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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Preliminary Investigations on Improving Air-Augmented Rocket Performance

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I. Introduction

IT is well known that an air-augmented rocket[1,2] (AAR) can offer higher values of specific impulse than a conventional rocket. Extensive theoretical and experimental investigations of ducted mixing as applied to the AAR have been reported earlier.[3-5] Recently, there has been a renewed interest in these airbreathing propulsive systems.[6-8]

In this type of propulsive device, shown in Fig. 1, the combustion products from a primary chamber containing hot, gaseous, fuel-rich affluents enter an afterburning combustor. In this secondary combustor, combustion proceeds to completion when the fuel-rich exhaust gets mixed with atmospheric air ingested through the air inlets. It has been shown that the primary nozzle geometry plays a significant role in the mixing of the two streams and subsequent combustion.[9]

Recently, considerable progress has been made towards improving the process of mixing of two coaxial, high-speed streams.[10-12] This method relies on a large-scale, inviscid mixing process as oppposed to conventional shear-mixing techniques. This is accomplished by a lobed supersonic primary nozzle referred to as the "Petal" nozzle.[10] This nozzle has shown excellent results when used for studies on piloted supersonic combustion and supersonic ejectors.[12]

In the present investigation, the Petal nozzle was employed as the primary nozzle for air-augmented rocket studies. Experiments were also conducted with an equivalent conventional, conical nozzle for comparison. Results of these tests are presented in this Note.

II. Details of the Experiment

A. Experimental Setup

The experimental arrangement is shown in Fig. 2a, while Fig. 2b shows the two nozzles, Conical and Petal. Design pressure ratio of both nozzles was 5:1. Kerosene was employed as the fuel. The primary (subsonic) combustor consisted of a gas turbine flame tube with a swirler, fuel injector, and outer air casing. It ended in a contraction piece and a straight throat to which either of the two nozzles, Conical or Petal, may be attached. For a primary air-fuel ratio of 27, combustion was incomplete in the primary chamber as seen by the color and nature of flame outside the chamber. Thus, the primary stream simulated a kerosene burning rocket operating at fuel-rich condition. The secondary, outer airflow was annular and coaxial with the primary stream. Both streams entered and mixed within the axisymmetric mixing chamber located downstream. Primary and secondary flow Mach number at inlet to the mixing chamber were 1.7 and 1.0, respectively. The mixing tube, which also acted as the secondary combustor, had a semidivergence angle of 1 deg.

B. Instrumentation

Total pressure and static pressure profiles at the exit of the diverging mixing chamber were measured by appropriate probes. For total temperature measurement a Winkler-type[13] probe was employed. A traversing mechanism was employed to move these probes radially. Fuel flow rate was measured by a metal-tube rotameter, and airflow rates by flow meters.

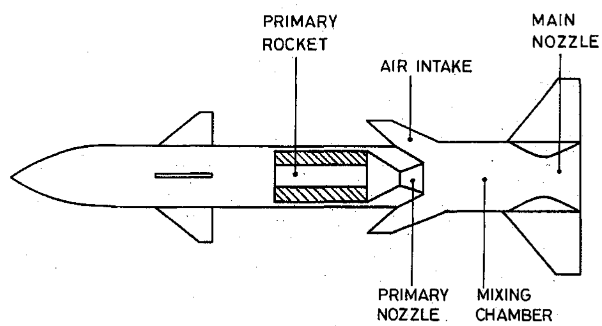

Fig. 1 Air-augmented rocket.

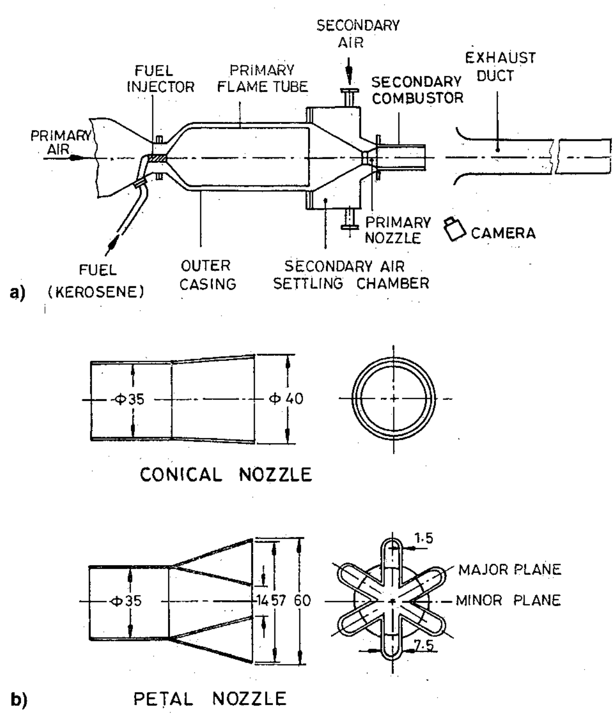

Fig. 2 a) Experimental setup and b) nozzles.

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C. Test Runs

Inner and outer flow blowing pressure were maintained at 4 and 1.2 atm, respectively. Outer airflow was annular for the Conical nozzle, while for the Petal nozzle it took place through the minor plane (trough) regions.

III. Results and Discussion

A. Photographic Study

Figure 3 shows a photograph, taken perpendicular to the flow axis of the combustor when the Conical nozzle was used for the primary stream. The flame containing unburned fuel can be seen exiting the secondary combustor. For similar conditions, when a Petal nozzle was used for the primary stream, secondary combustion should have been completed within the secondary combustor itself because no flame can be seen to issue out of the combustor.

B. Momentum Profiles

The mechanism of mixing due to large-scale axial vortices associated with the Petal nozzle has been discussed in detail in Ref. 12. The geometry of the Petal nozzle makes it easy to study and quantify the mixing process between the two streams. One has merely to examine and compare flow profiles in the two planes: 1) major and 2) minor. Figure 4a compares the momentum profiles at the exit of the secondary combustor when the two nozzles, Conical and Petal, were employed for the primary stream. Profiles for the Conical nozzle show little momentum transfer between the primary and secondary streams. Similar profiles for the Petal nozzle in the major and minor planes show that almost complete mixing has occurred between the two streams.

C. Temperature Profiles

Figure 4b shows a comparison of the total temperature profiles at the exit of the secondary combustor for the two nozzles used. The efficacy of the Petal nozzle in bringing about rapid mixing and subsequent combustion is clearly brought out by this figure. For the conical nozzle, the inner, hot, fuel-rich flow is seen to maintain its separate identity from the cold outer airflow. Core temperatures were very high and comparatively little heat transfer took place in the radial direction.

D. Net Momentum

From the radial momentum flux profiles, the total momentum of the flow exiting the secondary combustor was calculated. Net momentum loss for the Conventional nozzle was found to be about 6%, compared to 14% for the Petal nozzle.

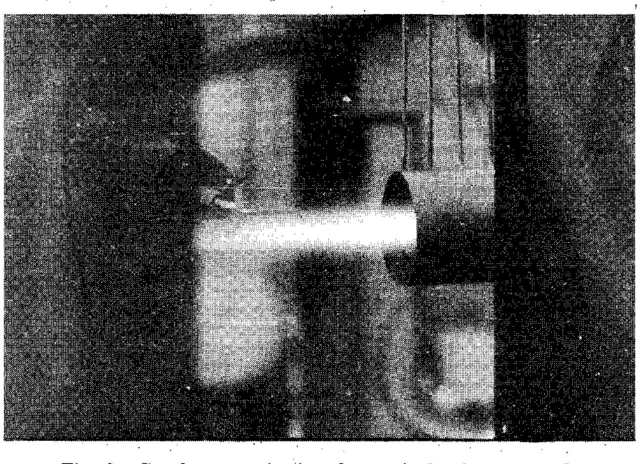
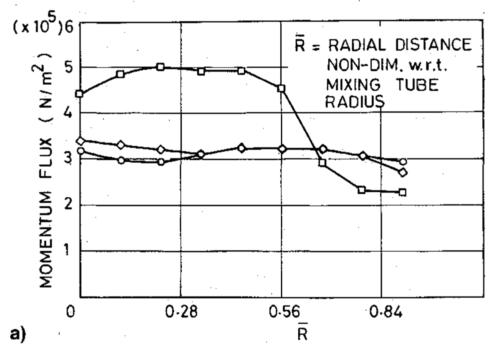


Fig. 3 Combustor exit view for conical primary nozzle.



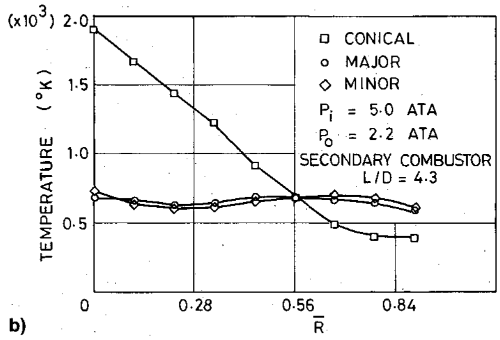


Fig. 4 a) Momentum flux and b) temperature profiles at combustor exit.

E. Combustion Efficiency

The overall fuel efficiency of the air-augmented rocket using the Petal nozzle, calculated from the exit total temperature profile and fuel and airflow rates, was found to be 0.95.

IV. Conclusions

The use of the Petal nozzle instead of a conventional, Conical nozzle for the primary stream representing fuel-rich gases exiting from a rocket nozzle has demonstrated considerable improvement in the performance of an air-augmented rocket. This can be attributed to improved mixing of the hot, exhaust gases containing unburnt fuel with the surrounding airstream and subsequent heat release.

Acknowledgments

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Turbulent Combustion Regimes for Hypersonic Propulsion Employing Hydrogen-Air Diffusion Flames

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Introduction

UNCERTAINTIES about turbulent combustion in hydrogen-air systems have an impact on our abilities to develop supersonic-combustion devices for applications such as the National Aerospace Plane. Most designs of supersonic-combustion engines involve turbulent hydrogen injection into supersonic airstreams in the combustor, thereby leading to nonpremixed combustion representative of turbulent diffusion flames. To begin combustor analyses it is helpful to have a firm identification of the regimes in which this turbulent combustion is likely to occur. The objective of the present communication is to report results of calculations performed to determine these combustion regimes.

Parameters Defining Regimes

A variety of nondimensional parameters are relevant to regimes of turbulent diffusion flames.[1,2] These include different Damköhler numbers, Reynolds numbers, convective Mach numbers (in compressible turbulence[1]), Zel'dovich numbers (measuring the strength of the temperature dependence of the chemistry), and the ratio of a rms mixture-fraction fluctuation to a reaction-zone width in mixture-fraction space (which is small in a connected-flamelet regime[3]). Of these, the most important for combustion is a large-eddy Damköhler number D_l, the ratio of a large-eddy turnover time $l/\sqrt{2k}$ (where l is the integral scale and k the kinetic energy of the turbulence), to a chemical time τ_c. Combustion occurs in a distributed-reaction regime for $D_l \ll 1$ and in a reaction-sheet regime for $D_l \gg 1$. The large-eddy Reynolds number $R_l = \sqrt{2k}l/\nu$, where ν is a kinematic viscosity, is also relevant in that turbulent structures appear in some sense to become truly fully developed for $R_l > 10^4$. Other Damköhler and Reynolds numbers that may be considered are D_k, the ratio of the Kolmogorov time to τ_c, and R_t, the Reynolds number based on the Taylor scale.

Figure 1 is a plane having R_l and D_l as coordinates, for the purpose of exhibiting turbulent combustion regimes.[4] The influence of parameters such as Mach number and Zel'dovich numbers do not fit well in this plane; in principle they require extension to additional dimensions. However, since the combustion regimes are so strongly influenced by the chemical and flow times, the Damköhler and Reynolds number may be deemed the two most significant parameters, and therefore, to leading order this plane may serve as groundwork for regimes. Plotted on this plane are lines of constant values of other parameters, fully discussed earlier,[4] that are relevant mainly for premixed turbulent combustion, as are the multiple, single, and weak-turbulence subregimes. The results reported here concern the location in this plane of projected supersonic-combustion processes for hypersonic air-breathing propulsion employing hydrogen as fuel.

Specification of Flight Parameters

Flight Mach numbers M_f from 1 to 25 are considered at altitudes from 11 to 80 km, with the U.S. standard atmosphere (NOAA, 1976). An average diffuser efficiency of 95% (recommended by engine manufacturers) is employed, with combustor air Mach numbers of $M_f/2$ for $M_f \leq 4$ and $M_f/2 - 1$ for $M_f > 4$, fuel-stream Mach numbers from 1 to 4, temperatures from 300 to 1200 K, and a characteristic combustor dimension of 0.3 m. Resulting combustor static pressures range from 0.3 to 5.0 atm.

The chamber static temperature and pressure are first calculated for any given altitude and M_f from standard quasi-one-dimensional gasdynamic formulas, and ν is then obtained from NASA polynomial fits, using the average of the static temperature and the diffusion-flame extinction temperature[5] as a first estimate, since temperatures in the regions of flow where ν is relevant are distributed between these limits. The turbulence intensity is approximated as 50%, and the integral scale as the chamber dimension for the purpose of estimating

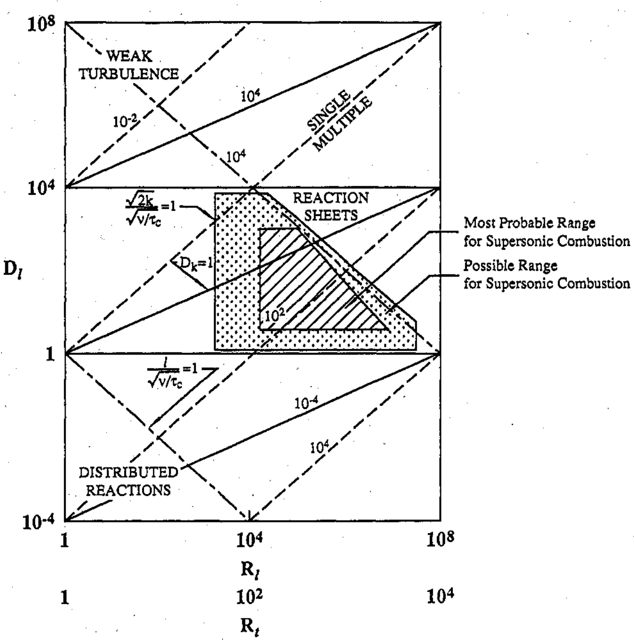

Fig. 1 Diagram of the regimes of turbulent combustion.

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