Applied Thermal Engineering 71 (2014) 62–71

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Novel supersonic nozzles for mixing enhancement in supersonic ejectors

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HIGHLIGHTS

- Two novel supersonic nozzles are developed for higher mixing with minimal losses.
- ESTS lobed nozzle has an easily producible, exotic elliptic lobed geometry.
- Tip ring nozzle uses a ring at the exit of the nozzle.
- Three dimensional flow structure is explained by flow visualizations of the free jet.
- Testing in a supersonic ejector, the nozzles enhance entertainment and mixing by 30%.

ARTICLE INFO

Article history:
Received 17 February 2014
Accepted 12 June 2014
Available online 25 June 2014

Keywords:
Supersonic ejector
Gaseous mixing
Mixing enhancement
Lobed nozzle

ABSTRACT

Two novel supersonic nozzles – Tip Ring Supersonic Nozzle and Elliptic Sharp Tipped Shallow (ESTS) Lobed Nozzle have been developed to enhance mixing at high speeds which is beneficial to supersonic ejectors. A circular ring protruding at the exit of a conical nozzle forms the tip ring nozzle. The innovative ESTS lobed nozzle comprising of four elliptic lobes with sharp tips that do not protrude deep into the core supersonic flow is produced by a novel yet simple methodology. A comparative experimental study is conducted between a conical nozzle, an ESTS lobed nozzle and a tip ring nozzle with exit Mach number of 2.3. For the first time, the three dimensional flow structure from ESTS lobed nozzle and tip ring nozzle is revealed from laser scattering flow visualization experiments on the free jet. A doubling of jet spreading rate is observed in the ESTS lobed nozzle. When applied to a supersonic ejector, both nozzles achieve a 30% increase in entrainment of secondary flow. The loss of compression ratio is 15% for the ESTS lobed nozzle while it is 50% for the tip ring nozzle. Further, the behavior of wall static pressure profile corroborates mixing enhancement.

1. Introduction

Supersonic ejectors are simple gasdynamics devices that utilize the augmentation of momentum and energy from a supersonic primary jet to entrain and pump a secondary flow [1]. Comprising of a supersonic nozzle within a variable area duct, the simplicity in construction and operation of the supersonic ejector makes it suitable for many applications. Conventionally ejectors have found use in thrust augmentation [2], refrigeration [3], fuel recirculation in fuel cells [4], to list a few. Recently they have been considered for applications in waste heat recovery [5], high altitude simulation facility [6], a device for safe dilution and purging of unspent fuel or gases [7]. The flow through the ejector is complex and not thoroughly understood. Currently extensive experimental, numerical and analytical studies are being carried out to study them [8–10]. Compressible turbulent mixing at high Mach numbers is crucial to the functioning of supersonic ejectors. However, a reduction in mixing due to the effects of compressibility was observed at high convective Mach numbers [11,12] which adversely affects the design of such devices. High rates of mixing between two gaseous streams at high Mach numbers is essential for designing short, high performance supersonic ejectors. Supersonic combustion is another flow scenario which is affected by this phenomenon and would be much benefited by enhancement of mixing. Since efforts to enhance mixing invariably leads to stagnation pressure losses, viable methods must strike a balance between rapid mixing and heavy stagnation pressure loss.

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http://dx.doi.org/10.1016/j.applthermaleng.2014.06.025
1359-4311/

A comprehensive review on various active and passive methods for enhancing supersonic mixing was carried out by Gutmark et al. [13]. Passive techniques such use of cavities, three dimensional or asymmetric nozzles [14], vortex generating tabs [15] and active techniques such as counter jet suction, acoustic perturbations were discussed. Importantly, generation of streamwise or axial vortices by modifications to the supersonic nozzle exit geometry were found to be most promising. Lobed supersonic nozzle was found to improve entrainment and mixing within a rectangular ejector [16]. Radially lobed nozzle called petal nozzle significantly enhanced mixing in a tubular ejector, but significant loss of stagnation pressure (about 100%) was also observed [17,18]. Recently efforts were carried out to optimize the number and geometry of the lobes [19]. Specifically, numerical simulations of rectangular, elliptical and cross shaped nozzle geometries within a steam ejector showed that the cross shaped nozzle produced sufficient streamwise vortices to cause enhancement of entrainment by about 9% [20]. Exotic tear drop shaped supersonic nozzle were tested in an ejector for pulse detonation engine application and the generation of an exotic vortex loop and its interactions were studied [21]. Recent numerical simulations of a chevron nozzle within the supersonic ejector showed that increase in entrainment by 14.8% could be achieved [22]. From a brief survey of available techniques utilized in enhancing mixing within the ejector it can be seen that while complex nozzle geometries like the petal or cross shaped nozzle produce significant enhancement of mixing and entrainment, however, they produce significant loss of stagnation pressure as well. These geometries protrude deep into the core of the supersonic jet and cause large alterations to the shock and flow structure which result in the loss of stagnation pressure. The complexity of the nozzle geometry is such that it is not easy to fabricate them. Further, the mechanisms and detailed flow structure from these supersonic nozzles have not been understood. Much of the recent work have anchored on numerical simulations of the flow. Detailed flow images that explain the behavior of mixing enhancement devices can be found in the subsonic domain [15,23]. The general understanding is that supersonic nozzle flows associated with complexities of shock and compressibility can hardly be inferred by extrapolations from studies in subsonic domain. There is a lack of understanding on the topology of the flow through complex nozzles at supersonic Mach numbers. Investigations to fundamentally understand flow structure from complex nozzles is essential. Schlieren images of free jets from petal nozzles [24] provide hints on the three dimensionality of the flow but are unable to give a clear picture on the flow especially along cross-sectional planes which is important to understand such flows. An exhaustive experimental investigation to understand the flow structure within the supersonic ejector was carried out by the authors [8]. The utility of a dilution cum purge ejector in the fuel cell circuit was investigated in the doctoral work [7], where it was seen that the requirements demanded low entrainment ratios at low operating primary stagnation pressures. In this context it can be emphasized that while enhancing mixing is crucial towards the design of a compact ejector geometry, the stagnation pressure losses have to be minimal. This need, motivated the authors to design two novel supersonic nozzles for mixing enhancement, especially for use in supersonic ejectors.

Sufficiently overexpanded supersonic nozzles were found to have higher mixing rates due to shock-boundary layer interactions happening within the supersonic nozzle that disturbed the mixing layer [25]. This effect was observed in a two dimensional supersonic ejector where the length of mixing was found to reduce by nearly 50% [8]. The Tip Ring Nozzle utilizes a ring attached at the very tip of the nozzle exit to provide disturbances to the mixing layer by means of vorticity generated by shock-boundary layer interactions within the nozzle and vortices shed in the wake of the ring, as depicted in Fig. 1a.

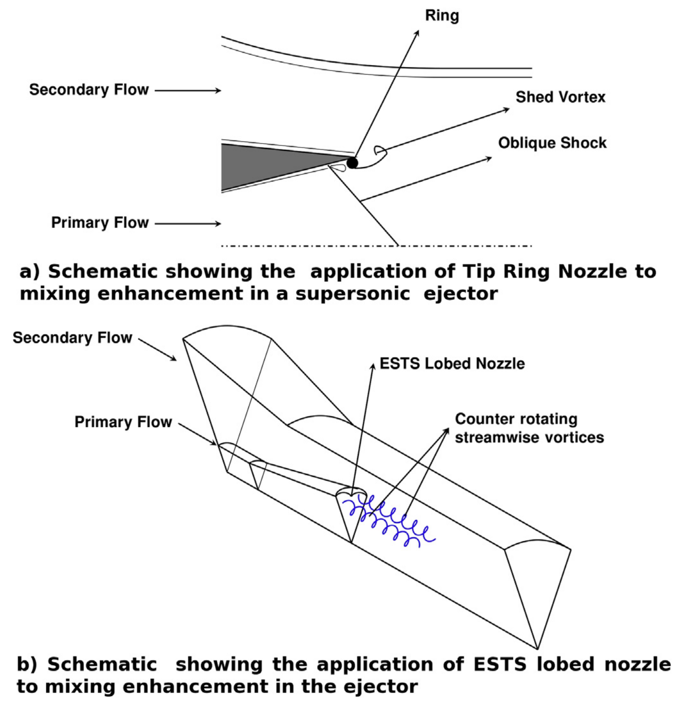

Fig. 1. An illustration depicting the application of two novel supersonic nozzles for mixing enhancement in the ejector.

The Elliptical Sharp Tipped Shallow (ESTS) lobed nozzle is a unique development where elliptical lobes are generated from the throat to the exit of the nozzle such that streamwise vortices and significant azimuthal velocity components are introduced into the mixing layer which must lead to enhanced mixing as shown in Fig. 1b. The authors have devised the innovative ESTS lobed nozzle that enhances mixing at minimal stagnation pressure loss. A new technique of generating the elliptical lobes by angular drilling at locations offset from the center of the nozzle using standard drill bits is developed, thereby simplifying their production. This method generates elliptic lobes with sharp tips that do not deeply protrude into the supersonic jet, as evident in Fig. 2, hence named – Elliptic Sharp Tipped Shallow (ESTS) lobed supersonic nozzle.

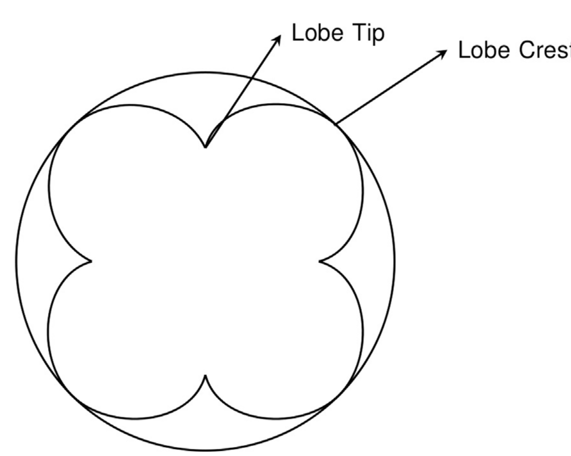

Fig. 2. A diagram showing the profile of the ESTS nozzle at the exit plane.