.

Figure 3 shows the Isp with respect to the Mach number along a typical trajectory of 1000-psf constant dynamic head for turbojet/ramjet, turbofan/ramjet, turbojet/rocket, and turbojet/ramjet/rocket. Figure 3 shows that Isp in turbo/ramjet is more sensitive to area ratio at lower Mach numbers, while because at high supersonic Mach numbers, a turboengine behaves like a ramjet, the effect of area ratio is not significant. It also shows that combination of rocket with turboengines drastically reduces the overall Isp and that such a combined-cycle will not be greatly advantageous over rocket engines.

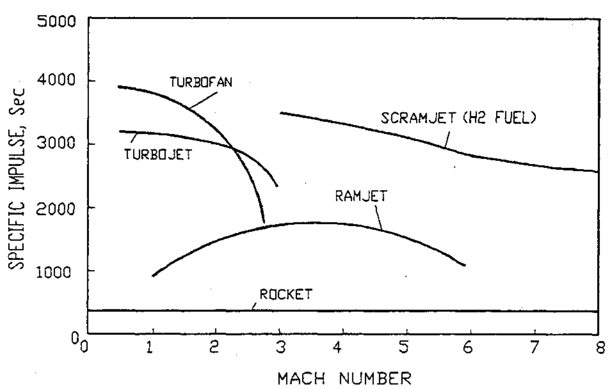

Fig. 1 Variation of Isp of turbofan (no afterburning), turbojet (no afterburning), ramjet, scramjet, and rocket along a typical flight trajectory (1000 psf dynamic head).

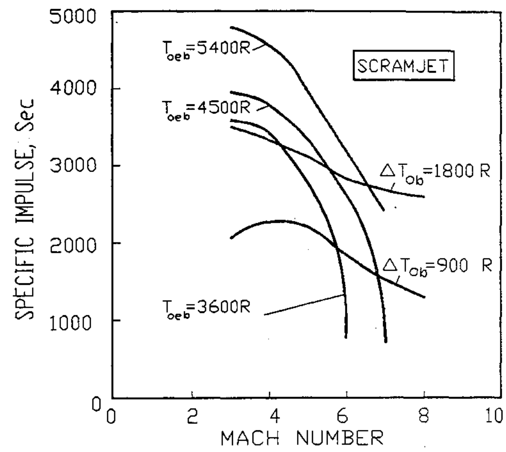

Fig. 2 Variation of the Isp of a hydrogen-fueled scramjet along a typical flight trajectory (1000 psf dynamic head) for two cases of a) constant stagnation temperature at the combustor exit; and b) constant stagnation temperature rise in the combustor, $M_{e,d}$ = 2. Thru-duct L/D = 4, combustor A_e/A_i = 2.5, and A_{wall}/A_i = 25.

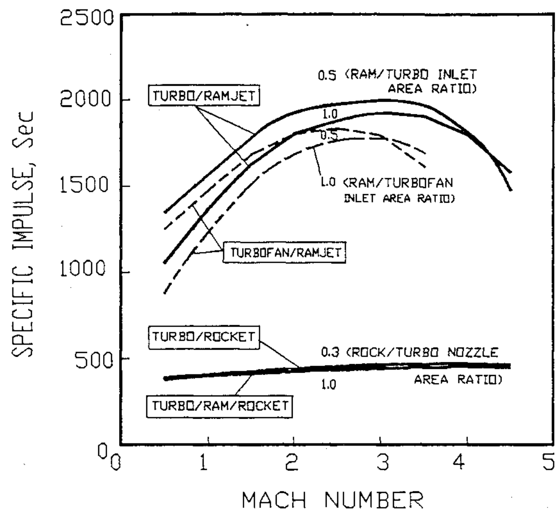

Fig. 3 Variation of Isp of turbojet/ramjet, turbofan/ramjet, turbojet/rocket, and turbojet/ramjet/rocket along a typical flight trajectory (1000 psf dynamic head). All nozzles are unmixed.

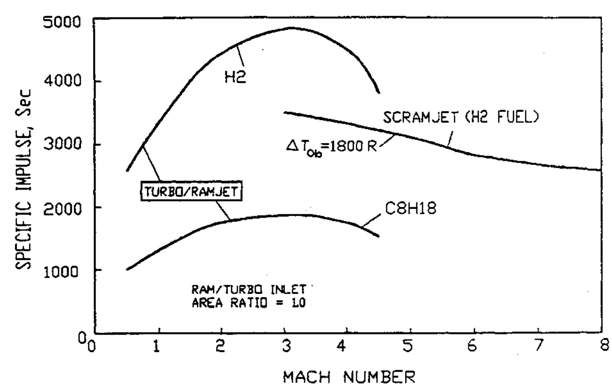

Fig. 4 Comparison of hydrogen-fueled turbojet/ramjet, scramjet, and hydrocarbon-fueled turbojet/ramjet along a typical flight trajectory (1000 psf dynamic head).

Finally, Fig. 4 compares the performance of turbo/ramjets with hydrogen and hydrocarbon fuels, along with a hydrogen-fueled scramjet. This figure shows that (from an aerothermodynamic standpoint) a combination of turbo/ramjet/scramjet will be an excellent choice for engines from takeoff to hypersonic flights. The results of the program have been validated for the cases of turbojet/ramjet and turbofan/ramjet.[8]

Appendix—Common Data for the Figures

The following data are common for all figures, except when the parameter is considered as a variable or explicitly expressed otherwise. The symbols b, c, ch, d, E, P, PR, and T_0 refer to burner (combustor), compressor, rocket chamber, diffuser (inlet), efficiency, pressure, pressure ratio, and stagnation temperature, respectively.

$\Delta P_b = 0$ (except in scramjet)	$T_{0,b} = 1800°R$
$E_b = 0.96$	$T_{ch} = 3600°R$
$E_d = E_n = 0.9$	$P_{ch} = 50$ atm
$T_b = 3600°R$	$PR_c = 20$

Acknowledgments

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Effects of Bypass Air on Boron Combustion in Solid Fuel Ramjets

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Introduction

THE use of boron as an additive in the polymeric fuel of a solid fuel ramjet (SFRJ) motor seems to be very promising because of its remarkably high theoretical heat of combustion.[1] However, extracting this energetic potential is a difficult task mainly due to the very complicated ignition and combustion processes of the boron particles.

Though the ignition and combustion of boron particles in oxidizing, temperature controlled atmospheres have been the subject of numerous studies,[2–5] there have been only few open literature publications[6–9] that provide information on the boron particles behavior inside a solid fuel ramjet motor.

The boron particles tend to accumulate and form large agglomerates on the fuel surface. As a result, the particles that enter the SFRJ flowfield are considerably larger[6–8] (up to 100 μ) than the original boron particles (typically below 10 μ).

Under regular conditions, the particles that are ejected from the fuel surface to the gas flowfield in the combustion chamber are covered by a thin boron oxide layer, serving as a barrier for further oxidation. The removal of this layer, mainly by evaporation of the oxide due to the particle heat up, sets the conditions for ignition.[2] Previous research by Natan and Gany[9] showed that for the conditions that exist in a solid fuel ramjet flowfield, the requirements for ignition of individual boron particles can barely coexist with the requirements for complete combustion of these particles. Natan and Gany[9] provided the following explanation to this phenomenon: Particles whose trajectories allow them sufficient residence time in the hot gas phase diffusion flame zone within the boundary layer, ignite fairly readily. However, even long residence times in this area do not permit high particle burning rates due to the low oxygen content in this zone. On the other hand, particles whose high ejection velocities bring them to the oxygen rich region, above the flame zone, may not ignite at all due to their short residence time in the hot environment. These peculiar constraints enable complete burning of relatively small particles (less than 30 μ) only, and only when they are ejected from the fuel surface at a very limited velocity range. The result is that the total fraction of boron that can burn within the combustion chamber is very little.

One method for improving the ignition process is by introducing in the fuel certain additives (such as Teflon® or titanium) that react with boron exothermically, thus producing the heat necessary for the ignition of the particles. Yet, the likely result of fast ignition does not promise that the particles can reach the oxygen rich zone and burn at high burning rates. Moreover, these additives may reduce the specific impulse of the motor. In general, most of the particles are able to ignite inside the grain port, but cannot burn completely.

Logically, if already ignited boron particles reach an oxygen rich environment, they can burn at relatively high burning rates. This can be achieved by separating the airflow that enters the SFRJ motor into two parts: 1) main flow that passes through the solid fuel port (main combustor), and 2) bypass flow which mixes with the main flow in a mixing chamber (afterburner), downstream of the main combustor.

Presumably, the use of bypass air may have a number of beneficial effects: 1) it promotes the ignition of boron particles because of the lower air mass flux through the main combustor resulting in a thicker and hotter flame zone[10] and increased residence times of the particles; 2) it enhances the combustion of the already ignited particles due to the better mixing of the particles with the air in the afterburner; and 3) it permits control of the solid fuel regression rate and the overall fuel-to-air ratio as a result of the effect of the main combustor mass flux on the fuel regression rate.

The main idea is to divide the motor into two sections, each performing different functions regarding the interactions of the boron particles with their surroundings. The first section is the main combustion chamber, where the solid fuel is placed. This section supplies the boron particles and provides the conditions necessary for their ignition (i.e., zones of high local temperatures). The second section, the afterburner, provides conditions where combustion of already ignited particles

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