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Experimental Studies on Piloted Supersonic Combustion Using the Petal Nozzle

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In recent times, high-speed, airbreathing propulsion research has been receiving considerable attention all over the world. This has come about primarily because of renewed interest in the development of reusable launch vehicles employing multimode propulsive systems. The scramjet, a critical subsystem of these composite engines, is still in the developmental stage. A crucial problem in this development is the realization of rapid mixing and heat release with minimum pressure losses inside the supersonic combustor. Recently, a new mixing technique for high-speed flows employing large-scale axial vortices was developed. This involved the use of a lobed supersonic primary nozzle referred to as the petal nozzle. The possibility of applying this novel mixing mechanism to piloted supersonic combustors was examined in this work. Results showed that rapid mixing took place between the hot primary (pilot) stream and the cold secondary airstream when the petal nozzle was used. Piloted secondary (supersonic) combustion of kerosene and acetylene was achieved with satisfactory efficiencies.

Nomenclature

A = area
M = Mach number
m = momentum
P = pressure
R = nondimensionalized radial distance
T = temperature
γ = ratio of specific heats

Subscripts
i = primary (inner) stream
o = secondary (outer) stream
s = static
ws = wall static

I. Introduction

AS human endeavor in space extends into the future, low cost and reliable access to space have become essential requirements for military, civil, and commercial applications. Existing expendable launch vehicles have been found to be very expensive in getting large payloads into space. To reduce transportation costs, fully reusable space planes have been proposed and are under development. The propulsion systems of these vehicles are being configured to utilize aircraft, ramjet, scramjet, and rocket technologies. While turbojet, ramjet, and rocket technologies are well known, the scramjet is still in the development stage.

Many demanding technological problems are still to be overcome in the development of an operational scramjet. Critical among these is the problem of enhancing the mixing between two high-speed streams, for example, fuel and air. The length and weight of the engine, as well as the efficiency of heat release, depend on the rapidity of this mixing process. Rapid mixing and high-energy release rate are especially important in supersonic combustors for the following reasons[1]: 1) the innately low shear-induced mixing that is typical of high Mach number, fully developed turbulent free shear layers; 2) extremely short combustor residence time because of high local flow velocities; 3) the dependence of cooling requirements, drag, and weight fractions of the vehicle on combustor size; and 4) high shear layer transition Reynolds number at high Mach numbers. Available data indicate reduction in the mixing rate by a factor of 3 between Mach numbers 1–5. Therefore, mixing enhancement constitutes a very important consideration for scramjet combustor design.

The flight envelope of the scramjet may be divided into two broad regions based on the flight speed: 1) moderate (M = 4–9) and 2) high ($M > 10$) Mach numbers. For the latter case, combustion systems employing shock-induced ignition have been considered and are known to be under development by the leading countries in aerospace technology. For moderate flight Mach numbers, however, shock strength in the supersonic combustor is insufficient and the designer is forced to look for alternative means of initiating and sustaining combustion. Currently, two techniques are being investigated in this respect: 1) an external ignition source, like a plasma torch[2] and 2) a pilot flame. Developments with regard to the latter are the subject of this article.

A number of workers have been involved in high-speed mixing studies and a large body of literature exists on various aspects of the problem. These works range from studies on the basic physics of high Mach number mixing phenomena[3] to practical concepts for actual application.[4] Most of these efforts over the years, particularly in the U.S., have been summarized in a comprehensive article by Billig.[5] Note that a substantial proportion of the early studies had employed various forms of the shear-mixing concept. These studies led to the conclusion that shear, as applied to high-speed mixing, is intolerably slow for practical application. Since the need for novel mixing concepts has been established, there is currently a growing body of literature on nonconventional mixing techniques for high-speed flows.[6,7] In general, there has been increasing awareness that 1) large-scale flow structures are crucial for rapid mixing and 2) these structures must be axial and of low intensity to ensure low-pressure loss.

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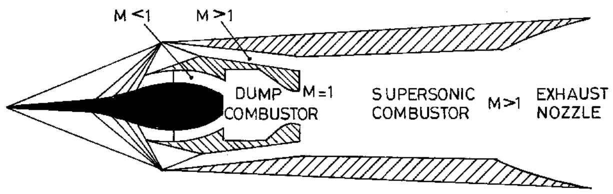

Fig. 1 Dual-mode ramjet (DMRJ).

The authors investigated the effect of axial vorticity on the mixing process in high-speed flows.[8,9] They developed a lobed supersonic nozzle, referred to as the petal nozzle, which was found to give very rapid mixing in short combustor lengths with moderate pressure loss. This was attributed to large-scale axial vortices generated by the petal nozzle in the mixing/combustion chamber. This concept was later applied to air-augmented rockets[10] and supersonic ejectors,[11,12] with interesting results.

The present investigation was undertaken to examine the possibility of employing the petal nozzle for scramjet application. Piloted supersonic combustion, as applied to the dual-mode ramjet configuration[13] (DMRJ) (Fig. 1), was chosen for this study. In this flexible design a dump-type subsonic combustion ramjet is embedded within the main supersonic combustion ramjet so that the former can act as a hot-gas pilot or a fuel-rich gas generator. Such an arrangement may also permit the use of conventional hydrocarbon fuels for scramjet operation at low hypersonic flight Mach numbers.

A brief examination of the DMRJ mixing problem reveals the following:

1) The two mixing streams are likely to be at different thermal levels.

2) The mixing process may include combustion effects as well.

Accordingly, the present experimental investigation was divided into two phases. Phase I consists of purely mixing studies between the primary, hot pilot gases, and the cold secondary air. This phase is actually an extension of the studies carried out in Ref. 9, where the mixing of two isothermal streams at different momentum and Mach number levels was considered. Phase II consists of tests in which fuel is added to the secondary airstream with secondary combustion taking place at supersonic speeds in the secondary combustor. Two types of primary nozzles were used for comparison purposes: 1) the petal nozzle and 2) a conventional conical nozzle.

II. Experimental Facility and Testing

A. Test Setup

The basic test setup is shown in Fig. 2a. The hot-gas generator (subsonic ramjet) is composed of a gas turbine flame tube with a stainless-steel air casing. A convergent section is provided downstream of the air casing. At the end of this section is a constant area piece to which either of the two nozzles, petal or conical, may be attached. The secondary airstream is annular and coaxial with the primary stream for the conical nozzle case. For the petal nozzle, the secondary airstream enters through the crest region or minor plane. The secondary throat plane coincides with the exit plane of the primary nozzle. The two flows, primary and secondary, enter and mix within the mixing/combustion chamber located downstream. The two primary nozzles are shown in Figs. 2b and 2c. They were designed for a critical pressure ratio of 5 and exit Mach number of $M = 1.7$. Detailed descriptions of the petal nozzle may be found in Refs. 8 and 9. For purely mixing studies (phase I), cylindrical mixing chambers were employed. For supersonic combustion studies (phase II), a diverging mixing/combustion chamber of 1-deg half-angle was used. Kerosene was employed as the primary fuel (subsonic ramjet), whereas both kerosene and gaseous acetylene were used as secondary fuels for supersonic combustion.

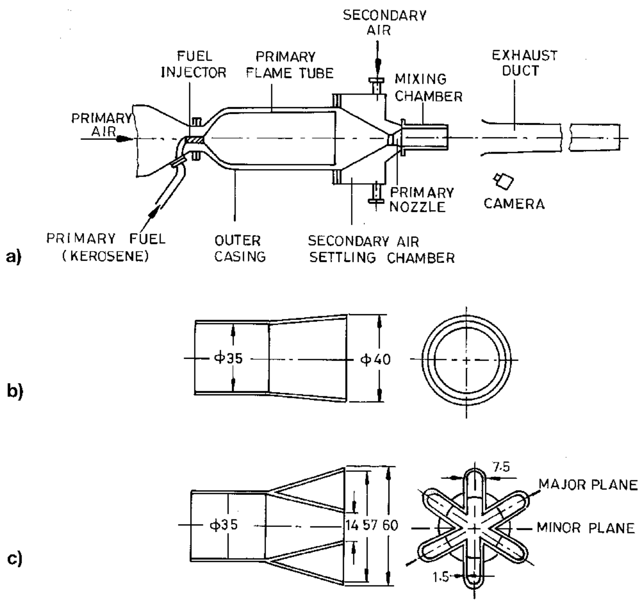

Fig. 2 Experimental facility: a) test setup, b) conical nozzle, and c) petal nozzle.

B. Instrumentation

Total and static pressures were measured by the respective probes connected to pressure transducers. The static pressure probe employed was insensitive to angle of attack up to about 10 deg. It was calibrated and found to have an error in the range of <0.3%. The total pressure probe employed was found to be insensitive to angle of attack of up to 6 deg. It was observed to give an error after shock correction in the range of <1%. For total temperature measurement, a Winkler-type stagnation temperature probe[14] with a chromel–alumel sensing element was employed. On calibration it was found to be insensitive to angle of attack up to about 8 deg. The error was found to be in the range of <3%. These probes were mounted on a three-dimensional traversing mechanism for axial and radial movement. Orifice meters were used to measure primary and secondary airflow rates, whereas rotameters were used to measure the kerosene and acetylene flow rates. Supersonic combustor wall-static pressures were measured using a Hg–multimanometer arrangement.

C. Testing Details

Primary flow blowing pressure was maintained at 5 atmospheres absolute (ata) for all of the tests so that the primary nozzle operated at its design condition. Unless specified otherwise, primary fuel flow rate was maintained at 28 liters per hour (LPH) (7.8 ml/s), which resulted in an equivalence ratio (ER) of 0.14 for the primary combustor. Secondary air pressure was varied to give high subsonic ($M = 0.8$) to supersonic ($M = 1.2$) mixing/combustion chamber Mach numbers in the entry region for the secondary flow. Entry total temperature of the secondary airflow was about 300 K. Total and static pressures and total temperature were measured along the radial direction in the exit plane of the mixing/combustion chambers of various lengths. From these readings, flow variables like Mach number and momentum flux, etc., were calculated. Supersonic combustion tests were performed using secondary kerosene flow rates of 4, 8, and 12 ml/s, and acetylene flow rates of 2 and 4 g/s.

For shock correction of experimentally measured pitot pressure and Mach number calculation, the following Rayleigh formula[14] was employed:

$$\frac{P_s}{P_{02}} = \frac{[2\gamma M^2/(\gamma + 1) - (\gamma - 1)/(\gamma + 1)]^{1/(\gamma - 1)}}{[(\gamma + 1)M^2/2]^{\gamma/(\gamma - 1)}}$$

where P_s and P_{02} are the measured static and total pressures, respectively.

Momentum flux (momentum per unit area) was determined from the following one-dimensional equation[14]:

$$m/A = P_s(1 + \gamma M^2)$$

III. Results and Discussion

A. Phase I: Mixing Studies

1. Primary Flow Only, with No Mixing Chamber

Figure 3a shows the radial Mach number distribution at the exit of the petal and conical nozzles for the primary hot flow only. In both cases, exit Mach number is seen to be very close to the design value of $M = 1.7$. The corresponding radial distribution of total temperature at the exit of the two nozzles is shown in Fig. 3b. A maximum temperature of about 870 K occurs at the axis and is seen to gradually decrease in the radial direction.

2. Confined Mixing, Total Temperature Profiles

Radial distributions of total temperature at the exit of a cylindrical mixing duct of length-to-diameter ratio (L/D) of 4.3, for various secondary blowing pressures, using the conical primary nozzle, are shown in Fig. 4. The primary (inner) flow temperature is seen to be more or less unaffected by variations in the secondary flow pressure. This supplements the conclusions from momentum and Mach number data, presented in Refs. 8 and 9, regarding the poor supersonic shear-mixing characteristics of the conical nozzle.

The petal-type nozzle and its axial vortex mixing mechanism are described in Refs. 8 and 9. The momentum and Mach number data presented in Ref. 9 show that complete mixing of two isothermal supersonic streams ($M = 1.7$ and $M = 1.2$) was obtained within a mixing chamber of $L/D = 4.3$ using the petal nozzle. Figures 5a and 5b show radial distributions of total temperature at the exit of a mixing chamber of $L/D = 0.95$, at secondary pressures of 1.66 and 2.2 ata, respectively. In the core region ($0 < R < 0.3$), which is common for both major and minor planes, the two profiles are nearly identical, as may be expected. However, in the lobe region ($R > 0.3$), the two profiles are quite dissimilar. Temperatures in the major plane, corresponding to the inner hot flow, are seen to be substantially higher than those in the minor plane, which correspond to the colder secondary air.

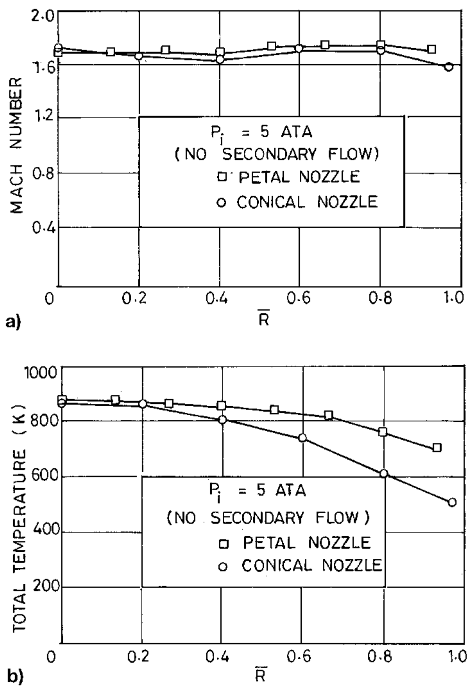

Fig. 3 Primary nozzle exit Mach number and temperature profiles.

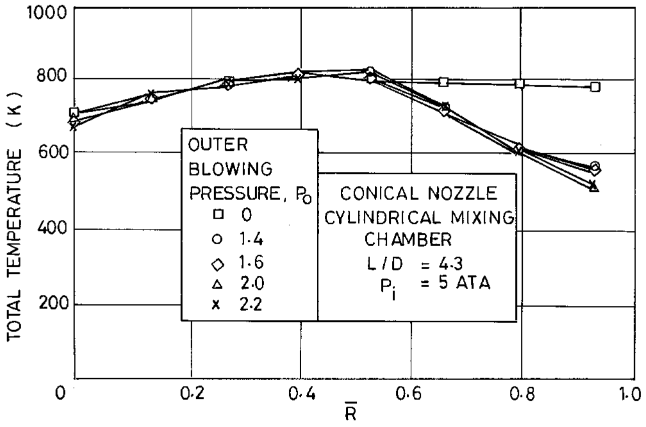

Fig. 4 Radial temperature profiles for conical nozzle.

Similar profiles for a mixing chamber of $L/D = 2.7$ are presented in Figs. 5c and 5d. It can be observed from these figures that total temperatures in the minor plane are now higher than those in the major plane in the lobe region. This substantial increase in the minor plane temperature is expected to be, as explained in detail in Refs. 8 and 9, because of the presence of large-scale axial vortices transferring energy and mass from the major to the minor plane in a large-scale stirring process.

Figure 5e shows similar distributions for a mixing chamber of $L/D = 4.3$ for secondary pressures of 1.4, 1.66, 2.0, and 2.2 ata. It can be observed that for a secondary blowing pressure of 2.2 ata, the temperature profiles in the major and minor planes are almost identical, indicating complete mixing of the hot primary and cold secondary streams. It may be recalled from Ref. 9, in which data for the mixing of two isothermal streams are presented, that the large-scale vortex subsequently breaks down to smaller scales and finer levels of mixing until the two streams are fully mixed within a chamber of $L/D = 4.3$. The variation of temperature profiles in Fig. 5e is very similar to that presented in Ref. 9 for momentum flux. A schematic figure from Ref. 9 depicting the large-scale axial vortex mixing mechanism is reproduced in Fig. 6.

To investigate the effect of primary fuel flow rate (or primary exit temperature) on the mixing efficacy, radial temperature profiles were measured at the exit of a mixing chamber of $L/D = 4.3$ for a secondary pressure of 2.2 ata and for primary fuel flow rates of 28 and 30 LPH. These distributions are presented in Fig. 7. Both sets of profiles show complete mixing between the primary and secondary streams. The average exit total temperature for the 30-LPH case is seen to be about 30 deg higher than that for 28 LPH.

3. Confined Mixing, Momentum, and Mach Number Profiles

Figure 8a shows momentum flux profiles at the exit of the mixing chamber of $L/D = 4.3$ for inner and outer blowing pressures of 5 and 2.2 ata, respectively. It can be observed that for the conical primary nozzle, the core momentum of the inner flow is maintained, with little momentum having been transferred in the radial direction. The profiles for the petal nozzle in the major and minor planes, however, show that almost complete mixing has taken place.

From the exit momentum profile, net momentum of the flow exiting the mixing chamber was calculated by a summation process. Also, net momentum entering the mixing chamber was estimated from known entry conditions by employing one-dimensional gasdynamic relations.[14] The difference between these net momenta represents the net momentum loss within the mixing chamber. Net momentum losses in the mixing chamber for the conical and petal nozzles, for the previous flow conditions, were found to be 4.5 and 21.5%, respectively.

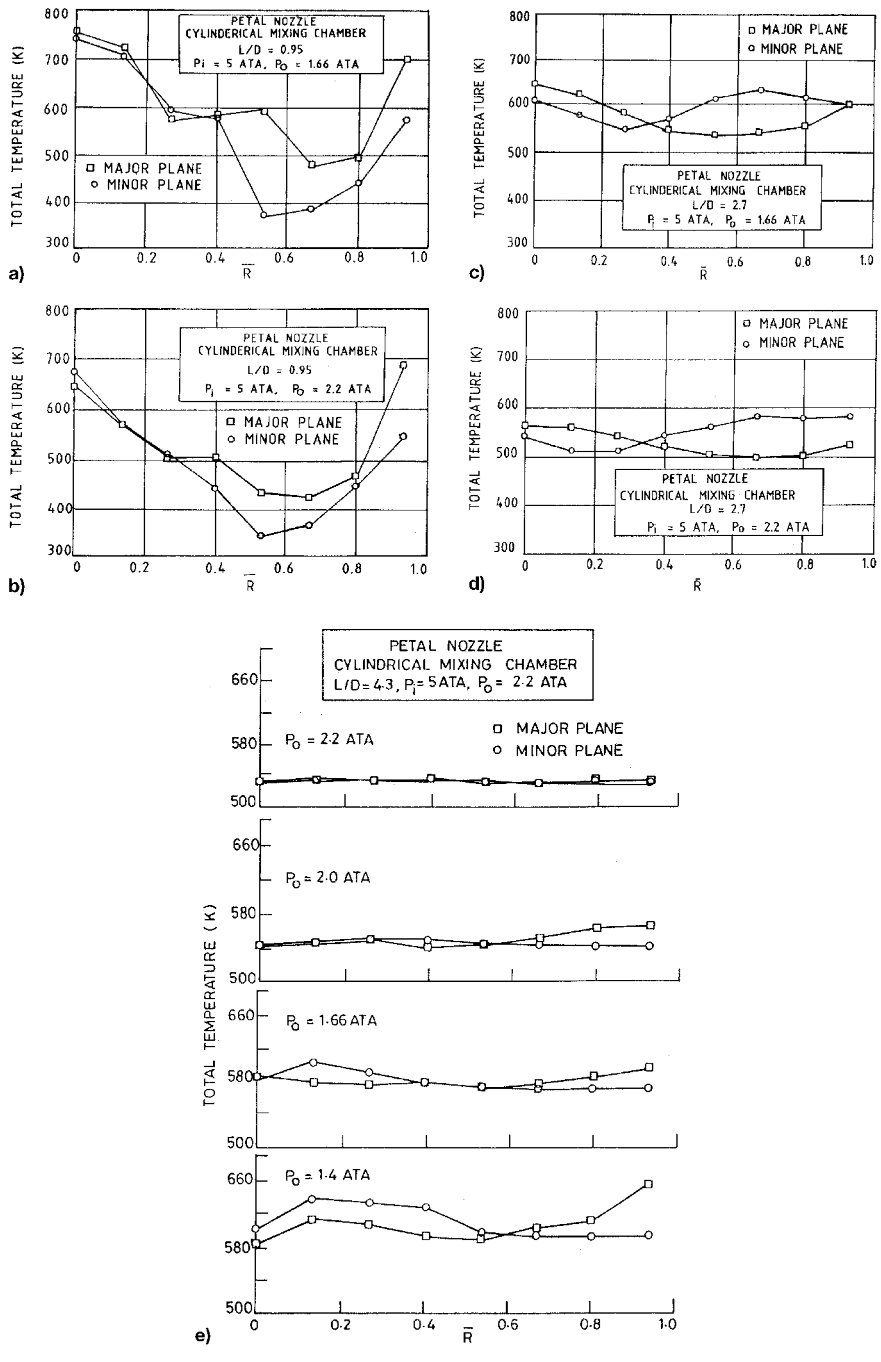

Fig. 5 Radial temperature profiles for petal nozzle.

It may be recalled from Ref. 9, for mixing of isothermal streams, that while there was negligible net momentum loss for the conical nozzle, the corresponding value for the petal nozzle stood at 10%.

A similar trend, as observed for the momentum profiles, may be seen from the exit Mach number profiles shown in Fig. 8b. Again, the inner flow from the conical primary nozzle is seen to maintain its separate distinct identity from the outer secondary stream, signifying poor mixing. Core Mach number is observed to be almost equal to the nozzle exit Mach number of $M = 1.7$. For the petal nozzle, however, profiles in the major and minor plane show that almost complete mixing has taken place between the two streams.

B. Phase II: Supersonic Combustion Studies

The basic test facility for supersonic combustion studies was the same as that used for the mixing studies. The cylindrical mixing tube was replaced by a diverging mixing/combustion chamber having a half-angle of 1 deg. Secondary fuel (liquid kerosene and gaseous acetylene) for supersonic combustion was added to the secondary stream at six locations. These additions are shown schematically in Figs. 9a–9c. For the conical nozzle (Fig. 9a), the secondary fuel tubes were arranged circumferentially, whereas for the petal nozzle these were introduced in the minor plane region as shown in Figs. 9b and 9c. For kerosene injection, the fuel was directed at the nozzle outer surface at an angle of about 60 deg to promote breakup and atomization of the liquid jet. For injection of gaseous acetylene, however, it was found by preliminary tests that maximum heat release occurred when the secondary fuel was injected near the lobe top and close to the mixing chamber wall (Fig. 9c). Note from Fig. 6 that this is the region where the large-scale vortex action begins to transfer mass and momentum from the primary to the secondary stream.

It was also found that when acetylene alone was injected into the secondary stream, no secondary combustion took

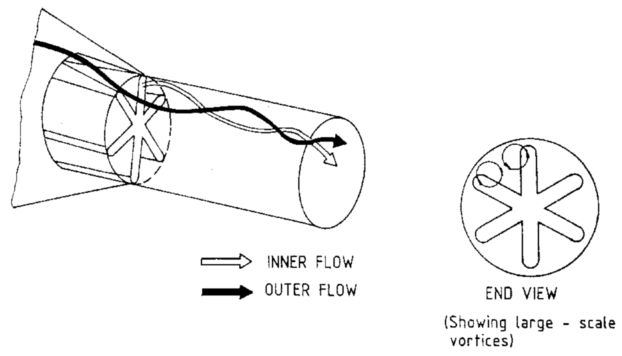

Fig. 6 Large-scale axial vortex mixing mechanism.

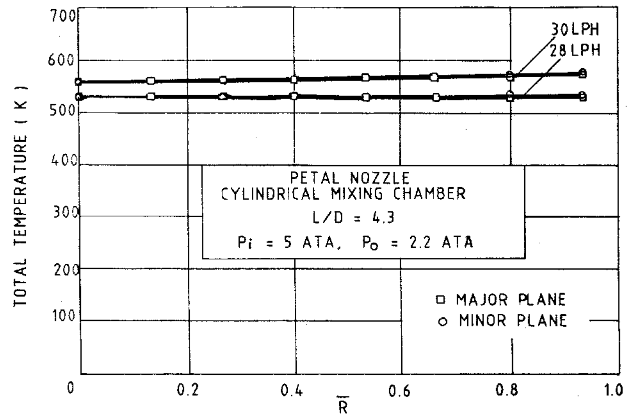

Fig. 7 Variation of radial temperature profiles with primary fuel flow rate.

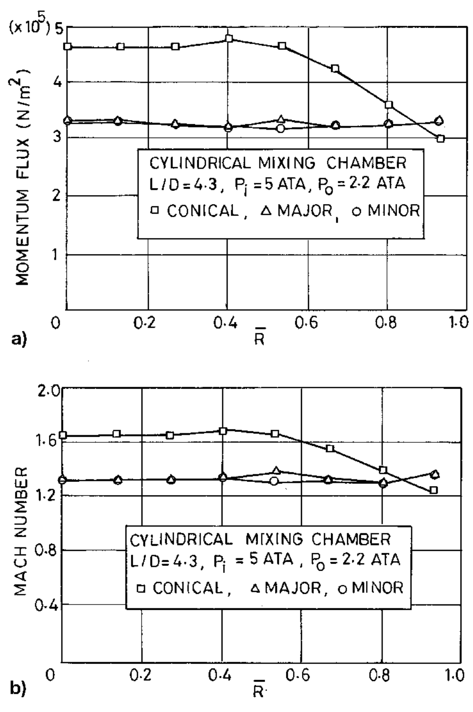

Fig. 8 Radial momentum flux and Mach number profiles.

place. This was because of the fact that the autoignition temperature of acetylene is about 580 K, whereas the static temperature of the primary flow at primary exit was somewhat lesser than this value. However, when acetylene was used in conjunction with kerosene, the combustion of acetylene could be discerned from the experimental data.

To examine the secondary combustion process of the petal nozzle visually, photographs were taken with and without secondary (kerosene) fuel injection. Figure 10a shows a photograph looking upstream from the secondary combustor exit, for zero secondary fuel flow. The hot pilot flow exiting the primary (petal) nozzle can be clearly seen. For secondary fuel addition, when the six-point injection (Fig. 9b) was carried out, intense combustion made it impossible to discern any details from the photograph. Hence, it was decided to photograph it using a reduced secondary fuel flow rate with fuel injection at a single point only. Figure 10b shows a photograph with fuel

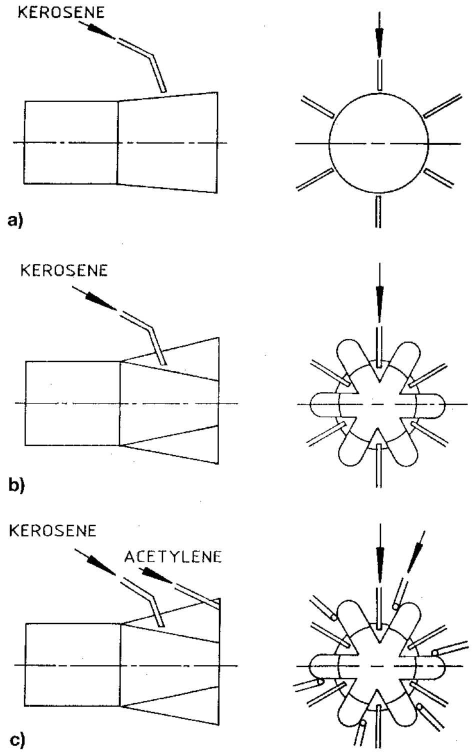

Fig. 9 Secondary fuel addition.

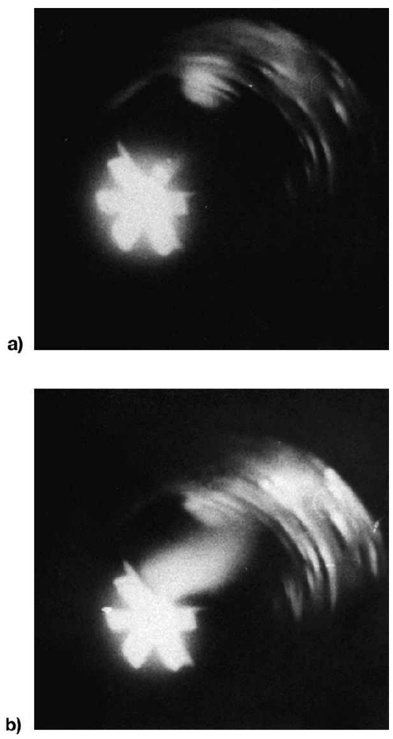

Fig. 10 Photograph of secondary combustion for single-point injection (petal nozzle).

injection of 1 ml/s in the top minor plane only. This photograph clearly shows secondary combustion taking place in the top minor plane region. Similar photographs were not taken for the conical nozzle because of reasons explained in the next section.

1. Combustion Wall Static Pressure

Variation of wall static pressure along the supersonic combustor can give an indication of the flow dynamics and heat release occurring inside. It is well known that combustion heat release in a confined supersonic flow tends to decelerate the flow, thereby increasing the static pressure.[15,16] Figure 11a shows the axial variation of combustor wall static pressure for the conical nozzle at $P_i = 5$ ata and $P_o = 2.2$ ata, for secondary (kerosene) fuel flow rates of 4 and 8 ml/s. Note that for both fuel flow rates, for $0 < L/D < 1.0$, there is practically no change in the wall static pressure. In the region of $L/D = 1.3$, both cases show an increase in static pressure, which may signify combustion heat release. Thereafter, for $L/D > 1.5$, secondary fuel flow is seen to result in decreased wall static pressure at all axial locations. It is felt that this decrease is caused by the vaporization of kerosene, which would remove heat from the flow and result in lowered static pressure. This is confirmed from the fact that for $L/D > 1.5$, increasing the kerosene flow rate from 4 to 8 ml/s lowers the static pressure further. These conclusions are further verified by visual observation. While a small yellowish–orange flame can be seen near the primary nozzle lip, the flow exiting the combustor is diffused with thick white-colored (unburnt) kerosene vapor. These observations lead one to conclude that almost no secondary combustion is taking place in the supersonic combustor. It is felt that this is because, as seen from the mixing studies, little heat is being transferred from the hot primary flow to the secondary flow, thereby resulting in poor ignition of the secondary fuel. Because of the unsatisfactory supersonic combustion and mixing performance of the conical primary nozzle, no further tests were conducted with it.

Figure 11b shows the axial variation of combustor wall-static pressure using the petal nozzle for $P_i = 5$ ata and $P_o = 2.2$ ata for various secondary fuel flow rates. As in Fig. 11a, little change is seen here in the wall-static pressure in the near region ($0 < L/D < 1$) for various kerosene flow rates. However, for gaseous acetylene injection, a considerable increase is seen, even in this region. This is because of the fact that unlike kerosene, acetylene does not require vaporization before undergoing combustion. Figure 11b clearly brings out the heat release effect caused by the addition of acetylene. After $L/D = 1.0$, increasing secondary fuel flow rate is seen to result in increased static pressure at all axial locations. From this figure, it may be concluded that heat release has occurred in a controlled manner inside the mixing/combustion chamber. The cyclical variation of the wall static pressure with axial distance also points to the flow being supersonic inside the secondary combustor.

2. Exit Mach Number and Momentum Profiles

Mach number profiles in the radial direction in the major and minor planes at the exit of the supersonic combustor, for $P_i = 5$ ata, $P_o = 2.2$ ata, and a secondary kerosene flow rate of 4 ml/s, are shown in Fig. 12a. Firstly, note that these exit profiles are not flat as in Fig. 8b. This is attributed to the divergence of the mixing/combustion duct employed for these tests as compared to the cylindrical mixing chambers for Fig. 8b. Secondly, observe that the average exit Mach number in Fig. 8b (no secondary combustion case) is about 1.3. Thus, after secondary fuel addition and combustion, this value may be expected to decrease further. However, the increasing flow area (divergence) of the mixing/combustion chamber is seen to reaccelerate the flow to an average exit Mach number of about 1.6. The corresponding momentum flux profiles are shown in Fig. 12b. Again, it is noted that the profiles are not flat. A comparison of Fig. 8b with this figure shows the momentum loss caused by combustion.

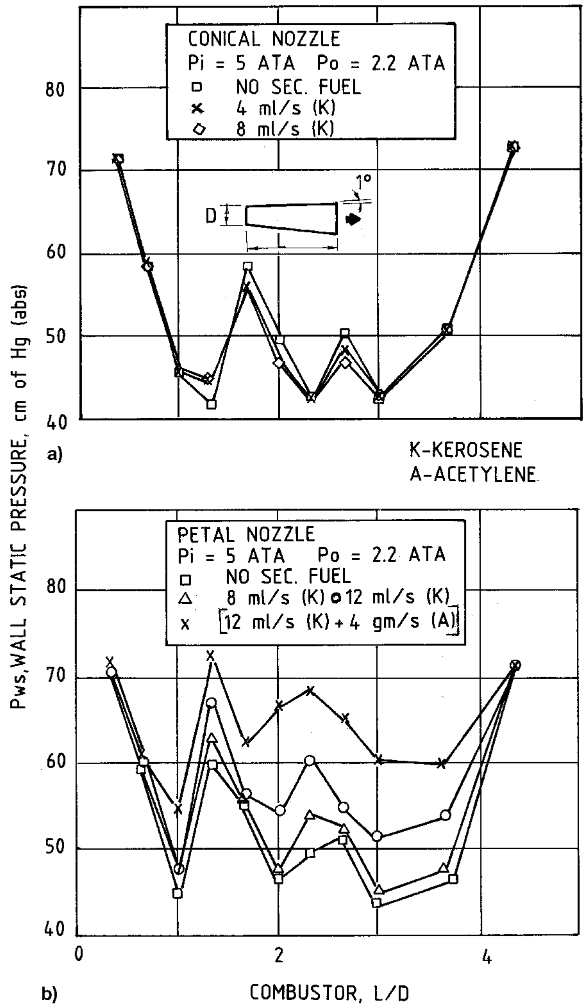

Fig. 11 Axial variation of combustor wall-static pressure.

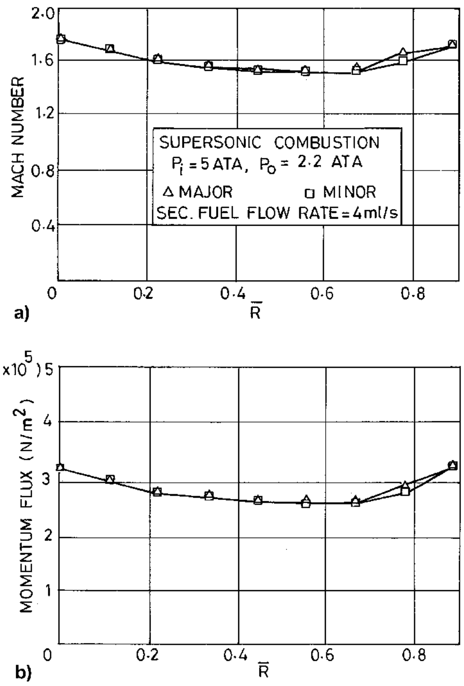

Fig. 12 Radial Mach number and momentum flux profiles.

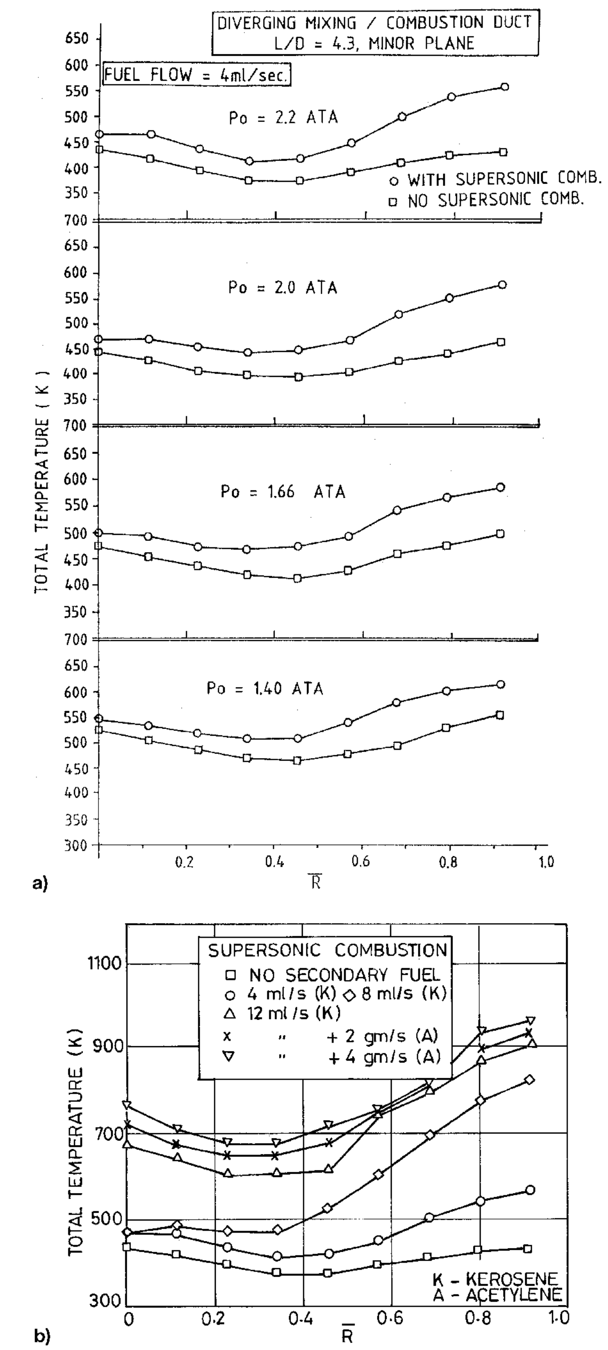

Fig. 13 Secondary combustor exit temperature profiles.

3. Total Temperature Profiles

The total temperature profiles in the minor plane at the exit of the supersonic combustor, with and without secondary fuel (kerosene) addition, for various outer airflow rates are shown in Fig. 13a. It can be seen that there is almost uniform heat release in the radial direction, signifying good mixing of the fuel-laden secondary airstream with the pilot stream. Average total temperature increases with a decrease in secondary flow blowing pressure (or secondary air mass flow) can be explained as follows. An increase in the overall fuel–air ratio results in the decrease of secondary flow pressures at a constant secondary fuel flow rate.

Figure 13b shows similar radial temperature profiles in the minor plane for various secondary fuel flow rates, for $P_i = 5$ ata and $P_o = 2.2$ ata. It may be observed that for kerosene injection, more heat is released in the lobe region as compared to the core. For acetylene injection, however, it is noted that more heat release occurs in the core region. The exact reason for this phenomenon is not clear. It is felt that it may have been influenced by the differences in molecular weight and the buoyancy between kerosene and acetylene.

4. Supersonic Combustion Efficiency

The efficiency of supersonic combustion was calculated from the exit total temperature rise with secondary fuel addition, secondary fuel flow rate, and total air mass flow rate. Average values of 0.79 and 0.76 were obtained for the kerosene-only and kerosene–acetylene cases. Combustion efficiencies for lower secondary airflow rates were found to be higher than those for higher secondary airflow rates.

Note that the static temperature of the primary flow exiting the primary nozzle is about 550 K. This is very close to the autoignition temperature of kerosene–air mixtures, which is about 520 K. With higher primary stream temperatures, combustion delay and combustion efficiency could be further improved.

IV. Conclusions

Conclusions drawn from this preliminary study on piloted supersonic combustion are as follows:

When a conventional, conical nozzle is employed for the primary stream, Mach number, momentum flux, and total temperature profiles indicate practically no heat or momentum transfer taking place between the two streams at the exit of a cylindrical mixing chamber of $L/D = 4.3$. When a petal nozzle is employed for the primary stream, all the previously mentioned flow profiles indicate that complete mixing has taken place between the two streams within a mixing chamber of $L/D = 4.3$.

The feasibility of a stable, piloted supersonic combustion of kerosene and gaseous acetylene has been demonstrated using a petal nozzle for the pilot stream.

Test facility limitations allowed a maximum total temperature of about 850 K for the primary stream. This is a low value for a pilot flame. Increasing the pilot flame temperature should result in better ignition characteristics and combustion for the secondary fuel. Also, these experiments were conducted with cold secondary air. Increasing the secondary air temperature, to simulate hypersonic flight conditions inside the supersonic combustor, should improve the combustion process further, possibly by an order of magnitude.

The excellent supersonic mixing characteristics of the petal nozzle could also be employed for rapid and low-pressure loss mixing of fuel and airstreams in premixed supersonic combustors that use plasma torches or shock ignition.

Acknowledgments

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