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Issues Associated with Long-Duration High-Enthalpy Scramjet Combustor Testing

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Long-duration direct-connect combustor tests are an essential element in the development of an effective supersonic combustion ramjet (scramjet). While test techniques and analysis methodology have been established for simulated flight Mach numbers at Mach 8 and below, phenomena associated with higher flight simulations require additional attention. In this article, technical issues associated with long-duration high-enthalpy direct-connect scramjet combustor tests are discussed. Since ground tests form the basis by which flight hardware is designed, it is important to quantify the differences between flight and ground test conditions. Analyses are presented herein which characterize the differences between ground test and flight combustor inlet properties. In particular, the effects of dynamic pressure and chemical nonequilibrium kinetics are investigated. Analytical results will also be presented which characterize aspects of the performance of a generic combustor operating at Mach 8, 11, and 12 flight simulations. One-, two-, and three-stream mixing models are used to assess combustor performance, and the predictions derived from the various models are contrasted.

Nomenclature

A = cross-sectional flow area
ER = fuel equivalence ratio
F = stream thrust, $(P + \rho V^2)A$
H = hydrogen atom
h_t = stagnation enthalpy
I_{SP} = specific impulse, thrust/fuel flow
N = atomic nitrogen
O = atomic oxygen
P = static pressure
P_t = stagnation pressure
V = velocity
η_C = heat release combustion efficiency
η_{mix} = fuel/air mixing efficiency
ρ = density

Introduction

A PROGRAM is currently underway to develop a hydrogen-fueled supersonic combustion ramjet (scramjet) engine for the National Aerospace Plane (NASP) program. As part of this program, the Johns Hopkins University Applied Physics Laboratory (JHU/APL) and the National Aeronautics and Space Administration Ames Research Center (NASA/ARC) have established the direct-connect arc facility (DCAF)—a long duration direct-connect combustor test facility at NASA/ARC. The DCAF employs a 100-MW arc heater to produce air total enthalpies simulating up to Mach 13 flight. In the past, scramjet combustor tests above Mach 8 have been accomplished by utilizing short-duration shock tunnels. Test times in the DCAF range from 10 to 30 s. This is a relatively long period of time considering that pulse (shock tunnel) combustor tests typically last less than 3 ms. It is possible to operate pulse facilities so they provide combustor inlet flow conditions which are very similar to those produced by the DCAF. Comparisons between data from pulse facility and long-duration tests utilizing similar combustor hardware allow an assessment of flow establishment in a shock tunnel combustor rig. Despite inconsistencies caused by transient phenomena associated with pulse facility operation (e.g., wall heating), comparisons of wall static pressure distributions can give a first-order assessment of flow establishment in the pulse facilities. More detailed analyses of the data (such as determination of mixing efficiency) provide a better evaluation.

Long-duration direct-connect scramjet tests have previously been accomplished by several agencies for simulated flight Mach numbers at or below Mach 8.[1–7] Analyses in support of tests like these have shown that for Mach 8 and below, proper assessment of combustor performance can be made using a chemical equilibrium-based cycle analysis code such as the JHU/APL ramjet performance analysis code (RJPA).[8] RJPA is a one-dimensional ramjet/scramjet engine cycle analysis code that allows the analysis of individual components or integrated engine cycles.

In higher enthalpy long-duration test facilities, however, the character of the facility nozzle exit flow properties and combustor performance are strongly influenced by finite rate chemical effects because of the high stagnation temperatures and relatively low stagnation pressures. For a given energy level, the lower the stagnation pressure, the greater the deviation from chemical equilibrium. Stagnation pressures are limited in a long duration facility because the heat transfers and structural loads associated with true flight simulations cannot be withstood by the test hardware for the relatively long test times. Because chemical kinetic effects must be considered for these types of facilities, a multistream, quasi-one-dimensional, finite rate chemical kinetics cycle analysis computer code based on the CHEMKIN package[9] was developed[10] and used to analyze the supply nozzle and combustor flowfields. Previous to this work, similar tools have been developed and applied for analysis of scramjet combustors.[11] In this article, the air chemistry is modeled using a 7-species, 5-reaction system in the facility nozzle, and a 14-species, 30-reaction system in the combustor.

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The purpose of this article is to document aspects associated with high-enthalpy long-duration combustor ground tests. This is done by presenting analyses which characterize the performance of the DCAF facility supply nozzle and combustor. Supply nozzle analyses characterize effects associated with high-temperature finite rate airflow through a supersonic nozzle. The chemical and thermodynamic properties resulting from the nozzle predictions are used as a starting point for multistream nonequilibrium chemical kinetic combustor analyses which contrast one-, two-, and three-stream mixing models. Further analyses assess combustor performance sensitivity to fuel-air mixing efficiency and fuel flow rate.

Experimental Apparatus

The hardware used for the tests considered in this article is shown schematically in Fig. 1. The rectangular area supply nozzle has a flow path identical to that used in direct-connect combustor tests carried out at JHU/APL[1] and is designed to provide a Mach 3.3 airstream to the combustor. The spray-cooled combustor is comprised of two isolator ducts, a section to house fuel injectors, a constant area combustor duct, and two varying area sections. Since the DCAF and JHU/APL combustor hardware have similar widths, fuel injectors which were tested at JHU/APL will be evaluated in the DCAF combustor.[1] In the initial test series, fuel can be injected through Mach 2.5 tangential slot injectors. These injectors accelerate ambient temperature hydrogen to Mach 2.5 and inject the fuel in the streamwise direction through slots which span approximately 1% of the duct height. It is these injectors that are addressed in the combustor analyses found in this article.

Facility Nozzle Analysis

When testing a scramjet engine in a ground-based test facility, current technology does not always allow for a comprehensive flight simulation. For the high Mach number test conditions analyzed herein, facility stagnation pressure limitations dictate that only flight total enthalpy can be simulated exactly. The expected DCAF facility operating conditions which were used in the current analysis are provided in Table 1. The stagnation enthalpies h_t represent those expected along a 2000 lb_f/ft^2 (95,734 N/m^2) dynamic pressure trajectory, while the stagnation pressures P_t represent dynamic pressures of 270 lb_f/ft^2 (12,924 N/m^2), 125 lb_f/ft^2 (5983 N/m^2), and 41 lb_f/ft^2 (1963 N/m^2), respectively for conditions I, II, and III.

The nature of the facility nozzle flowfield has been investigated for these test conditions using a finite rate chemical kinetics code and compared with equilibrium and frozen chemistry results generated using RJPA.[8] These comparisons

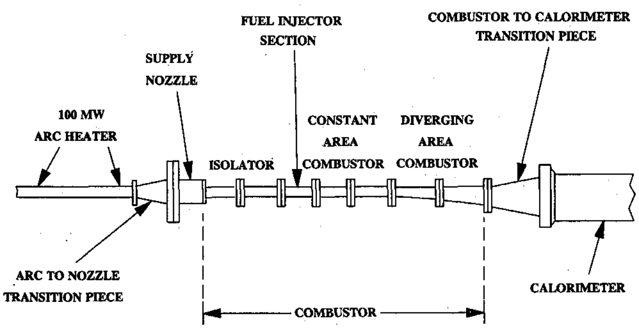

Fig. 1 Schematic of the DCAF test hardware.

Table 1 Facility supply conditions

Condition	P_t, $lb_f/in.^2$	h_t, Btu/lb_m	Simulated flight Mach number
I	400	1240	8
II	430	2470	11
III	400	3000	12

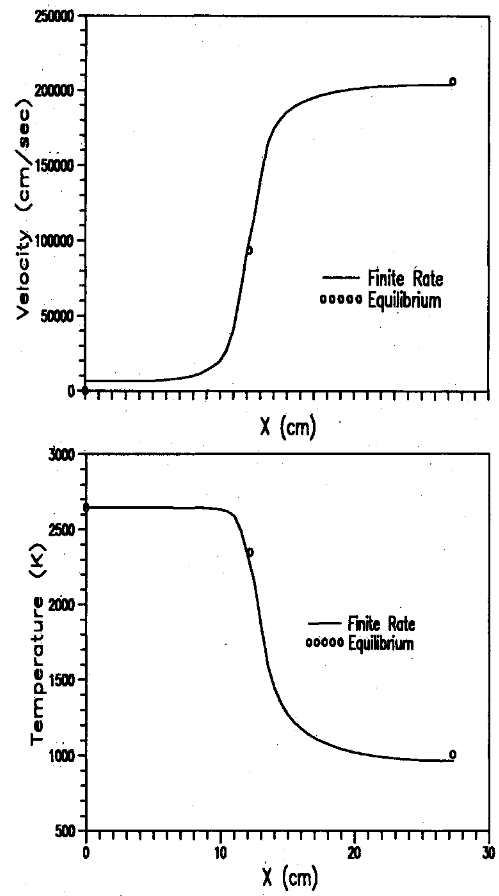

Fig. 2 Facility nozzle temperature and velocity distributions for the Mach 8 simulation.

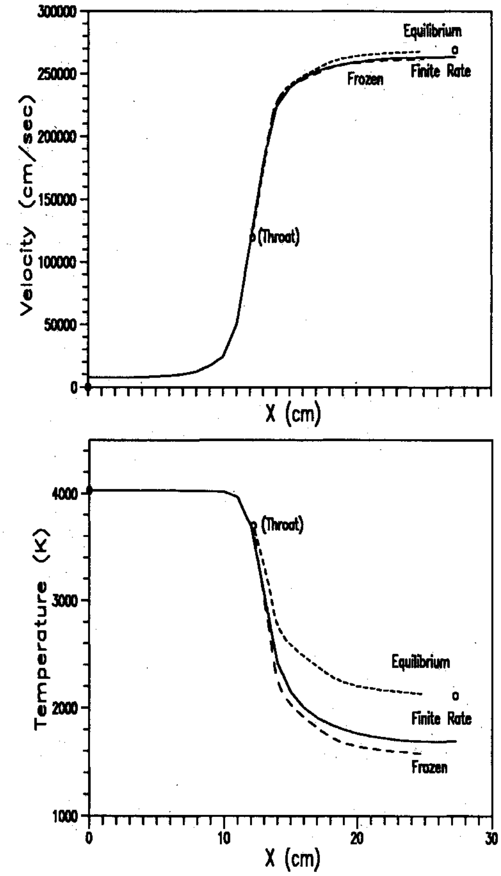

Fig. 3 Facility nozzle temperature and velocity distributions for the Mach 11 simulation.

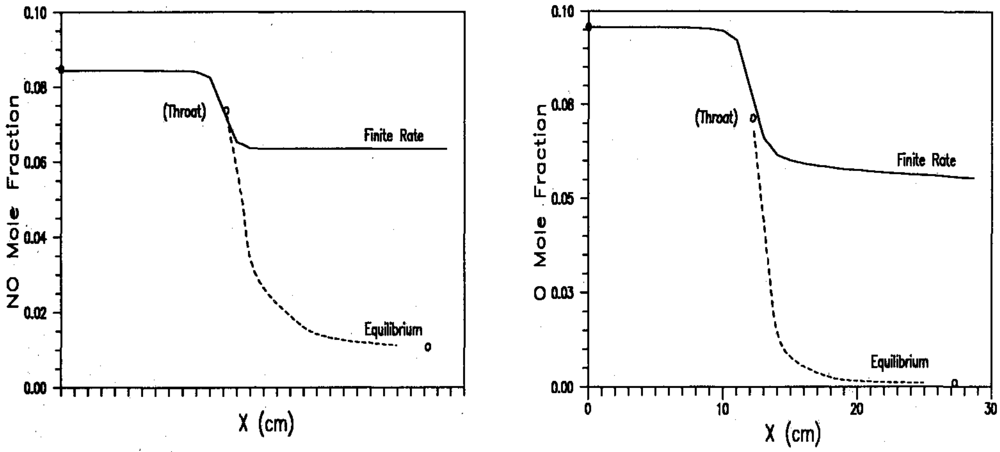

Fig. 4 Facility nozzle O and NO mole fraction distributions for the Mach 11 simulation.

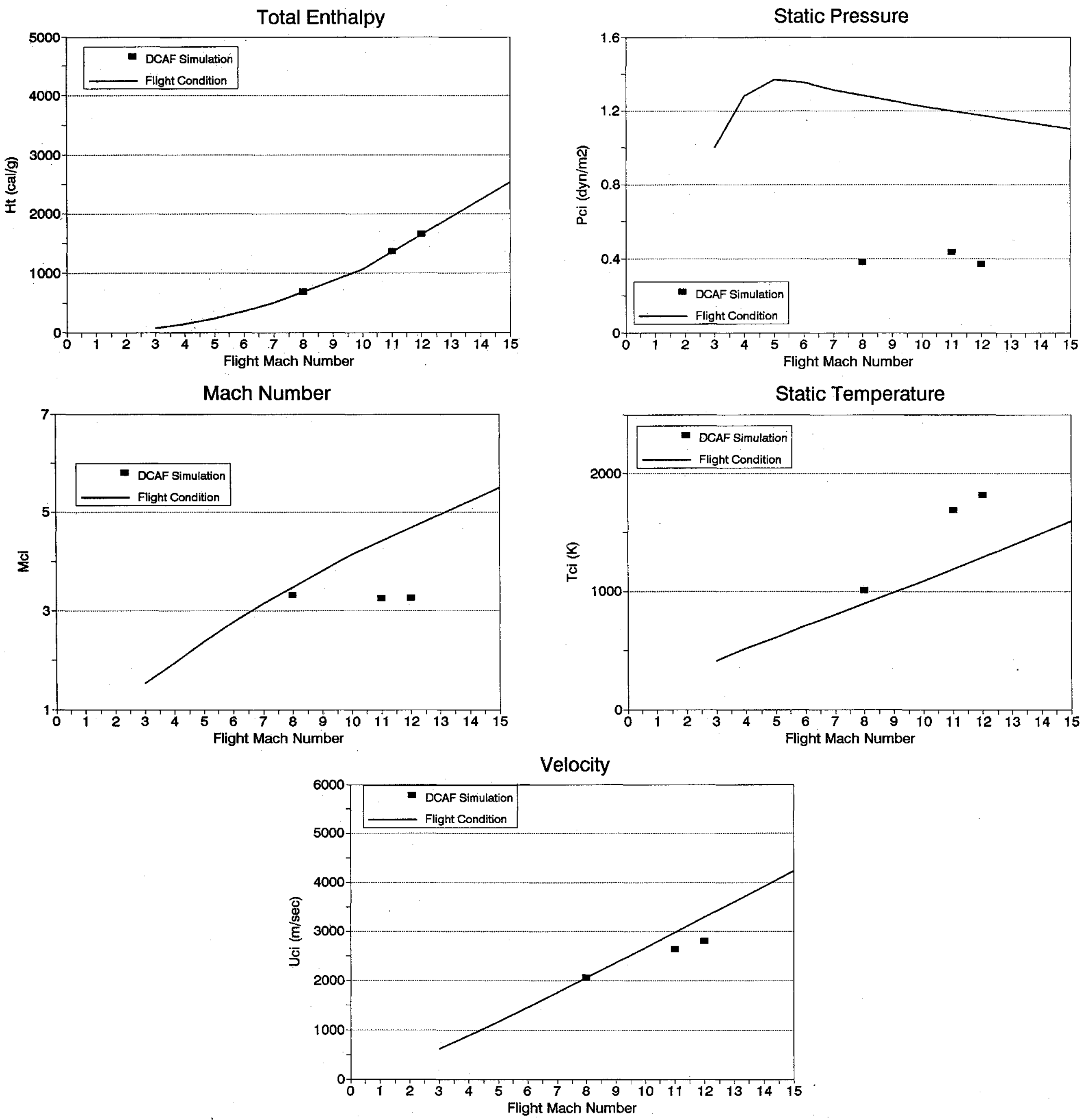

Fig. 5 Predicted test combustor inlet properties compared with those of a typical flight scramjet.

provide a relative measure of the effects of finite rate chemistry in the facility nozzle. For a 2000 lb_f/ft^2 (95,734 N/m^2) dynamic pressure flight trajectory, static pressures and temperatures in flight are such that the gas is expected to be in chemical equilibrium at the combustor inlet. As such, the difference between finite rate results and equilibrium results provides a measure of the difference between the chemistry found in the ground tests and those expected in flight. Heat loss and skin friction effects are neglected in this analysis since they are not likely to influence the conclusions.

Figure 2 presents axial air static temperature and velocity distributions predicted for the DCAF Mach 8 simulation. As expected, the finite rate calculations match the equilibrium results for this simulation. Since this is the case, Mach 8 nozzle analyses can be simplified by employing an equilibrium-based tool.

Results for the Mach 11 test condition are shown in Figs. 3 and 4. These results indicate that although the flow is in equilibrium in the subsonic portion of the nozzle, finite rate effects dominate the flow in the divergent section. Frozen and equilibrium calculations for the divergent portion of the nozzle are presented for comparison with the finite rate results. Figure 3, which compares predicted air static temperature and velocity distributions in the nozzle, indicates that the finite rate results are much closer to frozen chemistry than to equilibrium chemistry. Similarly, the results in Fig. 4 show that dissociated chemical species tend to freeze just downstream of the nozzle throat, resulting in significant quantities of dissociated monatomic oxygen O and nitrous oxide NO at the nozzle exit (combustor entrance).

A similar nozzle analysis for the Mach 12 case (condition III) has also been accomplished. As is the case at Mach 11, the chemistry remains in equilibrium up to the nozzle throat, only to freeze just downstream of the throat. While there are similar quantities of NO for the Mach 11 and 12 simulations, the Mach 12 condition results in a significantly higher mole fraction of O ($\approx$12%) at the nozzle exit because of the larger quantities of O in the plenum.

Figure 5 compares the predicted DCAF nozzle exit conditions as a function of Mach number with predicted scramjet engine combustor entrance properties for flight. These combustor inlet properties were calculated for a dynamic pressure trajectory of 2000 lb_f/ft^2 (95,734 N/m^2) assuming a 1% total enthalpy loss in the inlet.[12] As designed, the tests exactly simulate flight total enthalpy for all three test conditions. At Mach 8, the test differs from flight only in static pressure. Higher static pressures could be produced by operating the DCAF at higher stagnation pressures, but thermal and structural limitations associated with the hardware limit operation to below P_t = 600 psia (4,135,714 N/m^2). For flight simulations above Mach 8, the test variables differ from the flight parameters: combustor entrance Mach number and velocity are too low, and static temperature is too high; these differences are not strongly driven by finite rate chemical effects. While all three of these properties could be made closer to flight by employing a higher Mach number facility nozzle, only one nozzle is available for the initial DCAF test series.

In summary, the results from this analysis indicate that significant quantities of dissociated species exist at the combustor entrance for the Mach 11 and 12 total enthalpy test simulations. In addition, all other combustor entrance flow properties, except for total enthalpy, do not exactly match those expected for Mach 11 and 12 flight. For all three test conditions, combustor inlet velocity simulates flight fairly well. This is important with respect to fuel/air mixing and combustor residence time. In order for ground-based facilities to reach conditions closer to those expected in flight above Mach 8, a higher Mach number nozzle with a higher stagnation pressure capability is required. Higher total pressure operation also has the effect of reducing the amount of dissociated species provided to the combustor. On the downside, higher total pressure operation would require more robust and expensive hardware capable of withstanding higher heat transfers and larger mechanical and thermal stresses. Within the limits of the facility, the Mach number can only be increased to approximately Mach 3.8. This provides a relatively small improvement in combustor entrance conditions while significantly increasing the complexity (and cost) of the hardware. The advantage that pulse facilities have is that they can operate at stagnation pressures significantly higher than possible in the DCAF.

Combustor Analysis

The nozzle exit conditions predicted by the study discussed above are the initial conditions for combustor analyses which employ finite rate chemical kinetics and multistream mixing models. The combustor kinetics code begins with this information and marches through the combustor. For this analysis, skin friction and heat loss effects are again neglected because their effects do not influence the conclusions.

Fuel/air mixing efficiency can be modeled in a number of ways using a quasi-one-dimensional code. The easiest and most efficient way to study the process uses a one-stream model. In this model, the mixed and unmixed portions of fuel and air are treated as a single stream, and that portion of the fuel designated as unmixed is taken to be chemically inert (frozen). In reality however, there will be portions of the airstream that remain isolated from the mixed region. This failure to properly model the physics of the mixing process can bias the reaction rates, resulting in misleading test predictions and deceptive posttest data analysis. For example, if a large quantity of unmixed, highly reactive monatomic oxygen were modeled as mixed with the fuel (as is the case with a one-stream model) then heat release combustion efficiency would be overestimated.

In order to overcome some of the limitations associated with a one-stream model, two- or three-stream mixing models can be utilized. With these models, portions of the air and/or fuel are excluded from the mixing region while being allowed to react independently in their own isolated streams (e.g., monatomic oxygen/diatomic oxygen reactions occur in the airstream as conditions warrant). In this article, the streams are all assumed to be at the same temperature and pressure at a given axial location, similar to a model described by Jachimowski.[13] Isolation of the three components of the flow (air, fuel, and mixture) from each other is modeled by adjusting the chemical production rates so that reaction rates in each component are unaffected by the composition of the others. This improves the estimate of reaction rates, though

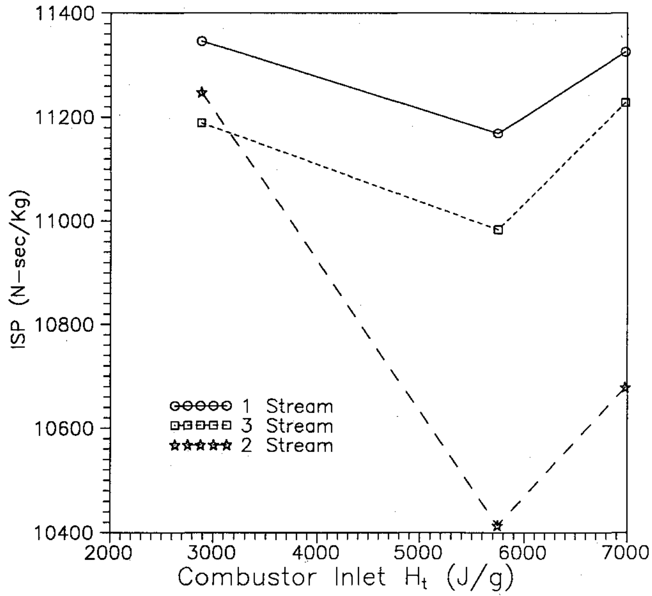

Fig. 6 I_{SP} sensitivity to applied mixing model, η_{mix} = 0.5, ER = 1.

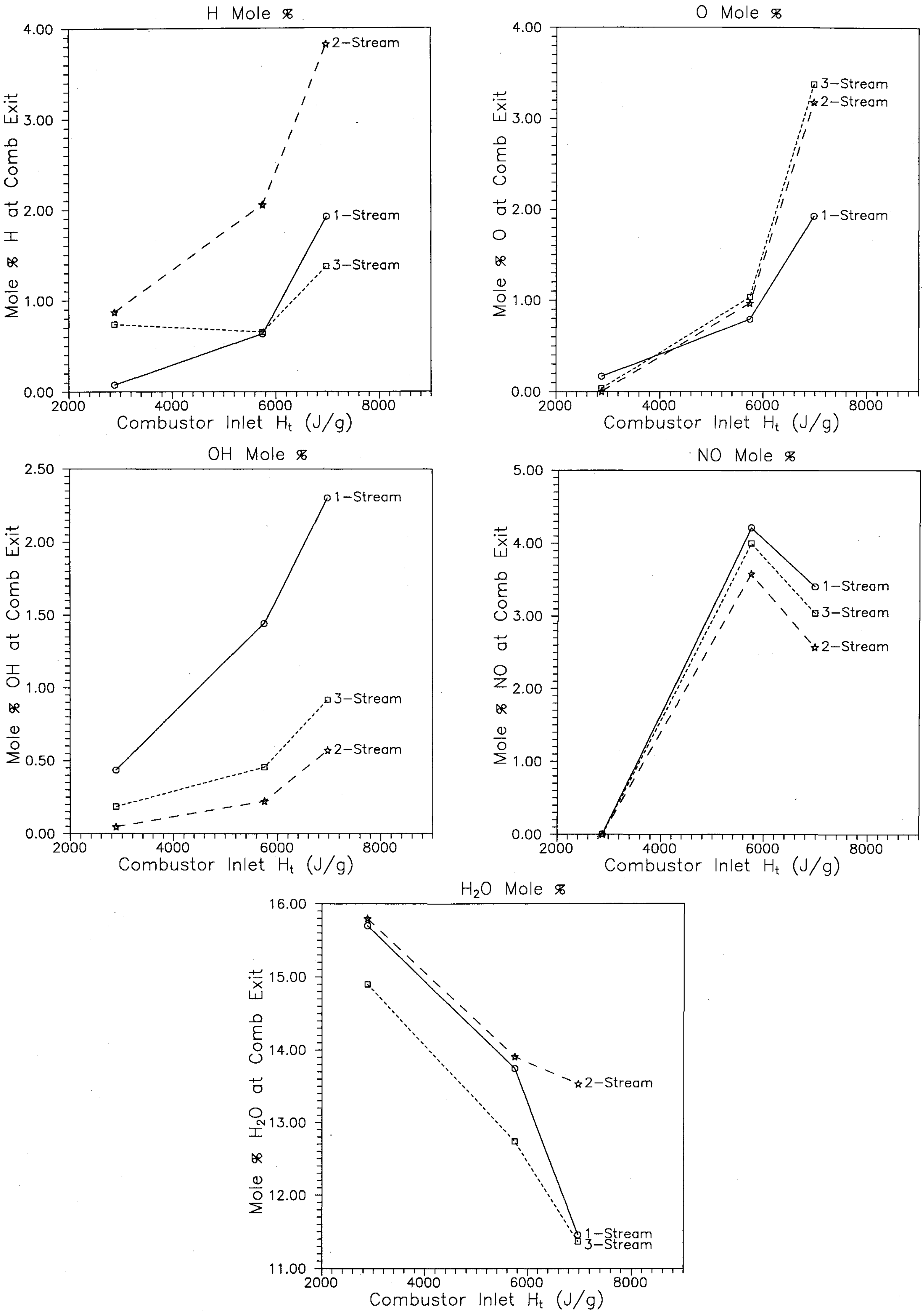

Fig. 7 Chemical sensitivity to applied mixing model: combustor exit mole fractions, η_{mix} = 0.5, *ER* = 1.

other inaccuracies remain due to the oversimplification of the fluid dynamic coupling between the streams.

In this article, results based upon three mixing models are compared. While approximate methods can be used to estimate fuel/air mixing,[14–19] these methods are not employed here; instead, the sensitivity of predicted combustor performance to applied mixing model is investigated. For $ER = 1$ and 50% mixing, these mixing models are described as follows. The first model uses a one-stream analysis where half of the fuel is allowed to react with the entire airstream. In the three-stream model, 50% of the air and 50% of the hydrogen are allowed to mix while the balance of the air and hydrogen remain isolated. In the two-stream model, all of the fuel is allowed to react with 50% of the air. The actual mixing process associated with tangential fuel injection is most closely modeled by the two-stream model because mixed regions contain most of the fuel but only a portion of the air for mixing efficiencies below unity.[18,19]

The predicted specific impulse I_{SP} for each of the three models is presented in Fig. 6 for the Mach 8, 11, and 12 test conditions operating at a stoichiometric equivalence ($ER = 1$). I_{SP} is defined as the difference between the combustor exit stream thrust $[F = (P + \rho V^2)A]$ and the combustor entrance stream thrust, divided by the fuel flow rate. For the Mach 8 simulation $[h_t = 1240\ \text{Btu/lb}_m\ (2884\ \text{J/g})]$, the three mixing models provide results which compare reasonably well with each other. At the higher Mach numbers, however, combustor performance is sensitive to which mixing model is used. At Mach 11 $[h_t = 2470\ \text{Btu/lb}_m\ (5745\ \text{J/g})]$ and 12 $[h_t = 3000\ \text{Btu/lb}_m\ (6978\ \text{J/g})]$, the two-stream model predicts I_{SP} significantly lower than the one- or three-stream models.

The fact that the agreement between the mixing models is good only at Mach 8 suggests that the differences between the results at Mach 11 and 12 are associated with nonequilibrium chemistry (below Mach 8, chemistry can be effectively modeled assuming equilibrium chemistry). Figure 7 illustrates combustor exit H_2O, OH, O, H, and NO species mole fractions predicted for a mixing efficiency of 50%. While the formation of water releases chemical energy and produces thrust, the formation of H, O, OH, and NO are the result of endothermic reactions which degrade combustor performance. The use of different mixing models results in chemical compositions that vary significantly. With the two-stream model, larger quantities of O, H, and H_2O are formed while smaller amounts of OH and NO are formed. The larger quantities of O and H formed using the two-stream model reduce the combustor performance (I_{SP}) markedly, even though more water and less OH and NO are formed. Effects associated with larger quantities of monatomic hydrogen H are most profound in this comparison because of its relatively large heat of formation. These nonequilibrium effects are not observed for Mach 8 predictions.

The predicted performance of the DCAF combustor with tangential injection at $ER = 1$ for the Mach 8, 11, and 12 test conditions is shown in Fig. 8; these results were generated using the two-stream mixing model. Note that increases in mixing efficiency have a smaller impact on combustor performance for the higher Mach numbers. This happens because of additional dissociated species (Fig. 7) and because the portion of mixed fuel (H_2) that fails to react increases with total enthalpy. Figure 9 illustrates the amount of H_2 that mixes but fails to react for $ER = 1$ assuming 100% mixing; this is a chemical phenomenon associated with the $O_2 + 2H_2 \rightarrow 2H_2O$ reaction at high temperatures (water decomposes into hydrogen and oxygen at a rate similar to that in which H_2 and O_2 form H_2O). Figure 9 implies that as the simulated flight Mach number increases from 8 to 12, the amount of fuel that remains

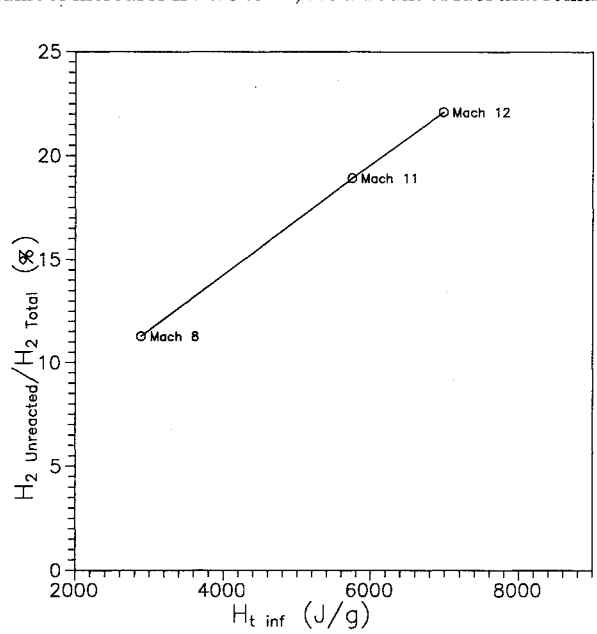

Fig. 9 Mixed hydrogen remaining at combustor exit, $ER = 1$, $\eta_{mix} = 1.0$.

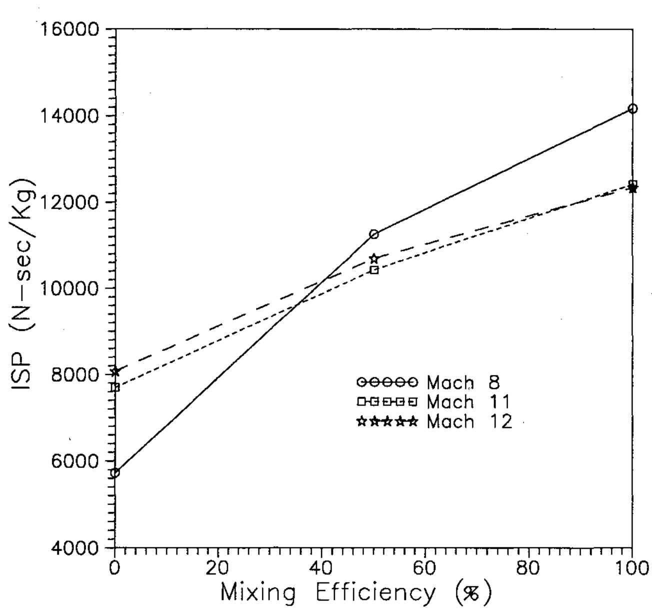

Fig. 8 Combustor performance—two-stream mixing model, $ER = 1.0$.

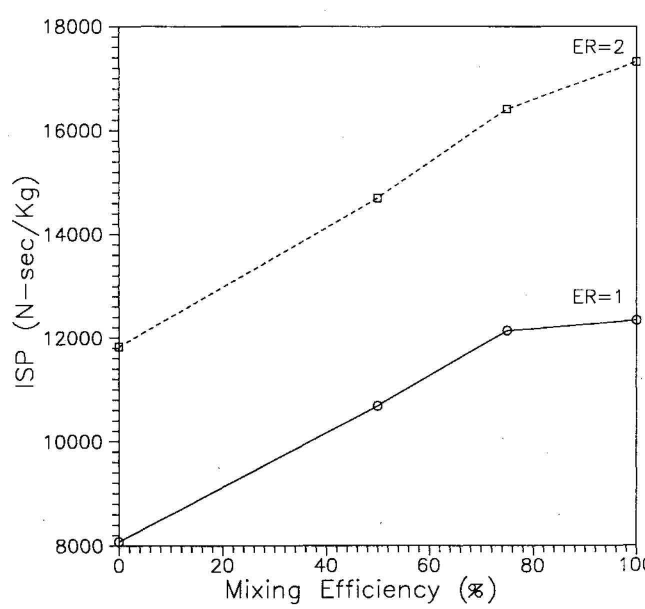

Fig. 10 Mach 12 results using the two stream mixing model.

unreacted increases from 11 to 22%, even though this hydrogen is fully mixed with ample quantities of O_2. Ignoring the effects of dissociation, this means that for $ER = 1$, the maximum possible heat release combustion efficiency is 89 and 78% for the Mach 8 and 12 simulations, respectively.

Dissociation has the effect of further reducing η_C, which is defined as the actual chemical energy release divided by a theoretical energy release that would be generated if the oxygen and hydrogen atoms combined to form the maximum number of water molecules. It is, however, important to remember that if this combustor were linked with a nozzle, recombination of dissociated species and/or hydrogen/oxygen reactions could occur as the area expands and the temperature decreases, depending on the Damkohler number.

Figure 10 illustrates the predicted performance of the DCAF combustor hardware with tangential fuel injection at the Mach 12 test condition for equivalence ratios of one and two; again, using the two-stream model. Note that increasing mixing efficiency from 0.75 to 1.0 does little to enhance combustor performance for $ER = 1$. For an equivalence ratio of 2, this phenomenon is apparent, but to a lesser degree because the added fuel injection lowers the mixture temperature thus reducing the effects of dissociation.

Although the chemical behavior of the flow in the combustor varies significantly between flight and ground tests, valuable fuel/air mixing characteristics can be gained from ground tests. Under conditions where mixing is not notably coupled with chemical kinetics, the mixing efficiency measured in the ground tests, through steam calorimetry,[1] can be extended to the flight vehicle.

Conclusions

In support of the direct-connect combustor tests in the NASA/ARC DCAF, non-equilibrium chemical kinetics calculations have been made. In these calculations, the thermodynamic and chemical characteristics of the facility supply nozzle and the combustor have been investigated.

At the Mach 8 condition, analyses have shown that the nozzle flowfield is in chemical equilibrium. At the Mach 11 and 12 flight simulations, significant dissociation and non-equilibrium chemical effects were predicted. While the nozzle flow is in equilibrium up to the throat, the chemistry freezes just downstream of the throat, resulting in near frozen flow at the nozzle exit. As such, finite rate chemistry affects the test combustion process above Mach 8 differently than expected in flight. Under conditions where fuel/air mixing and finite rate chemical effects are not strongly coupled, the mixing efficiency measured in ground tests can be extended to flight.

Predicted combustor performance proved to be sensitive to the type of mixing model used. For the test simulation discussed herein, a two-stream model appears to be the most appropriate. In this model, the entire fuel stream is allowed to react with a portion of the air while the balance of the air remains isolated.

Using the two-stream model, the DCAF combustor performance was predicted. Results show that the mixing process has a smaller effect on combustor performance at the higher test enthalpies due to chemical phenomena associated with the high temperature flows. Further analysis indicates that for Mach 12 operation, increasing mixing efficiency from 75 to 100% provides less gain than if the mixing efficiency is increased from 50 to 75% for both $ER = 1$ and $ER = 2$.

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