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Research Paper

Comparative studies on supersonic free jets from nozzles of complex geometry

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HIGHLIGHTS

- ESTS lobed nozzle, chevron, beveled and conical nozzle of Mach 1.80 are compared.
- Acetone PLIF, centerline pitot measurements and CFD computations are conducted.
- Mixing enhancement is 430% in ESTS nozzle, chevron (222%) and beveled (138%).
- Streamwise vorticity production is widespread in ESTS lobed nozzle.
- Mechanism of vorticity production in ESTS nozzle is explained for the first time.

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ABSTRACT

Experimental and numerical studies are conducted to compare free jets from different supersonic nozzles for mixing enhancement. A conical nozzle of Mach 1.80 is the reference. Three complex nozzles are a beveled nozzle, a nozzle with six chevrons and a six lobed ESTS nozzle.All nozzles have the same throat diameter and designed average exit Mach number. The studies are conducted at NPR = 6, using acetone PLIF, centerline pitot pressure measurements, and 3D RANS simulations. A novel method of decomposing PLIF images based on intensity histogram and then recomposing after applying selective gains to emphasize the growth of shear layers is discussed. PLIF images are processed to extract the growth rate of jet width which indicates the rate of mixing. The ESTS lobed nozzle shows the highest enhancement of mixing (430%) followed by chevron (222%) and the beveled nozzle with a moderate (138%). The numerical simulations are validated and agree well with experimental results. ESTS lobed nozzle is found to produce widespread streamwise vortices compared to clustered vortices of the chevron nozzle. The mechanism of streamwise vorticity production from ESTS nozzle is clarified for the first time in this study.

1. Introduction

Novel supersonic nozzles with complex exit geometries are excellent passive techniques to enhance jet mixing rate [1–4]. Enhancement of mixing at supersonic speeds becomes particularly important after extensive research has conclusively shown that compressibility effects reduce growth rate of mixing layers [5,6]. Several engineering applications such as supersonic ejector, high speed air-breathing engines (SCRamjet engines), and aeroacoustic noise features of jet exhausts are solely dependent on the characteristics of mixing at supersonic speeds. A wide array of supersonic mixing enhancement techniques was reviewed by Gutmark et. al. [7], and the effectiveness of passive techniques that use geometrical modifications at the trailing edge of the nozzle was described. Lobes proceeding from the throat to exit of the nozzle that alternately deeply penetrate the core supersonic flow at the lobe trough, and expand at the lobe crest are the characteristic of lobed supersonic nozzles [3,4]. Large streamwise vorticity generated by such convoluted nozzle structure was shown to have increased the mixing and entrainment rate greatly. They were particularly useful for applications in supersonic ejectors [4,8] and for improvements in supersonic combustion [9]. However, large stagnation pressure loss due to complex shock structure associated with such nozzles was also reported [8]. Recently, efforts have been made to optimize the lobe geometry to maximize pressure recovery in supersonic ejector [10]. Tabs, on the other hand, were discrete simple triangular shaped protrusions placed at the nozzle exit with only moderate penetration into the jet core flow [11]. Number of studies using optical tools have shown that the vortex evolution from such tabs lead to enhanced mixing in jets [12–14]. Chevron nozzles evolved from tabbed nozzles with an aim to reduce parasitic stagnation pressure loss, as detailed in the review by Zaman et al. [15]. Chevrons are continuous sawtooth shaped modification to the exit of the nozzle with minimal penetration into the

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jet core flow in comparison to the tabs [15] that have now found practical use in mixing enhancement and noise reduction from jet exhausts [16–19]. Recently, Kong et al. [2] have shown an increase of 14.8% in the entrainment ratio of a supersonic ejector when chevron nozzles were used. A simple modification to the round supersonic nozzle is by beveling it at a certain angle thereby upsetting its symmetry, which has shown a deflection of the jet towards the shorter end of the bevel, an increase of mixing, and noise reduction in various studies [20,21]. There are many modifications to these template shapes that have been studied by different investigators such as the clover nozzle [22] and cross-shaped nozzle [23] (lobed nozzles), or crown nozzle [24] (chevron nozzle).

A novel lobed nozzle was devised by Rao and Jagadeesh [1], after giving due consideration to the fact that deep penetration and extreme convolution of the geometry caused severe stagnation pressure losses in the lobed nozzles. The new nozzle named as ESTS (Elliptic Sharp Tipped Shallow) lobed nozzle has the advantage that it is easy to produce (being formed by angular drilling from location offset from the center of the nozzle), and has shallow penetration thereby reducing stagnation pressure losses considerably. The free jet flow structure from a four lobed ESTS nozzle was explored using the Laser scattering method. The application within a supersonic ejector showed significant improvement of entrainment ratio by 30%.

Specification of complex nozzles involves combination of multiple geometrical parameters, such as number of lobes/chevrons, length/width/depth of lobes/chevrons, and penetration angles, to list a few. Further, it has been observed that small changes to certain parameters can bring about drastic changes to the flow phenomena in a non-linear manner [15,17], making optimization a very laborious task yet to be fully accomplished [10]. This complicates the understanding of such nozzles toward a cohesive design framework since the domain of parametric combinations is very large. Most of the studies try to differentiate the flow mechanism of one kind of nozzle with a reference round nozzle. Comparative studies among nozzles of different kinds are few, limited to comparisons in particular applications such as noise reduction or mixing enhancement in supersonic ejectors [13,18,23]. Although, eventually all the complex nozzles aim to produce large vorticity, there are fundamental differences in the manner of their production. The lobed nozzles involve an azimuthal variation of Mach number within the core supersonic flow right from the nozzle throat to the exit of the nozzle. In contrast, the chevrons are introduced only very close to the exit of the nozzle and the supersonic flow in a large part of the nozzle is essentially not very different from the round conical nozzle. This is bound to produce differences in vorticity production and rate of mixing. These observations motivate this study of comparing the supersonic free jet flow from four supersonic nozzles belonging to different classes of geometrical modifications.

The supersonic free jet is an ideal platform to fundamentally study such aspects since it offers much greater optical access compared to confined jets. Being easy to set up, much of the previous work also has been carried out on supersonic free jets. Laser based optical tools can easily slice through different sections of this complex three dimensional flow field giving a detailed comparison among different nozzles. In this study we utilize the planar laser induced fluorescence (PLIF) technique using acetone as the seeding agent within the supersonic jet. Though Mie scattering of laser from seeded particles produces strong signals that are readily visualized through digital cameras, it is difficult to distinguish between seeded and entrained particles when such interactions occur. PLIF is sensitive only to that particular seeding particle that can produce florescent emissions upon excitation from a definite wavelength of light. This is an advantage when conducting experiments to study mixing since the tagging of the flow and spread of the passive tracers is unambiguously captured. Acetone PLIF has been applied in the study of supersonic free jets [25,26] and supersonic flows in tunnels as well [27].

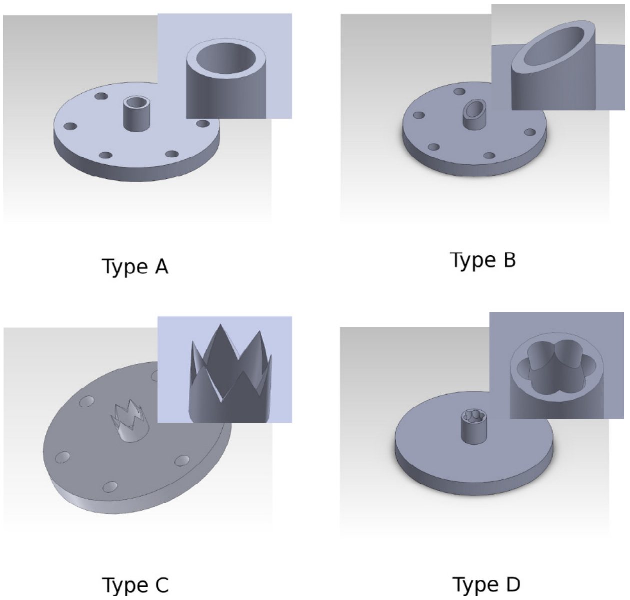

Fig. 1. The four different nozzles tested in this study. The insets show details of the nozzle contour. Type A is the reference conical nozzle. Type B is a bevel nozzle where a bevel of 26°C is introduced on the reference geometry. Type C has chevrons cut at the exit of the reference geometry. Type D is an ESTS lobed nozzle with the average exit Mach number same as the reference nozzle.

The objective of this current study is to compare the supersonic free jet structures from four different nozzles which are shown in Fig. 1. Type A is Mach 1.80 conical supersonic nozzle with round exit and is the reference. Type B is the simplest modification to the nozzle geometry wherein the geometry of Type A is beveled off at 26 °. Six chevrons are cut at the exit of the reference nozzle to form the chevron nozzle Type C. Type D is an ESTS lobed nozzle with six lobes designed such that the exit area is the same as that of Type A; hence, the average exit Mach number is 1.80 [1]. The nozzles shall henceforth be referred to as Type A, Type B, Type C and Type D respectively. The experimental study involves the use of acetone PLIF to capture the flow visualizations along the streamwise and spanwise planes. Pitot measurements are carried out along the centerline which indicate the rate of change of centerline Mach number. To fully understand the details of the complex three dimensional flow field numerical studies are conducted using FASTAR, an unstructured CFD code developed by JAXA, Japan. Full three dimensional RANS equations are solved using the Spalart–Allmaras turbulence model. The numerical results are in good agreement with the experimental visualizations as well as the centerline pitot measurements. Results that compare and contrast the flow features from the four different nozzles are described in this article. The rate of mixing is evaluated from acetone PLIF images by extracting the rate of growth of jet width. A new methodology to process the acetone PLIF images by decomposing the images according histogram of intensities is described that enables to emphasize the growth of mixing layers in the images. Numerical results are used to elaborate on mechanisms for increase in mixing through vorticity distributions. The mechanism of vorticity production from ESTS lobed nozzle is clarified for the first time.

The details of the experimental setup and diagnostics used are first described. This is followed by a description of the analysis of experimental data, particularly the processing of acetone PLIF images. Details of the numerical procedure are given next. A discussion where the results from experiments and numerical simulations are used to compare the four supersonic nozzles is detailed before concluding the article.