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Numerical investigation of flow separation behavior in an over-expanded annular conical aerospike nozzle

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Abstract A three-part numerical investigation has been conducted in order to identify the flow separation behavior—the progression of the shock structure, the flow separation pattern with an increase in the nozzle pressure ratio (NPR), the prediction of the separation data on the nozzle wall, and the influence of the gas density effect on the flow separation behavior are included. The computational results reveal that the annular conical aerospike nozzle is dominated by shock/shock and shock/boundary layer interactions at all calculated NPRs, and the shock physics and associated flow separation behavior are quite complex. An abnormal flow separation behavior as well as a transition process from no flow separation at highly over-expanded conditions to a restricted shock separation and finally to a free shock separation even at the deign condition can be observed. The complex shock physics has further influence on the separation data on both the spike and cowl walls, and separation criteria suggested by literatures developed from separation data in conical or bell-type rocket nozzles fail at the prediction of flow separation behavior in the present asymmetric supersonic nozzle. Correlation of flow separation with the gas density is distinct for highly over-expanded conditions. Decreasing the gas density or reducing mass flow results in a smaller adverse pressure gradient across the separation shock or a weaker shock system, and this is strongly coupled with the flow separation behavior. The computational results agree well with the experimental data in both shock physics and static wall pressure distribution at the specific NPRs, indicating that the computational methodology here is advisable to accurately predict the flow physics.

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1. Introduction

The flow separation in supersonic convergent–divergent nozzles is a basic fluid-dynamics phenomenon that occurs at a certain nozzle pressure ratio (NPR), resulting in the presence of shock waves and shock/boundary layer interactions inside nozzles. It has been the subject of various experimental and

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numerical studies in the past. Today, with the renewed interest in supersonic flights and space vehicles, the subject has become increasingly important, especially for aerospace applications for rockets, missiles, supersonic aircraft, etc. There has been a widespread desire to investigate features with shock/boundary layer interactions in highly over-expanded rocket nozzles, since these interactions are responsible for acoustic, vibrate-acoustic, thermal, and mechanical-induced loads that act on the structure. Conventional bell-type nozzles suffer from the above interactions with reduced engine performance at low-altitude highly over-expanded conditions due to fixed geometries. Based on the above background, different types of nozzle concept with altitude-adapting capabilities have been developed and tested on the ground in the past, and the aerospike nozzle is included as a strong contender for the propulsion system of reusable spacecraft.[1,2] In the recent years, a renewed interest in the aerospike nozzle flowfield has been generated for both rocket and aeronautic applications.[2–6] However, while flow separation in over-expanded planar or bell ideal and optimized contour nozzles has been widely investigated to elucidate the phenomenon of boundary layer separation and shock interactions, aerospike nozzles have received little attention in the frame of this study. Verma[4] and Kapilavai et al.[7] presented pioneering work upon flow separation behavior in aerospike nozzles that operated at NPRs below 10, and both of the two studies indicated that the presence of flow phenomenon was associated with nozzle flow separation, and unsteady shock oscillation induced by the interaction of the shock/boundary layer seen in conventional supersonic nozzles with diverging sections could also be expected in aerospike nozzles at off-design operating NPRs. In spite of few rare studies on this subject, understanding of the flow separation behavior as well as fundamental knowledge of supersonic flow physics in the presence of shock wave propagation, shock reflection at walls, and shock/shock and shock/boundary layer interactions in such a convergent-divergent nozzle are still needed.

Studies of flow separation in supersonic nozzles dated back to the 1960s with the first work of Arens and Spiegler[8], who published the first approach to include the Mach number influence in the theoretical prediction of free shock separation. Schmucker[9] continued the research through the later years in the 1970s, and based on a simplified boundary layer integral approach, Schmucker proposed the famous purely empirical criterion for free shock separation (FSS) which is still widely used to date. From several experimental studies, performed on either full-scale[10] or subscale[11–13] optimized nozzles, and corroborated by different numerical simulations[14–18], the presence of two distinct flow separation patterns, namely FSS and restricted shock separation (RSS), is demonstrated. A transition in the separation pattern from FSS to RSS and vice-versa might occur, which was firstly observed in the early 1970s by Nave and Coffey.[10] At the initial state of start-up or when a supersonic nozzle operates at low NPRs, the flow mostly resides in an FSS state[19], as shown in Fig. 1.[20] A single incipient separation of the flow along the interior surface of the nozzle is triggered by an adverse pressure gradient between the regions of isentropic expansion and subsonic entrainment. The shock that originates from the incipient separation line interacts with a reflected shock; this shock emanates from the triple-point which is the location where the Mach disk, internal and reflected shocks coincide. In the FSS state, a separation region forms which encompasses a series of compression/expansion waves, and this separated flow fails to reattach back to the wall at low NPRs due to the lack of outward radial momentum as a free supersonic annular jet. A recirculating subsonic region forms between the separated free annular jet and the nozzle wall, which entrains ambient air along the nozzle wall and adapts the static wall pressure to the ambient condition.

The RSS state refers to the canonical shock/boundary layer interaction which is present in many high-speed devices. For example, RSS is known to occur in thrust optimized parabola nozzles of engines like Vulcain, space shuttle main engine (SSME), or J-2S during the start-up process. RSS is characterized by a small separation region or bubble which exists immediately downstream from the shock wave, in which the mean flow circulates and separates or tilts away from the wall before

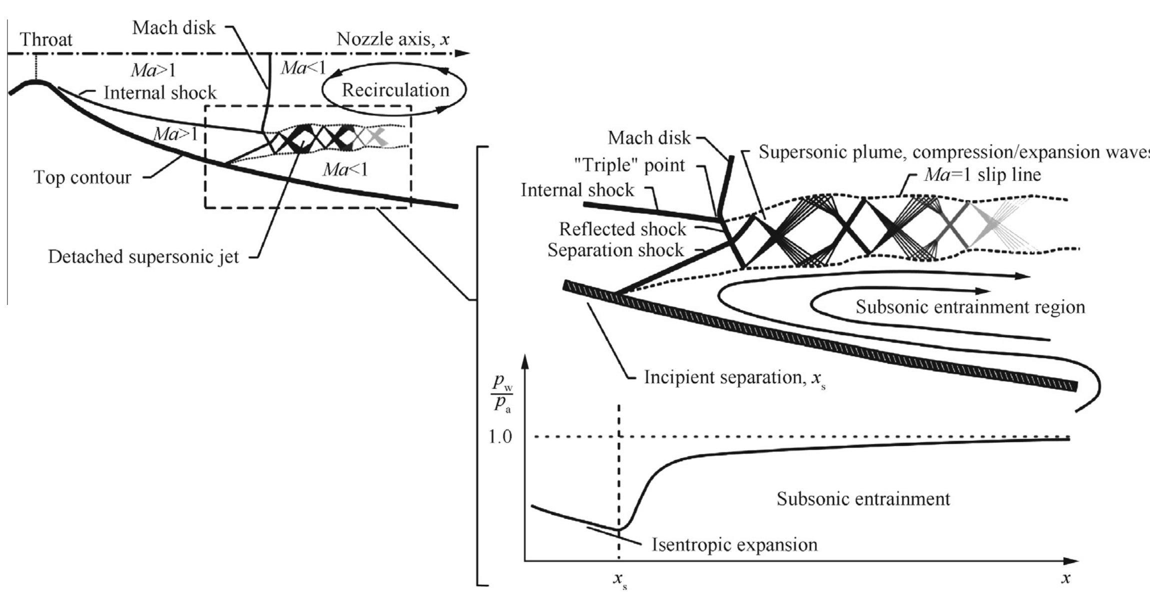

Fig. 1 Illustration of the internal shock structure in a thrust optimized parabolic nozzle during an FSS state.[20]