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Enhancement of Thermal Mixing in Coaxial Supersonic Jets

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An experimental study was conducted to investigate the thermal mixing of a hot, supersonic, primary jet of combustion gases with a coflowing secondary jet of air at ambient temperature. The Mach numbers of the two jets were 1.2 and 1.7, respectively. To enhance the mixing, the core (primary) jet was admitted through a three-dimensional, radially lobed nozzle, referred to as the petal nozzle. The uniformity of stagnation temperature in the flowfield was used to characterize the extent of mixing between the jets. The effect of confinement on the mixing was also investigated. The mixing performance of the lobed nozzle and the associated loss in stagnation pressure were compared with those for a conventional conical nozzle. The study confirms the efficacy of the radially lobed nozzle in thermal and momentum mixing of supersonic jets and highlights its potential in supersonic combustion systems.

Nomenclature

T = stagnation temperature, °C
μ = momentum flux, N/m^2
σ = standard deviation
ϕ = uniformity factor

Subscripts
av = average value
um = unmixed condition
1 = properties of primary jet at nozzle exit

I. Introduction

ONE of the major problems associated with the practical implementation of advanced aerospace propulsion concepts is the difficulty in achieving proper mixing between two high-speed streams in a short mixing chamber. The performance of advanced propulsion systems like scramjets, dual combustion ramjets (DCR), air augmented rockets (AAR), and supersonic ejectors depends to a large extent on the efficient mixing of two high-speed jets. Concentration mixing, which takes place at a molecular level, plays a dominant role in the performance of combustion systems. Thermal mixing is also important when it is desired to heat a cold jet by mixing it with a stream of hot gases, as in the case of piloted supersonic combustors. Momentum mixing (also referred to as bulk mixing) is of importance in applications like supersonic ejectors and in noise reduction systems (noise suppressors).

Mixing of coaxial jets issuing from conventional conical nozzles is controlled by the growth of the shear layer between the two jets. In the case of high-speed jets, the compressibility effects retard the shear-layer growth and slow down the mixing process.[1,2] One of the most efficient methods for enhancing mixing in high-speed coaxial jets is to use a lobed nozzle, often referred to as the forced mixer, for issuing the core jet, instead of a conventional circular nozzle. Paterson[3] reported a benchmark experimental study of a three-dimensional, subsonic flowfield inside the mixing duct of a multilobed forced-mixer. One of the conclusions of the study was that the enhanced mixing achieved by the lobed nozzle was because of the formation of axial vortices in the mixer flowfield, which gave rise to large-scale secondary circulations.

Both experimental and theoretical studies have been reported on various aspects of mixing enhancement by the lobed nozzle in subsonic flows. The flow structure in the periodic array of axial vortices created by the forced-mixer nozzle was studied by Werle et al.[4] using flow visualization. Results of the study confirmed that the mixing process, dominated by axial vortices, is basically of an inviscid nature. Further experimental evidence to the inviscid origin of axial vortices was provided by Skebe et al.[5] Computational investigations of the three-dimensional flowfield of the forced-mixer also demonstrated the validity of the assumption that the vortex mixing is mainly an inviscid process.

Even though the lobed nozzles served the cause of mixing in subsonic streams well, their effectiveness in supersonic mixing was demonstrated experimentally only very recently.[6,7] These pioneering efforts indicate the methodology to be adopted for enhancing mixing in coaxial jets that are slow to mix.

The mixing of a supersonic jet issuing from a two-dimensional-lobed nozzle, with a coflowing subsonic jet has been experimentally studied by Tillman et al.[6] Profiles of pressure and velocity were used to characterize momentum mixing. The study concluded that the axial vorticity that dominates the mixing process in subsonic flow is also effective in enhancing mixing in the supersonic flowfield. Thermal mixing between the hot core jet and the coflowing cold jet was also studied and it was shown that the lobed nozzle resulted in a much more uniform total temperature distribution in the flowfield than the conventional circular and rectangular nozzles. Narayanan and Damodaran[7] used for the first time a three-dimensional, radially lobed nozzle, referred to as the petal nozzle, to enhance the mixing of a supersonic jet with a coflowing sonic jet. Uniformity of momentum distribution at the end of the mixing duct was used to characterize the extent of mixing. The results showed that the lobed nozzle could achieve nearly complete momentum mixing in a very short length of mixing chamber. Narayanan[8] also examined the feasibility of using the radially lobed petal nozzle in high-speed combustion systems.

A review of the literature reveals that the information available on the performance of lobed nozzles in supersonic flows is scant. This is particularly so in the case of the radially lobed nozzle, which is of three-dimensional geometry. Also, most of the mixing studies concentrate on isothermal mixing and the enhancement of heat transfer between the coaxial supersonic streams has not been adequately studied.

The mixing enhancement in supersonic flow by the lobed nozzle is necessarily accompanied by a concomitant increase

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in stagnation pressure drop, a problem that has not been adequately studied so far. Recently, Srikrishnan et al.[9] obtained experimental data on pressure drop for conical and lobed nozzles for isothermal mixing. The present study is an experimental investigation of the enhancement of thermal mixing by a radially lobed petal nozzle in coaxial supersonic jets. Incidentally, the study encompasses momentum mixing as well. It focuses attention on the mixing of a heated primary jet with a coaxial, cold secondary jet, both issuing at supersonic velocities.

The major objective of the study is to make a critical assessment of the utility of the radially lobed nozzles in high-speed combustion systems for aerospace propulsion. In the regime of relatively low flight Mach numbers ($M < 6$), the static temperature of the shock-heated, supersonic stream of air entering the combustor will not be high enough to ignite the fuel injected into it, and hence, a constant source of ignition will be required to ensure stable combustion. In scramjets with piloted supersonic combustion, a pilot jet of hot gases is used to heat the incoming air. Often the pilot stream is also supersonic. In DCRs and AARs a fuel-rich supersonic stream of hot gases issuing from a subsonic combustor serves the purpose of stabilizing the flame in the supersonic combustor. In all of these cases good heat transfer between the hot core jet and the relatively cold outer jet is essential for stable supersonic combustion. Hence, thermal mixing of the two streams plays an important role in the performance of a supersonic combustor, whereas the study of momentum mixing is of direct importance in applications like supersonic ejectors and noise suppression devices. The experimental setup used in the present study resembles the configuration of the supersonic combustor of a DCR in as much as it provides two coaxial supersonic jets, the inner one issuing at a higher temperature, and both issuing into a cylindrical mixing chamber.

The investigation entails an experimental study of mixing between a hot supersonic jet and a coflowing cold supersonic jet. The uniformity of stagnation temperature in the flowfield is a measure of thermal mixing between the hot core jet and the cold outer air jet. A comparative study of the confined and open mixing of the two jets is done to gain insight into the role of the confining mixing tube in enhancing the mixing process. (Confined mixing refers to the case in which the mixing of the jets takes place inside a mixing tube attached to the exit of the nozzles. In open mixing, the two jets issue into the atmosphere.)

When both the jets issue from circular nozzles, the flowfield is axisymmetric, in contrast to that when the inner jet issues from a petal nozzle. In the latter case there will be gradients in the angular direction as well. In such a case, it is therefore necessary to study the temperature distribution in both the radial and the angular directions. With this objective, a survey of stagnation temperature distribution in the transverse planes has also been carried out besides that in the radial direction.

The momentum mixing of the two jets is also concurrently investigated. This is done by analyzing the radial distribution of momentum flux at various axial locations downstream of the nozzle exit. The performance of the petal nozzle in momentum mixing is compared with that of the conical nozzle. In the case of the lobed nozzle, the progress of thermal mixing along the axis of the mixing tube is compared with that of momentum mixing, using a mixing parameter.

The loss in stagnation pressure while using the petal nozzle is compared with that for the conical nozzle under identical conditions of approach flow. For the petal nozzle, the total pressure loss caused from heat transfer is determined by subtracting the pressure drop for isothermal mixing from the measured pressure drop. A tacit assumption is made here that the two pressure drops are additive, a common practice in combustor design. The pressure drop in such systems is the combined effect of friction, shock-losses, etc., besides that caused from heat addition.

II. Description of the Experiments

A. Test Setup

Figure 1 shows the schematic diagram of the experimental arrangement. Two coaxial supersonic jets are employed. The inner jet, referred to as the core or primary jet, issues at a temperature of 750°C. It is a stream of hot gases issuing from a subsonic kerosene combustor. The stream exiting the combustor is accelerated to supersonic speed by the primary nozzle (either petal or conical). The jet temperature is controlled by regulating the fuel flow to the combustor. The outer stream is a jet of air at ambient temperature and is referred to as the secondary jet, issuing coaxially. The Mach numbers of the primary and the secondary jets are 1.2 and 1.7, respectively. As explained before, detailed experiments have been performed for the two cases, namely the jets being confined by a mixing tube and the jets merely issuing into the atmosphere without any confinement.

The instrumentation includes conventional static and stagnation pressure probes, a diaphragm-type pressure transducer, and a three-dimensional traverse mechanism. The pressure transducer has an accuracy of ±0.5%. The temperature measurements were made using a Winkler-type total temperature probe (having a radiation shield) with a calibrated chromel–alumel thermocouple. The error caused by radiation has been estimated to be within 1.5%. The traverse mechanism is driven by a dc stepper motor.

B. Nozzles

A six-lobed petal nozzle was used for issuing the primary hot jet at a Mach number of 1.2 in one set of experiments. Later the petal nozzle was replaced by a conical nozzle with the same design Mach number. The secondary nozzle, which is circular, was formed by a convergent–divergent passage around the primary nozzle and has an exit Mach number of 1.7. Both the primary nozzles are made of stainless steel and the mixing tubes and the secondary nozzle of mild steel.

Two principal planes are identified in the flowfield downstream of a petal nozzle (Fig. 2a). The plane that contains the middle of the lobed region is referred to as the major plane. Similarly a minor plane is the one that contains the middle of the interlobe region. For a six-lobed nozzle the angle between the two planes is 30 deg.

C. Experimental Procedure

For each run, the upstream stagnation pressures of the two streams were maintained at the predetermined values by means of pressure regulators. The flow of kerosene to the subsonic combustor was regulated by using a flow control valve. Surveys of static pressure, stagnation pressure, and total temperature were made using a three-dimensional traversing mechanism. Before each traverse, the probes were carefully positioned at the desired radial and axial locations. In experiments on confined mixing, mixing tubes of different lengths were used to study the extent of mixing at various axial locations. For each mixing tube, the pressure and temperature readings were taken close to the downstream end of the tube.

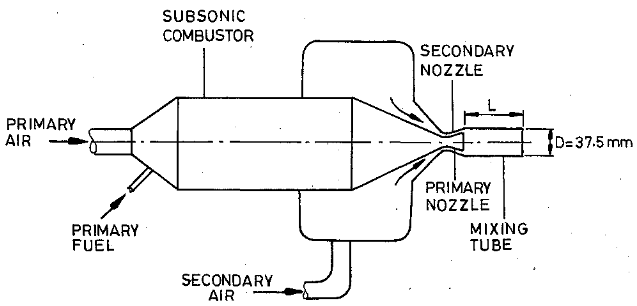

Fig. 1 Schematic diagram of the experimental setup.

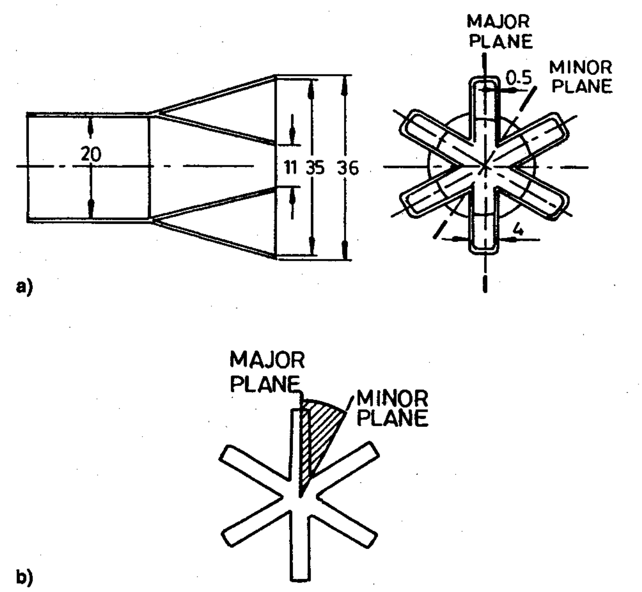

Fig. 2 a) Six-lobed petal nozzle and b) the 30-deg angular segment between major and minor planes (all dimensions are in millimeters).

The probe's movement in the radial direction was controlled by a stepper motor.

III. Results and Discussion

A. Radial Distribution of Stagnation Temperature

Figure 3 shows the radial distribution of stagnation temperature in the minor plane of the petal nozzle, at various axial locations characterized by L/D (L is the distance from the nozzle exit, and D is the diameter of the secondary nozzle that is also equal to the i.d. of the mixing tube, used in studies on mixing with confinement). r/R on the abscissa denotes the radial distance from the centerline r normalized by the radius of the secondary nozzle R. Temperature distributions are shown for both confined and open mixing. (The temperatures are normalized by the stagnation temperature of the primary jet.)

At $L/D = 1.07$ (Fig. 3a) it can be seen that the distribution of total temperature in the radial direction is nonuniform. The temperature is high near the centerline ($r/R = 0$) and is low in the region away from the centerline. This shows that over this length there is no appreciable mixing between the hot stream that issues close to the axis (through the primary nozzle) and the cold secondary stream that issues in the interlobe region. However, the temperature distribution for the case of mixing with confinement is somewhat better than that for open jets. At $L/D = 1.60$ (Fig. 3b) the trend is not much different from this. However, at $L/D = 2.67$ (Fig. 3c) the temperature distributions in both cases are much more uniform, indicating thereby that a good thermal mixing has taken place between the jets. Further downstream, at $L/D = 5.33$ (Fig. 3d), the distributions are still better, suggesting that the two streams are more or less completely mixed. The temperature distributions for the two cases become almost identical at this location.

This observation reveals that confinement has no effect on temperature field in the far field. However, it does have an effect on near-field mixing. The observation that the petal nozzle provides a uniform distribution of temperature in supersonic jets is an indication that it can be successfully used in supersonic combustors. Though the Mach number of the combustor flow achieved in the present study is below the range that one would expect in an actual scramjet flight, the results are encouraging pointers to the use of the petal nozzle in supersonic combustors. Their success would ultimately depend on molecular mixing, vital for combustion.

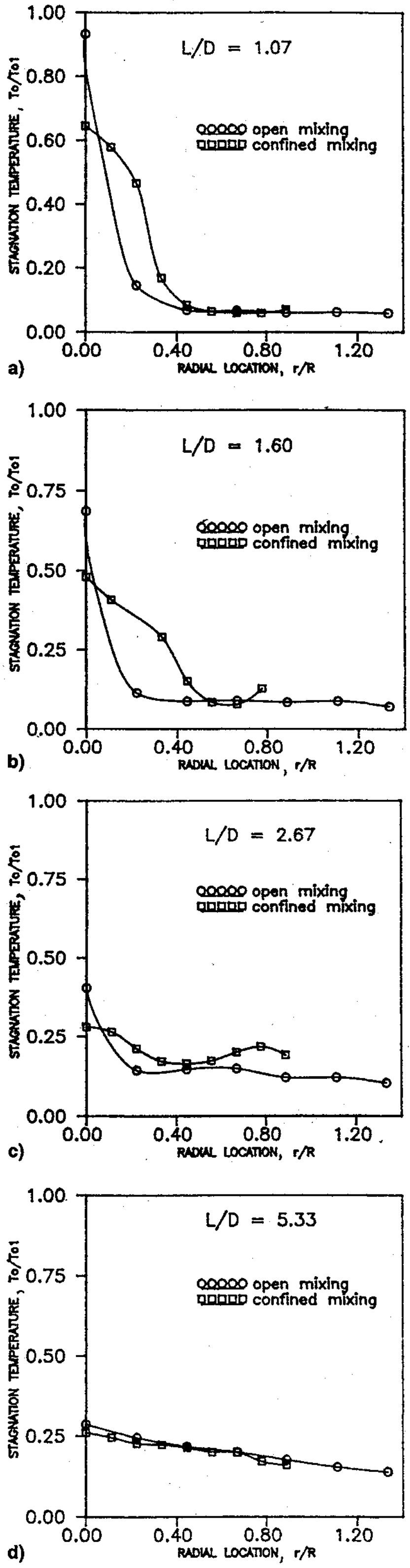

Fig. 3 Radial distribution of stagnation temperature at various axial locations for petal nozzle.

B. Comparison of Thermal Mixing with Petal and Conical Nozzles

The qualitative analysis of stagnation temperature distributions just discussed has shown that nearly complete thermal mixing can be achieved in the radial direction when the primary jet issues from a petal nozzle. It will be instructive and informative to compare the mixing performance of the petal nozzle with that of a conical nozzle under identical conditions.

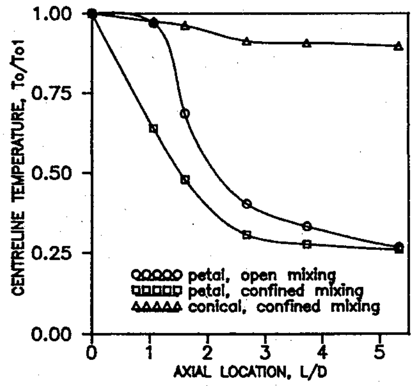

Fig. 4 Comparison of centerline temperature decay for petal and conical nozzles.

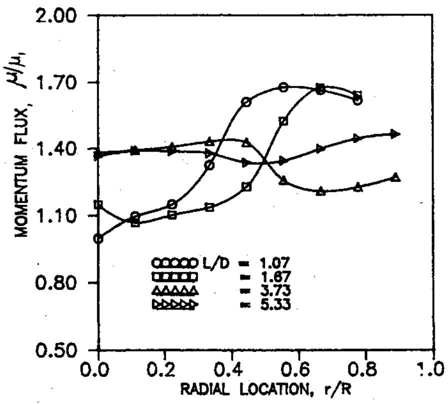

Fig. 5 Radial distribution of momentum flux at various axial locations for petal nozzle.

It is done by comparing the decay of the centerline temperature along the axis of the jet. Temperature measurements made at various axial locations with the conical nozzle issuing the primary jet rendered such a comparison possible.

Figure 4 shows the decay of centerline temperature for the following three cases: 1) open mixing with petal nozzle, 2) mixing, with confinement, with petal nozzle, and 3) mixing, with confinement, with conical nozzle. The distinctly slow rate of temperature decay for the conical nozzle is a clear indication of the inefficiency of the conventional nozzle in achieving thermal mixing, whereas the petal nozzle approaches the state of nearly complete mixing at an L/D of 3.73. It can also be seen that the decay of centerline temperature for open mixing with the petal nozzle is markedly better than that for the conical nozzle for all L/D. This lends credence to the conclusion that the large-scale streamwise vortices that have been shown to accentuate the mixing process with a lobed nozzle dominate even in the absence of confinement. In other words, the mixing tube does not play any role in the creation of the axial vortices. Results of a previous study in subsonic flow support this conclusion.

C. Studies on Momentum Mixing

For the petal nozzle, the radial distribution of momentum flux is shown in Fig. 5 for four axial locations along the mixing tube. The uneven distribution at $L/D = 1.07$, showing remarkably lower values of momentum flux near the center ($r/R = 0$), indicates that over this length practically no mixing has taken place between the primary stream initially possessing lower momentum and the secondary jet with higher momentum. However, at $L/D = 3.73$ the distribution is much better, and at $L/D = 5.33$ it is nearly uniform over the entire radial section. That is at $L/D = 5.33$ the momentum mixing is almost complete. This observation is similar to the one already made with reference to thermal mixing.

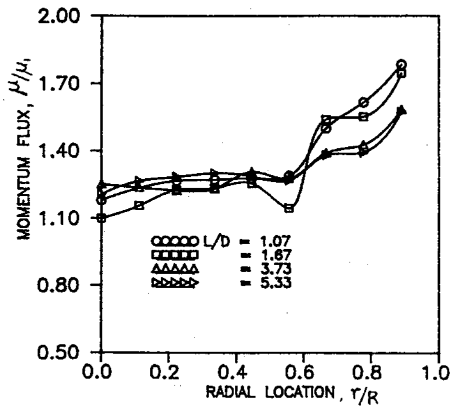

Fig. 6 Radial distribution of momentum flux at various axial locations for conical nozzle.

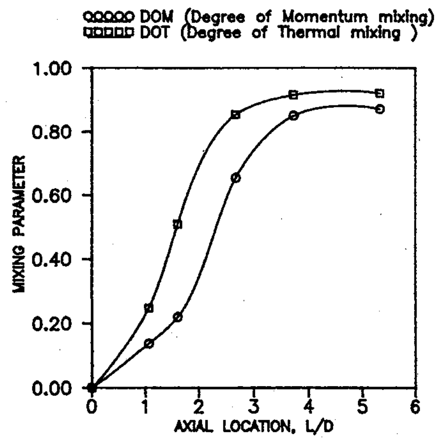

Fig. 7 Variation of the degrees of thermal and momentum mixing with axial distance (petal nozzle).

The radial distribution of momentum flux, with the primary jet issuing from a conical nozzle, is also presented for comparison (Fig. 6), for various L/D. It is seen that even at $L/D = 5.33$, the distribution is distinctly nonuniform, indicating that very little momentum mixing has taken place between the two streams. This observation is in consonance with the emerging viewpoint, namely, a lobed nozzle is far superior to a conical nozzle in effecting momentum mixing in supersonic flows. This aspect has been dealt with in greater detail in Ref. 9.

D. Comparison of the Degrees of Thermal and Momentum Mixing with the Petal Nozzle

Having established qualitatively the superiority of the petal nozzle in enhancing thermal and momentum mixing in supersonic jets, it is attempted to make a quantitative assessment of it. A mixing parameter is defined, which can be calculated appropriately both for thermal and momentum mixing. The mixing parameter is a measure of the uniformity of stagnation temperature or momentum flux, as the case may be. The method by which this parameter is deduced is explained later for momentum distribution. The procedure is identical for evaluating the parameter for thermal mixing as well. A dimensionless parameter called uniformity factor, denoted by ϕ, is first defined as

$$\phi = 1 - (\sigma_\mu / \mu_{av})$$

where σ_μ denotes the standard deviation of the radial distribution of momentum flux at a given axial location X along the mixing tube. The denominator is the average momentum flux along a radial line at the same location. For a perfectly mixed flow the distribution has to be uniform across the entire section

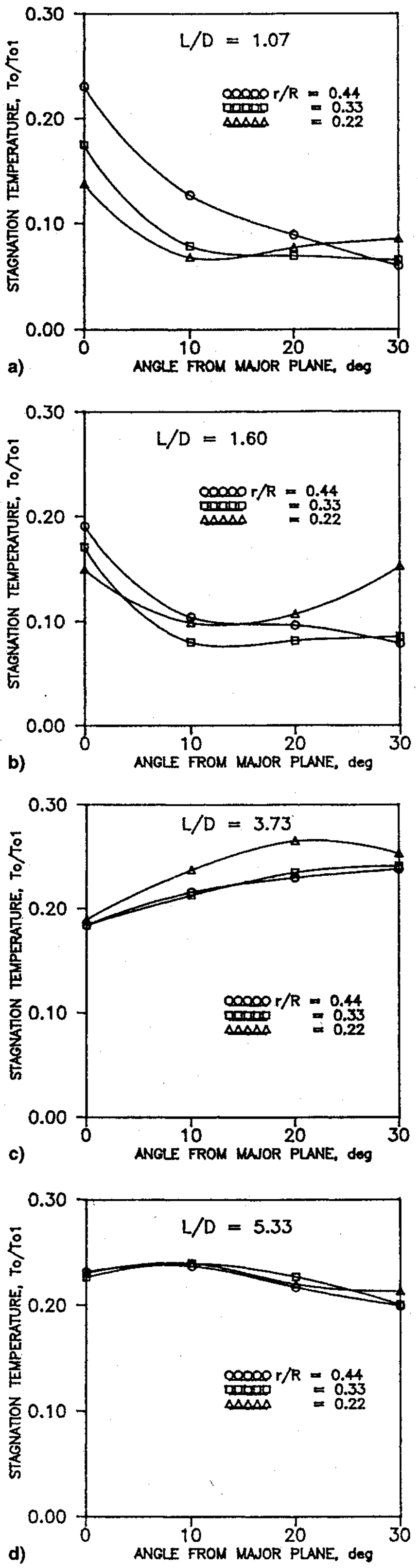

Fig. 8 Stagnation temperature distribution in azimuthal planes (petal nozzle).

(neglecting the thin viscous layer). For such a momentum profile ($\sigma_\mu = 0$), ϕ will be equal to unity, as it should be, stemming from the definition. The uniformity factor is used to define a mixing parameter, called the degree of momentum mixing (DOM), which is

$$\text{DOM} = \phi - \phi_{\text{um}}/1 - \phi_{\text{um}}$$

where ϕ_{um} represents the value of ϕ when the two streams are totally unmixed. This parameter (DOM) gives a direct measure of the momentum mixedness of the combined stream. When the two streams are completely mixed DOM will be unity (as $\phi = 1$), and when they are totally unmixed ($\phi = \phi_{\text{um}}$), DOM will be equal to zero. On similar lines a parameter called degree of thermal mixing (DOT) is defined based on the uniformity of radial distribution of stagnation temperature. This parameter characterizes the extent of thermal mixing that has occurred at any axial location.

The parameters are shown plotted as functions of axial distance for the petal nozzle attached to a mixing tube (Fig. 7). It can be discerned that at $L/D = 5.33$, both temperature and momentum fields achieve near uniformity. Another important aspect to be noted is that the general trend of the run of the curves is almost identical.

E. Stagnation Temperature Distribution in the Azimuthal Plane

To have further insight into the thermal field, it is also necessary to study the temperature distribution in the angular direction. Temperature measurements were made at four angular locations spread over the 30-deg angular segment shown in Fig. 2b. This angular segment is enclosed by major and minor planes, and from the geometry of the six-lobed nozzle it is clear that the flow pattern in the other segments should be similar.

Figure 8 shows the angular distribution of stagnation temperature. The nonuniformity in the angular distribution is clearly seen at $L/D = 1.07$ (Fig. 8a) and at $L/D = 1.60$ (Fig. 8b). The temperature is appreciably higher near the major plane (0), along which the hot primary jet issues and in the region of the secondary jet (i.e., near the minor plane) the temperature is quite low. However, the temperature distribution becomes much more uniform at $L/D = 3.73$ (Fig. 8c), and a nearly complete thermal mixing is achieved at $L/D = 5.33$ (Fig. 8d). Thus, the study of radial and angular distributions of stagnation temperature conclusively proves that the petal nozzle can achieve nearly complete thermal mixing in a three-dimensional supersonic flowfield.

F. Stagnation Pressure Loss with Petal and Conical Nozzles

The complex flowfield generated by a lobed nozzle results in a larger drop in stagnation pressure as compared with that for a conical nozzle. Hence, for a critical appraisal the performance of petal and conical nozzles has to be judged against the respective stagnation pressure loss they cause.

A pressure drop factor (PDF) for any axial location (L/D) is defined as the difference in the average stagnation pressure at the inlet and the given station, normalized by the weighted average of the inlet stagnation pressure of the two jets (inlet here denotes inlet to the nozzles). The PDF values are given in Table 1. The PDF for the petal nozzle is nearly 38% more than that for a conical nozzle, both nozzles having the same exit cross-sectional area and both tested under identical conditions. It demonstrates that the enhanced mixing achieved by the petal nozzle in supersonic flow is at the expense of an increased loss in stagnation pressure, a fact that must be reckoned with in the design of supersonic combustors.

The important question that would arise here is how far the loss (excessive drop in total pressure) is compensated by the gain (improved mixing). To answer this question studies on supersonic combustion should be conducted using the two

Table 1 Pressure drop factors

Primary nozzle	Isothermal mixing, $T_{01} = T_{02} = 30°C$	Nonisothermal mixing, $T_{01} = 750°C$; $T_{02} = 30°C$
Petal	0.350	0.361
Conical	0.256	0.260

types of nozzles and the combustion efficiency should be compared. Results of the study highlight the necessity of such a comparison before implementing this method of mixing enhancement in an actual system.

Another important observation is the increase in total pressure loss in the case of nonisothermal mixing as compared to the case of isothermal mixing for the petal nozzle. This increase, which is nearly 3%, is because of the heat transfer between the two jets. The loss because of heat addition alone is marginal as compared to the case of isothermal mixing. However, in an actual combustor a further increase in loss will occur because of combustion.

IV. Conclusions

Enhanced thermal and momentum mixing between two coaxial, supersonic jets is studied experimentally. The inner jet was admitted either through 1) a three-dimensional, radially lobed petal nozzle or 2) a conventional conical nozzle, and the outer jet issuing from a circular nozzle is maintained the same for both. The following are the conclusions drawn from the study:

1) A six-lobed petal nozzle provides complete thermal mixing in both radial and transverse planes, in a short length of mixing chamber. For the present case, when the inner and outer streams were of Mach numbers 1.2 and 1.7, respectively, the thermal mixing in both directions was nearly complete at an *L/D* of 5.33.

2) The momentum distribution also achieved near uniformity at an *L/D* of 5.33, indicating nearly complete momentum mixing between the two streams.

3) The confinement provided by the mixing tube has no appreciable effect on mixing. Nearly perfect thermal mixing could be achieved with the petal nozzle, even in the absence of the mixing tube. The confinement has no effect on the temperature field away from the nozzle.

4) In supersonic flow the petal nozzle also results in an appreciably higher stagnation pressure loss as compared with the conical nozzle.

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