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Technical Notes

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Preliminary Studies on Dual-Mode Combustion Ramjet Using Petal Nozzle

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I. Introduction

IN the present decade, airbreathing propulsion is receiving renewed attention as a result of the economic constraints of conventional expendable launch systems. Currently, efforts are underway in many countries to develop high-speed airbreathing propulsion systems in the Mach number range of 3–15. It has been accepted that such a system would be composite in nature with ramjet, scramjet, and rocket technologies being involved. But due to practical difficulties encountered in the supersonic combustion phase of the composite propulsion systems such a propulsion device is yet to be developed. Among various possible combinations, the dual combustion ramjet (DCR) is receiving considerable attention as a favorable candidate for the Mach number range of 4–8. A typical dual-mode combustion Ramjet as described by Billig et al.[1] consists of a subsonic combustion ramjet acting as a pilot for the supersonic combustion. This design ensures good ignition characteristics and performance in the supersonic combustor over a wide Mach number range. The major problem associated with the DCR concept is mixing of the hot pilot (ramjet) exhaust with the relatively cold airstream from the intake.

A pure analytical or numerical simulation of the flowfield inside the supersonic combustor is rather difficult because of the complicated mixing and combustion processes in addition to shock waves and viscous layers, though some efforts in this direction are seen in Refs. 2 and 3. Many investigations[4–8] in the recent past have been conducted experimentally to understand the various aspects of supersonic combustion. Recent studies by Gutmark et al.[9] and Schadow and Gutmark[10] have indicated that mixing in the supersonic combustor can be enhanced considerably by using nonconventional nozzle shapes for the gas generator. Later, Tillman et al.[11] developed a supersonic nozzle called splayed nozzle for the enhancement of mixing between supersonic streams. Narayanan and Damodaran[12] have proved that better mixing of high-speed streams can be achieved by employing a radically lobed primary nozzle called a petal nozzle. In the present work, utility of the petal nozzle for effecting complete and efficient combustion in the dual combustion mode of the ramjet is evaluated.

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II. Details of Experiments

The experimental setup is shown schematically in Fig. 1a.

A gas turbine type of combustion chamber, suitably modified aircasing, and radically lobed primary nozzle, as shown in the figure, were used as the primary engine (gas generator) for the present experiments. Based on experiments on a large number of petal nozzles the radially lobed nozzle with six lobes was found to be optimum and was used as the primary nozzle in the present experiments. The nozzle was designed for a Mach number of 1.7 at the exit plane and was operated at a stagnation pressure of 450 kPa. The corresponding air mass flow rate was 0.5324 kg/s.

The secondary combustion chamber (SCC) has a semidivergence angle of 1.5 deg and a length-to-diameter (*L/D*) ratio of 4.25. The SCC was connected to the secondary airflow line, which is annular and coaxial with the primary stream. Secondary fuel was distributed at the entrance of the SCC through six troughs (secondary lobes) of the primary nozzle. Fuel used, for both primary and secondary engines, was kerosene. The primary engine was operated at a fuel equivalence ratio of 0.43. The secondary fuel jets were at an angle of nearly 30 deg with respect to the vertical plane. The secondary fuel injection arrangement is schematically shown in Fig. 1b. The secondary airstream was operated at a stagnation pressure of 200 kPa and the air mass flow rate was 0.7466 kg/s. The secondary was operated with lean equivalence ratios of 0.015–0.08.

The total pressure of the jet at the exit plane of the mixing chamber was measured using an impact probe and static pressure by a long conical multiholed supersonic static probe. The total temperature at the exit of the SCC using a Winkler type of stagnation temperature probe and the fuel flow rates by a

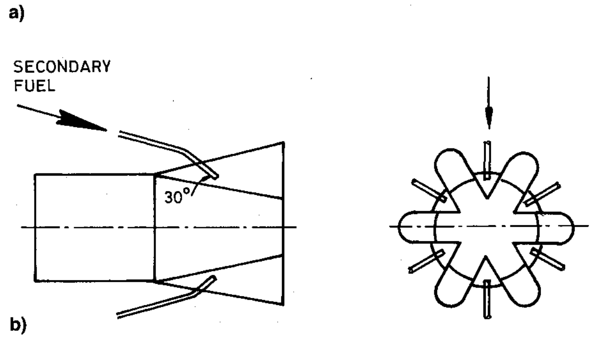

Fig. 1 a) Experimental setup and b) schematic of secondary fuel injection.

metal tube rotameter were also measured. The measurements were carried out in two reference planes: 1) the crest plane of the nozzle (referred to as major plane) and 2) the trough plane (referred to as minor plane). The probes and instrumentation used were the same as those in Refs. 11 and 12 and their combined accuracies were estimated to be less than ±3%. The temperature probe was estimated to have an uncertainty of ±15 K.

III. Results and Discussion

A. Mixing Performance of Various Petal Nozzles

For enhancement of mixing between two high-speed streams, petal nozzle is established to be far superior to conventional conical nozzles.[11] The mechanism of mixing is believed to be due to large-scale axial vortices in contrast to the shear mixing in the case of conical C–D nozzles. Evaluation of mixing performance by a petal nozzle is done by comparing flow properties like momentum, Mach number, static pressure, and static temperature in the two planes, namely, major and minor of the nozzle. As the formation of large-scale vortices can be thought to be dependent on geometry of the nozzle, an experimental study was done to ascertain the effect of a number of lobes on the mixing performance. Six different nozzles having a different number of lobes from three to eight were tested. It was seen[13] that most uniform occurrence of momentum flux, static pressure, and Mach number in the two planes is in the case of the nozzle with six lobes. This is indicative of best mixing performance among the six nozzles tested.

B. Temperature Profile in the DCR Mode

As mentioned earlier, the dual-mode combustion ramjet is a combination of two ramjet cycles: subsonic combustion in the primary combustor and supersonic combustion in the secondary. In our experimental arrangement a primary gas turbine engine simulates the subsonic ramjet. The hot products of combustion that act as the pilot issuing from this engine through the convergent–divergent radially lobed petal nozzle are mixed with the outer airstream and with the secondary fuel in the diverging chamber where the secondary fuel and air burn at supersonic speeds.

Results of measurements of temperature done at the exit plane of the mixing tube are shown in Fig. 2a. Static pressure measurements were carried out along the walls of the combustor that ensured supersonic flow in the combustor. Temperature distribution at the exit plane in the radial direction is shown for various secondary fuel flow rates and also for no secondary fuel flow. As seen, there is an increase in temperature with an increase in secondary fuel flow. This is due to the secondary combustion of fuel mixed with airstreams aided by the pilot torch provided by the radially lobed primary nozzle.

The temperature distributions at the exit plane of SCC with the petal and conical nozzles are given in Fig. 2b. The temperatures plotted are the area-averaged temperatures. The temperature distributions are very nearly uniform in the case of petal nozzle and very uneven in the case of outflow from conical nozzle. When conical nozzle is used for the primary hot flow the core temperature is that corresponding to the pilot flame, whereas at the periphery of the mixing tube the temperature remained as low as about 350 K. This is indicative of the poor thermal mixing between the primary and secondary streams.

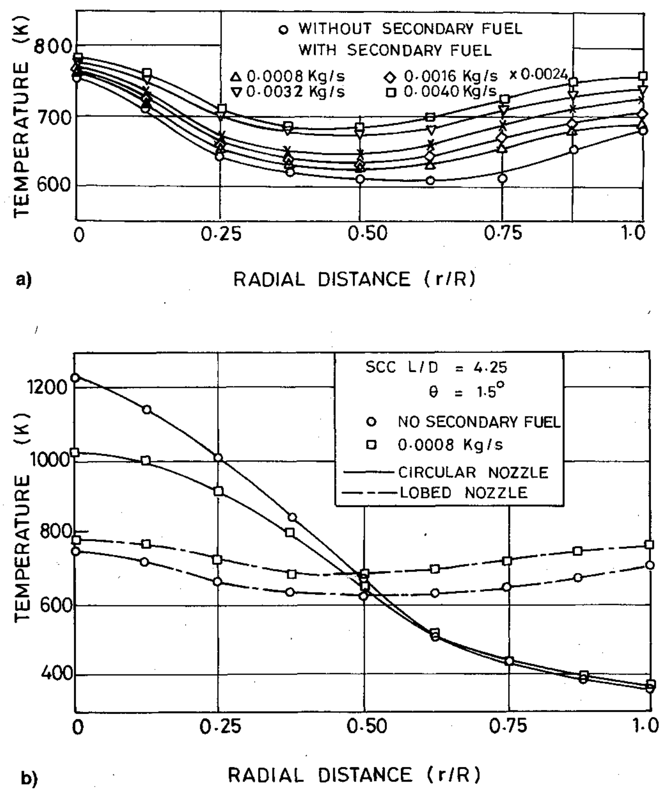

Fig. 2 a) Radial temperature distribution at the outlet plane of SCC and b) comparison of temperature profiles with conical and petal nozzle.

C. Efficiency of Combustion

The combustion efficiency of the combined system was estimated from the thermal energy produced by the primary and secondary engines together and the energy content of the total fuel used. The combustion efficiency of the supersonic combustor was estimated indirectly. The net thermal energy between the combined system and the system with only the primary fuel was estimated. Using this value and the energy content of the secondary fuel, efficiency of secondary combustion was calculated. From our experiments the average efficiency of combined system was found as 80.8% and that of secondary combustor was obtained as 84.8%. It may be mentioned here that in recent experimental investigations done by Chinzei et al.,[14] combustion efficiencies obtained were in the same range. In contrast, the combustors employed were two dimensional with a much higher *L/D* ratio.

IV. Conclusions

Dual-mode combustion ramjet making use of petal nozzle for the hot primary jet is proved to be a viable proposal. Combustion efficiencies obtained in our experiments are found to be comparable with the already existing values.

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Numerical Simulations of Unsteady Transonic Flow in Turbomachines

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Nomenclature

C_f = skin friction coefficient
p = unsteady pressure
q = velocity magnitude
v_g = vortical gust amplitude
β = flow angle
θ = momentum thickness
ρ = density
ϕ = phase angle
ω = reduced temporal frequency

Subscripts
chd = chordwise direction
1 = inlet quantity

Superscripts
$+$ = upper surface of blade
$-$ = lower surface of blade

Introduction

THE need for improved durability, reduced noise levels, and increased performance has motivated engineers to assess the effects of flow unsteadiness on the aerodynamic phenomena present in axial-flow turbomachines. For coupled systems of rotating and stationary blade rows, the relative motions between adjacent rows give rise to high-frequency unsteady aerodynamic excitations that can reduce performance and generate discrete-tone noise. Two categories of numerical procedures have been developed for determining the effects of relative motion between adjacent blade rows. In the first category of procedures, incoming wakes are specified at the inlet of isolated blade rows.[1] In these methods the wakes are usually assumed to be parallel, with uniform pressure and a prescribed total enthalpy and/or velocity variation. In the second category of analyses, both blade rows are modeled and the relative position of one blade row is varied to simulate blade motion.[2,3] The work in this study utilizes the first category of numerical procedures.

In a recent study, unsteady inlet and exit boundary conditions were formulated and implemented into an implicit two-dimensional Navier–Stokes procedure.[4] The inlet and exit boundary conditions were designed to be time-accurate and nonreflecting. In addition, the boundary conditions were constructed to allow the specification of entropic, vortical, and acoustic excitations at the inlet, and acoustic excitations at the exit of the computational domain. The focus of the current investigation is to study the unsteady response of a transonic compressor cascade to inlet vortical gusts.

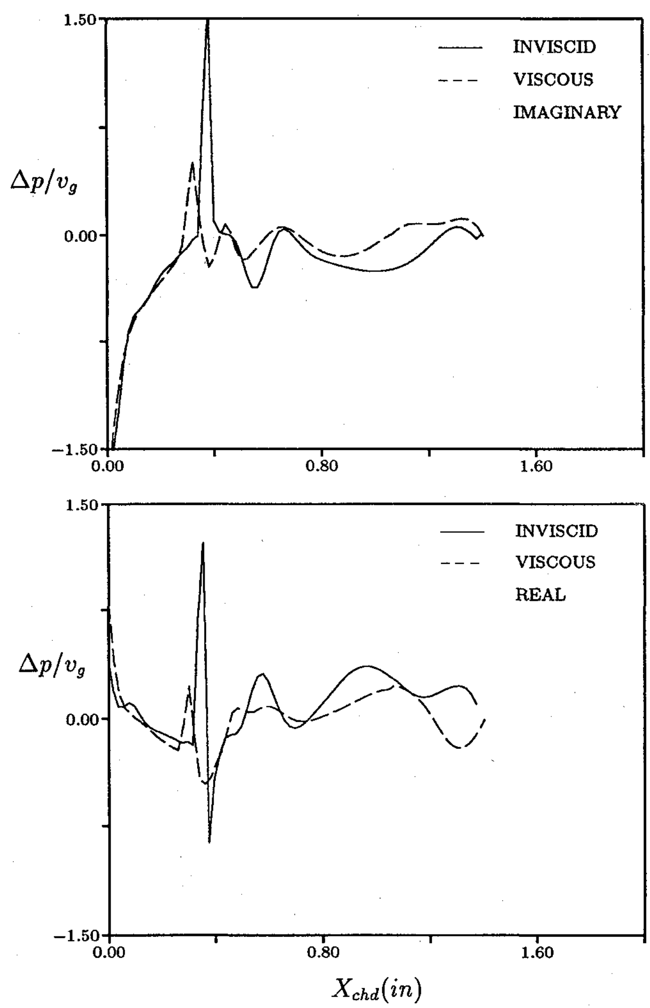

Fig. 1 Real and imaginary components of the unsteady pressure difference.

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