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Schnabel, Mark C.; Brophy, Christopher M.

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Pressure Distribution and Performance Impacts of Aerospike Nozzles on Rotating Detonation Engines

Mark C. Schnabel,[1] and Christopher M. Brophy[2]
Naval Postgraduate School, Monterey, CA, 93943

Rotating detonation engines (RDE) have the potential to further increase the performance of air-breathing propulsion devices and are currently being explored as an option for missions with wide altitude and flight Mach number ranges. Aerospike nozzles lend themselves well to this type of application because they possess altitude-compensating characteristics. However, the effects of the unsteady nozzle inlet dynamics associated with RDEs on aerospike nozzle performance have not been fully determined. Consequently, aerospike nozzle design has not yet been optimized for RDE applications. A contoured aerospike nozzle was designed for implementation on a RDE to examine the effect of ideal aerospike profiles on RDE performance. Currently, no simple nozzle design technique accounts for transient throat conditions inherent in RDE operation. Therefore, a nozzle contour was designed using a traditional, steady-state design methodology at both on- and off-design conditions anticipated throughout the combustion cycle. Steady-state, non-reacting computational fluid dynamics (CFD) simulations were performed on various nozzle geometries over multiple pressure ratios to investigate the flow field structure along the nozzle contour and justify design tradeoffs. Experimental thrust and nozzle contour pressure measurements will be used to determine the applicability of first-order design tools for performance estimation

I. Nomenclature

A	=	local flow area
A/A^*	=	isentropic area ratio
A_t	=	nozzle throat area
CF	=	thrust coefficient
F	=	force
p_{amb}	=	ambient pressure
p_o	=	chamber stagnation pressure
r	=	radial coordinate
r_e	=	radial coordinate of the expansion point
X	=	axial coordinate
μ	=	Mach angle
θ_t	=	throat inclination angle
θ	=	local flow direction

II. Introduction

DETONATION-based combustion is a type of pressure gain combustion (PGC) that offers improved thermodynamic efficiency over traditional constant-pressure, or deflagration-based, combustion systems. One PGC device that has shown potential to further increase the performance of air-breathing propulsion devices is the rotating detonation engine (RDE). A conventional RDE consists of an annular combustion chamber created by two concentric cylindrical bodies [2]. An unreacted, detonable mixture is injected at the forward-end of the chamber and a detonation wave propagates circumferentially around the combustion chamber as it consumes the reactants [2]. The chamber geometry forces the products to expand axially through the aft-end of the chamber, as shown in Figure 1.

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[1] Ensign, United States Navy.
[2] Associate Professor, Naval Postgraduate School, Department of Mechanical and Aerospace Engineering and Director, Rocket Propulsion Laboratory.

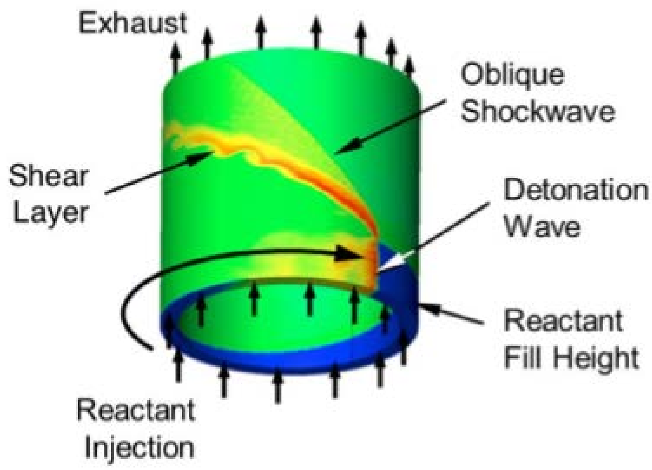

Fig. 1 Numerical Simulation of a Generic RDE. Source: [1]. *Model of a RDE combustion chamber showing relative temperature across the flow field.*

The products can be further expanded by a nozzle to produce thrust or directed through turbomachinery for power generation.

RDEs are currently being explored as an option for missions with wide flight Mach number and altitude ranges. Aerospike nozzles lend themselves well to this type of application because they possess altitude-compensating characteristics. However, the effects of the spatially and temporally varying flow fields associated with RDEs on aerospike nozzle performance have not been fully determined. Thus, no current nozzle design technique accounts for the unsteady nozzle inlet dynamics associated with RDE operation. This research sought to determine whether aerospike nozzle design could be optimized for RDE applications using a traditional steady-state design method for a first-order approach and then characterize the experimental performance of aerospike nozzles in unsteady RDE flow fields.

III. Steady State Flow Physics Background

The two flow regions of interest for plug nozzles are the expansion region along the contour and the recirculation region adjacent to the plug base. The flow characteristics in these two regions are heavily dependent on the operating pressure ratio. Steady state flow physics of these regions are well understood and a brief explanation is provided below.

A. Along the Contour

Figure 2 summarizes the principal flow features of annular plug nozzles with full length central bodies at on-design (2-2) and off-design conditions (2-1 and 2-3). (Note that the nozzles depicted do not have a base region. The geometry and behavior of the base flow region will be discussed later.)

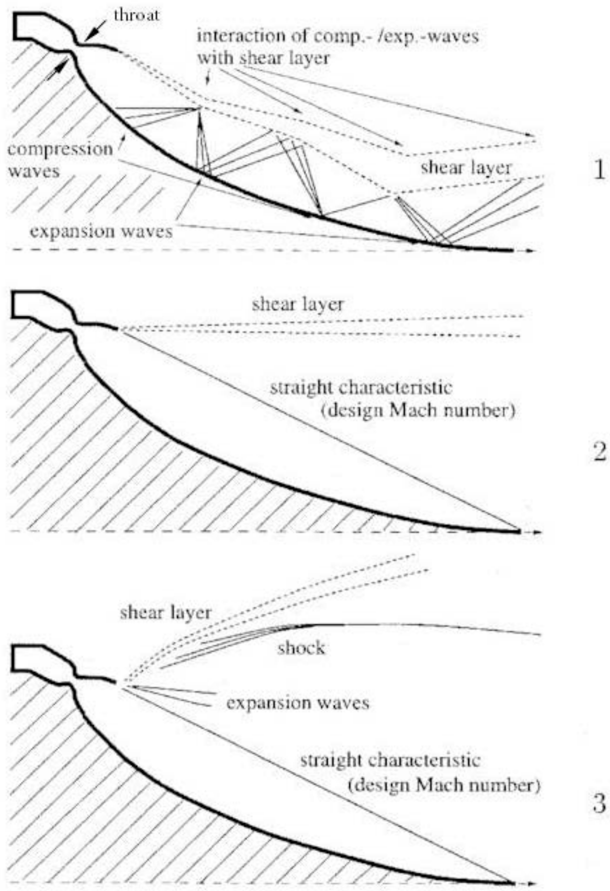

Fig. 2 Flow Features of a Plug Nozzle. Source: [3]. *Flow phenomena of a plug nozzle at different pressure ratios p_c/p_{amb}, overexpanded (top), on-design (center), and underexpanded (bottom).*

When the flow is choked at the throat, the exhaust gases undergo a centered expansion at the shroud lip and rotate up to the axial direction. The supersonic expansion flow features vary according to the operating conditions.
At the design condition, the last expansion wave emanating from the nozzle lip impinges on the tip of the plug contour (Figure 2-2). After passing this expansion wave, the jet exhaust pressure matches the ambient pressure at design altitude and the exhaust flows uniformly in the axial direction [4]. The corresponding computed wall pressure is a monotonic decreasing function [5]. The jet boundary (shear layer) profile assumes a straight line that is parallel to the nozzle centerline, originating from the shroud lip.

In overexpanded and underexpanded conditions, the pressure ratio dictates how the Prandtl Meyer expansion fan behaves along the plug contour. Specifically, in overexpanded conditions, the final expansion wave impinges somewhere along the nozzle contour, and the aerospike nozzle adapts the exhaust flow to ambient pressure via a system of recompression shocks and expansion waves that interact with the constant pressure jet boundary [5]. Conversely, in underexpanded conditions, the additional expansion waves required to match the exit pressure to ambient pressure do not impinge upon the plug contour, so the design Mach number and wall pressure distribution are maintained from the on-design case. Thus, an underexpanded aerospike nozzle behaves as an ideal nozzle at design conditions. The aforementioned complexities of aerospike nozzle flow yield a very unique thrust coefficient (CF) curve when compared to conventional nozzles, as shown in Figure 3.

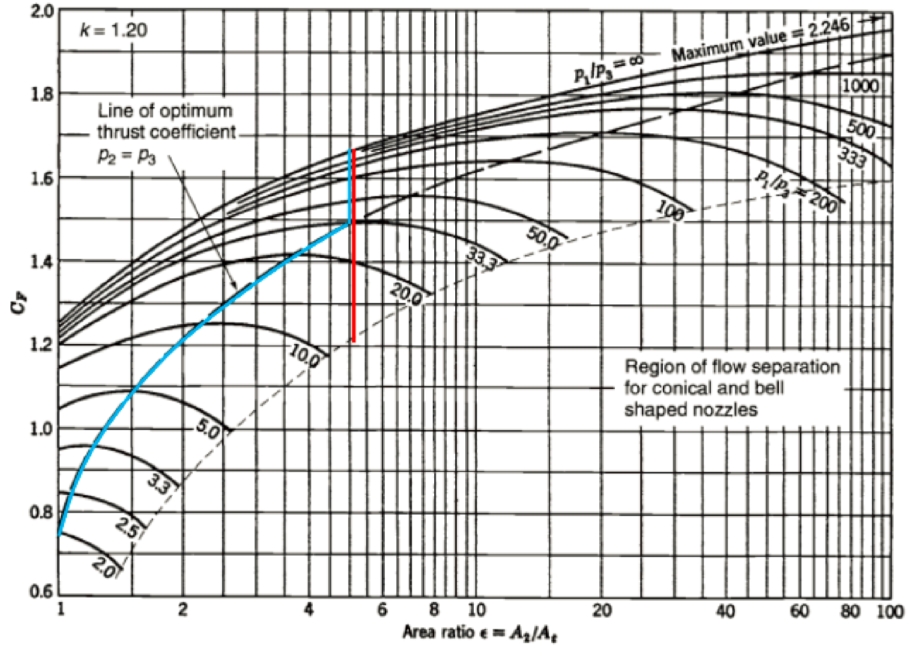

Fig. 3 Thrust Coefficient as a Function of Pressure Ratio.Derived from Source: [6]. *Conventional nozzle CF shown in red, Aerospike nozzle CF shown in blue.*

As pressure ratio decreases, a conventional nozzle (shown in red) will match the optimum CF value only at its design condition. The aerospike nozzle (shown in blue) performance is similar to conventional nozzles in underexpanded and on-design conditions. However, the aerospike nozzle tracks the line of optimum thrust coefficient in overexpanded conditions; a quality known as altitude compensation.

B. Along the Base

Due to lower pressure ratios for most RDE applications, the aerospike nozzle geometry will likely have a flat base when the plug contour stops short of the nozzle centerline. This situation occurs when a full-length nozzle is truncated or when the contour is designed using Angelino's approximate method for plug nozzle design [7]. For these cases, a recirculation region develops at the nozzle base. This is significant because recirculating flow at the nozzle base can affect the delivered thrust characteristics. Steady state experiments have shown that truncation does not significantly inhibit plug nozzle performance [5], but no experiments have observed wake flow for plug nozzles in time varying flow fields.

Many experimental and theoretical studies have confirmed the existence of two wake regimes that can be experienced by the base of a plug nozzle; the "open wake" and "closed wake" regimes. In the open wake regime, base pressure is dependent on ambient pressure and can reasonably be approximated as atmospheric pressure. Thus, the base flow does not affect overall thrust in the open wake regime. In the closed wake regime, base pressure is independent of ambient pressure, and may be contributing or detracting from overall thrust. Nasuti, Onofri, and Chutkey et al. [5], [8], [9], [10], [11] independently present detailed engineering models for prediction of transition between wake states in both still air and supersonic flow. Flow features at on- and off-design conditions in the open and closed wake regimes are shown in Figure 4.

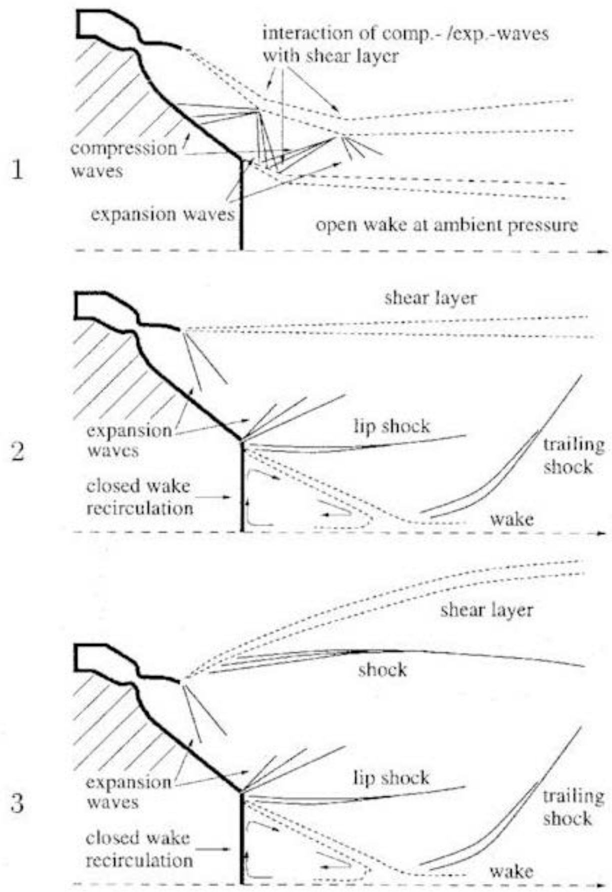

Fig. 4 Flow Features of a Plug Nozzle with Base Flow. Source: [3]. *Flow phenomena of a plug nozzle with a truncated central body at different pressure ratios p_c/p_{amb}, overexpanded (top), on-design (center), and underexpanded (bottom).*

IV. Nozzle Design

A. Current Nozzle Configuration

The Naval Postgraduate School (NPS) Rocket Propulsion and Combustion Laboratory (RPCL) has been developing an RDE over the course of several years. This RDE currently possesses a conical plug-nozzle design that serves as a back pressurization device to control combustion dynamics. This nozzle incorporates a straight conical profile and does not feature a contour to optimize thrust [2]. The current configuration is shown in Figure 5.

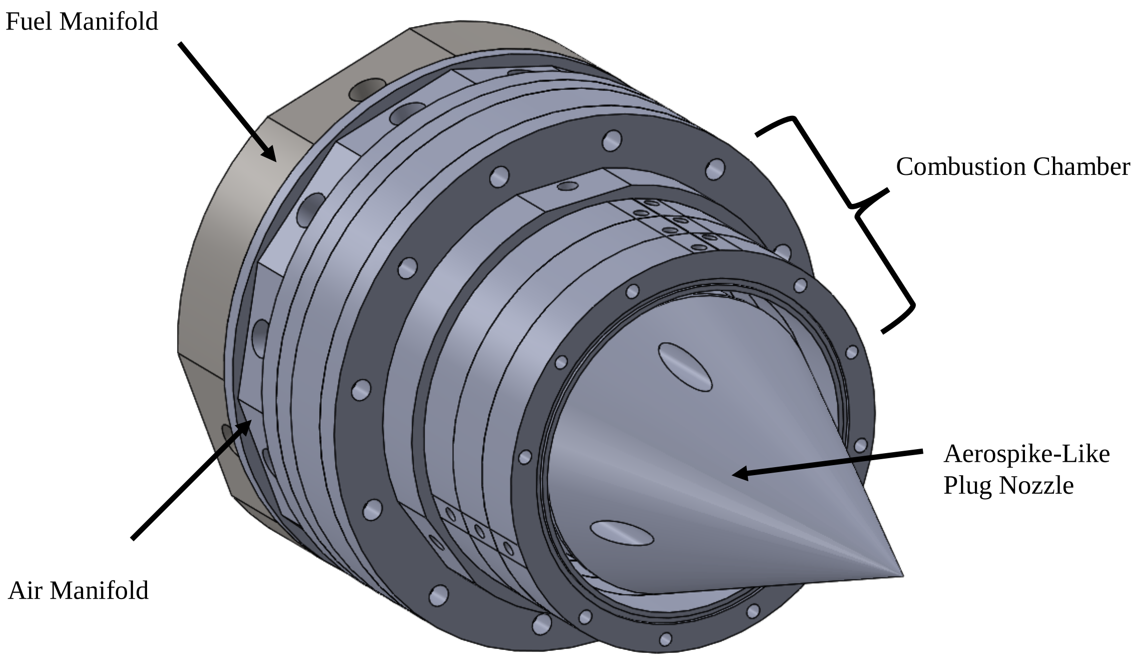

Fig. 5 RDE Diagram. *Current configuration of the RDE at the NPS RPCL. The conical aerospike nozzle is not optimized for thrust.*

A contoured aerospike nozzle was designed to replace the conical aerospike nozzle of Figure 5. This contour was designed using a traditional, steady-state design methodology although it is expected to experience both on and off-design conditions throughout the combustion cycle. To gain additional understanding of the flow field about the region of the contoured nozzle and to aid in the design process, a steady-state computational fluid dynamics (CFD) investigation was conducted on several geometries over a wide range of operating pressure ratios.

B. Steady-State Design Technique

In 1964, Angelino proposed an approximate design method for aerospike nozzle contours [7]. This method for plug nozzle design assumes steady flow and uses geometry and compressible flow relationships to transform the isentropic area ratio equation into the following set of equations that define the coordinates of the aerospike nozzle contour (see [3],[12] for derivation):

$$r = \sqrt{r_e^2 - \left(r_e^2 - r_t^2\right)\frac{A}{A^*}\left(\frac{\sin(\mu)\cos(\theta_t)}{\sin(\mu+\theta)}\right)} \tag{1}$$

$$x = \frac{r_e - r}{\tan(\mu+\theta)} \tag{2}$$

Where A = local flow area, A/A* = isentropic area ratio, r = radial coordinate, r_e = radial coordinate of the expansion point, x = axial coordinate, μ =Mach angle, θ_t = throat inclination angle, and θ = local flow direction.

Angelino’s approximate method has been widely adopted due to its simplicity and has proved successful in many experiments ([12]-[17]). However, no efforts to adapt nozzle design techniques to transient flow fields associated with RDEs have been found in the literature. Thus, Angelino’s approximate nozzle design method was applied to the RDE nozzle design recognizing that performance will differ from the ideal steady-state prediction. The expectation was that using on and off-design conditions with this technique could provide first-order design guidance until a full unsteady simulation can be obtained.

C. Application to the RDE

Selection of the proper design pressure ratio for a nozzle is critical to its performance. For aerospike nozzles, a property called altitude compensation allows for nearly ideal performance in the on-design and overexpanded flow regimes (that is, at all pressure ratios equal to or less than the design pressure ratio).

For RDEs, it has been shown that the maximum pressure at the exit of the combustion chamber is localized to a small region of the chamber cross section at any instant in time. Thus, by designing an aerospike nozzle for a chamber pressure equal to (or greater than) the maximum expected stagnation pressure ratio, most (or all) of the flow will be in the overexpanded regime, where altitude compensation can maximize thrust at all operating pressure ratios (see Figure 3). Thus, the ideal design pressure ratio (for a given atmospheric pressure) for the RDE aerospike nozzle was assumed to be equal to or greater than this maximum expected stagnation pressure ratio. This would yield the most favorable thrust characteristics by fully capturing the advantages of altitude compensation in the overexpanded regime.

Furthermore, because the flow in this case would always be optimally expanded or overexpanded, the nozzle base region can be reasonably expected to be operating in the open wake regime [8]. This is beneficial for constant altitude operation because the base pressure, on average, will be higher than for closed wake flow and close to ambient pressure [5]. Furthermore, research has shown the existence of a subsonic free-stream for the open wake case to cause the base to experience an average pressure higher than ambient [5]. This would be advantageous for subsonic missile applications because it means the nozzle base would contribute favorably to the overall thrust.

A nominal chamber pressure ratio of approximately 5:1 or 6:1 is characteristic for most test conditions and flow rates being run with the NPS RDE at the RPCL [2]. The highest expected nozzle entrance stagnation pressure ratio from the RDE at NPS is approximately 10:1. Thus, it is assumed that the chamber pressure ratio varies azimuthally from approximately 5:1 to 10:1, and that the effective pressure ratio "seen" by the aerospike is within those limits. For the experimental RDE, a design pressure ratio of 10:1 was selected in order to balance resolution of the pressure distributions over the nozzle contour and base. This nozzle was designed in SolidWorks to interface with the current RDE hardware. Both in the inner and outer sections are shown in Figure 6.

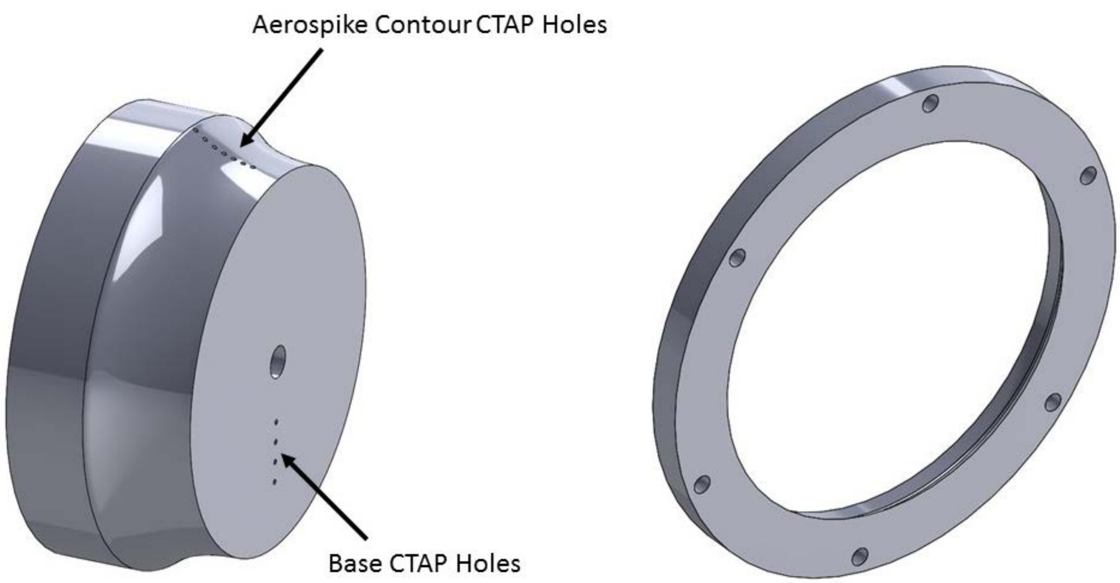

Fig. 6 Experimental Geometry for PR_{design} = 10:1. *Left: front isometric view of contoured aerospike center body piece; right: front isometric view of outer cowl piece.*

Once the nozzle has been machined, it will be instrumented with continuous tube average pressure (CTAP) taps and integrated into the RDE to investigate the effect of RDE-specific flow fields on nozzle performance. Experimental work will obtain the pressure distribution across the aerospike contour and base during RDE operation, and compare the time-averaged values with the steady-state computational results.

V. CFD Analysis and Results

Three design pressure ratios were selected as design inputs for CFD modeling, yielding three different aerospike nozzle geometries. Design pressure ratios of 10:1, 25:1, and 40:1 were selected to compare steady-state flow characteristics because all three meet or exceed the maximum expected stagnation pressure ratio at the combustor exit. These contours were designed using Angelino's approximate method and imported into ANSYS for simulation. The domain corresponding to the 10:1 design pressure ratio is shown in Figure 7. Each domain featured a 10° slice of the

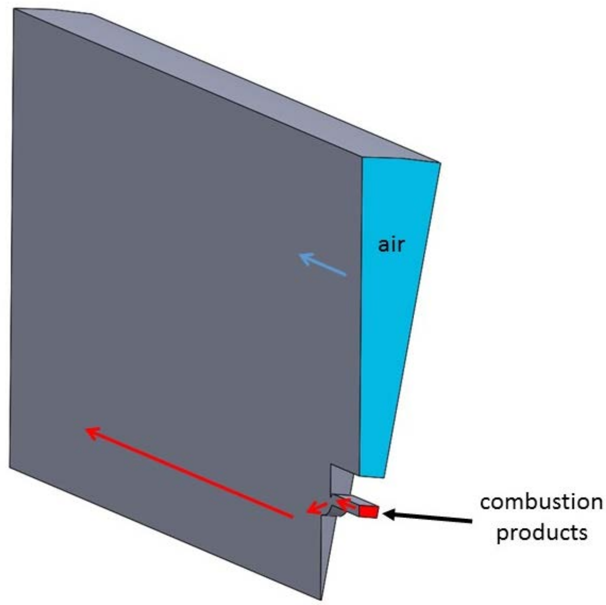

Fig. 7 CFD Domain for PR_{design} = 10:1. *All CFD domains consisted of a 10° slice about the nozzle centerline.*

engine and its surroundings about the centerline.

Numerical studies were conducted using ANSYS CFX modeling software to approximate nozzle performance. It was assumed that for some effective input pressure ratio, steady-state CFD simulations can be used to approximate the time-averaged flow characteristics of the contoured plug nozzle experiencing an RDE flow field.

Two important results from the simulations are the pressure distribution along the nozzle contour and the nozzle thrust coefficient. Figure 8 shows the nondimensional computed pressure distributions for the PR_{design} = 10:1 case under various pressure ratios at steady-state conditions. Figure 9 compares the steady-state thrust coefficient for all three nozzles at various pressure ratios to the thrust coefficient given by an ideal variable area ratio nozzle. A thrust coefficient was computed via a control volume analysis with the following equation:

$$C_f = \frac{F}{p_o A_t} \tag{3}$$

Where F is the net thrust across the combustor calculated by integrating pressures and mass flux values, p_o is the chamber average stagnation pressure ratio, and A_t is the nozzle throat area.

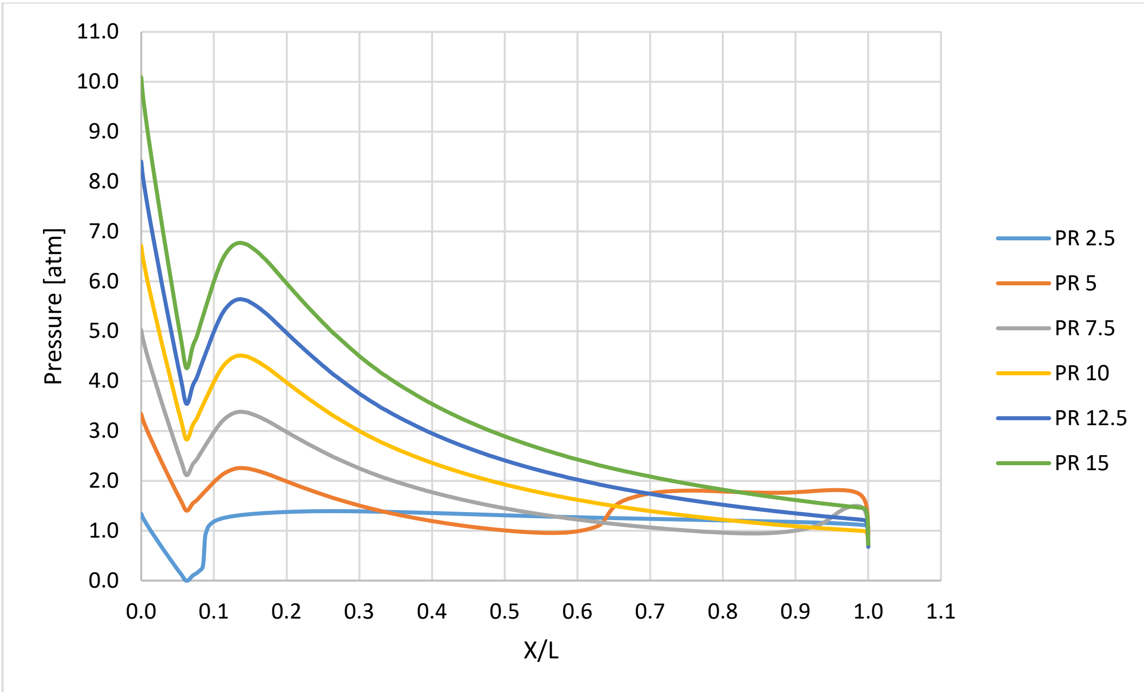

Fig. 8 Steady-State Nozzle Contour Pressure Distributions at Various Pressure Ratios for PR_{design} = 10:1.

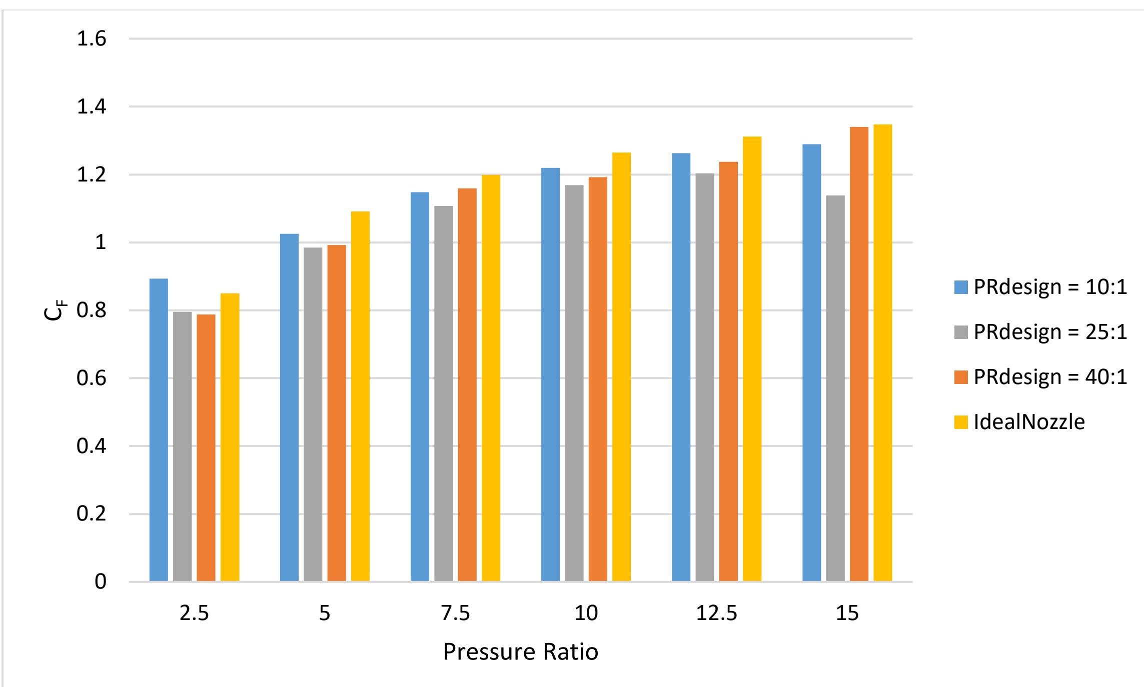

Fig. 9 Thrust Coefficient vs Pressure Ratio.

Thrust coefficient calculations neglected the contribution of base pressure to overall thrust. In order to justify this assumption, a numerical analysis was conducted on the geometry shown in Figure 6 to demonstrate that the nozzle will always be operating in the open wake regime. Using the method presented in [9], it was shown that for the nozzle designed in [18], the transition pressure ratio at which the wake changes from open to closed is 33:1. Because the RDE will never exceed a pressure ratio of 10:1 at any sector about the centerline, the nozzle base should always be operating in the open wake regime. Assuming the base is operating in the open wake regime for these pressure ratios, it is reasonable to expect atmospheric pressure to prevail over the base surface [5]. Thus, the base would not be contributing to or detracting from overall thrust, and can be neglected in force computations.

It should be pointed out that even though the thrust coefficient values appear inconsequential for low pressure ratio conditions, the expected operating conditions for most supersonic RDE systems will exceed PR values of 10:1and clearly have beneficial thrust coefficients with thrust improvements of 20-30% over simple sonic discharge plug nozzles.

VI. Summary and Future Work

The use of aerospike nozzles on RDE systems provides the capability for backpressurization and allows the expansion of high-pressure combustion products to high exit velocities while accommodating various pressure ratio conditions. Steady-state design methodology for truncated aerospike designs reveals the potential benefit of designing for the maximum local pressure ratio conditions generated by an RDE during operation. By doing so, overexpanded conditions would exist throughout most of the combustion cycle, but the external gas dynamics associated with the flow expansion would inherently adjust for this condition and preserve most of the ideal nozzle performance. At the expected operating pressure ratios, the base flow field region would be operating in an "open wake" conditions and therefore not experience reduced pressure conditions. The computational tools used have revealed performance advantages of up to 30% when an aerospike nozzle can be used with RDE system operating at nominal pressure ratios of 10:1 or greater. Experimental testing will confirm the predicted time-averaged pressure distributions through CTAPs and dynamic pressure probes.

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