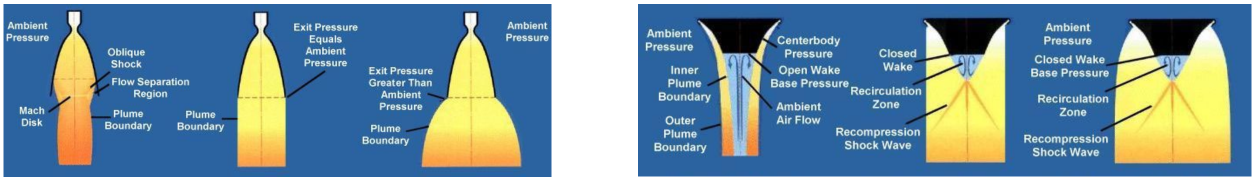
Supersonic Slipstream Effects on Rocket Nozzles

The goal of my research is to investigate an alternative to the bell rocket nozzle, the aerospike, I will do this by imaging cold flows through different nozzles in a supersonic wind tunnel using Schlieren optical techniques. I will use these images to study slipstream effects on plume formation. I will also be examining nozzle efficiency in terms of specific impulse which will be calculated from thrust measurements recorded by strain gages mounted on the nozzle stings.

The "bell" in bell nozzle refers to the diverging portion of a converging-diverging nozzle. These nozzles accelerate combusted fuel and oxidizer from subsonic velocities to supersonic velocities through expansion [1]. Because the nozzle walls are fixed, the exhaust pressure is only equal to atmospheric pressure at one design altitude; this is the point of maximum thrust efficiency. This results in a plume that is either under expanded or over expanded at all other altitudes [2]. These off-design pressure conditions can lead to losses of up to 15% in vehicle performance [3]. This substantial design inefficiency has prompted numerous nozzle design alternatives, none of which have delivered a payload to orbit. One of the most promising of these alternatives is a concept called the "aerospike". Rather than expand the combusted gas into a bell, the gas is expanded externally around what can be imagined as an inverted bell nozzle. Without a rigid wall to set the exit area of the flow, the exhaust is able to expand to ambient pressure, whatever it may be. This in effect eliminates the losses associated with under and over expansion [2].



Unlike that of a bell nozzle (left), an aerospike plume (right) expands to match exit ambient pressure [2].

Despite much analytical and numerical analysis supporting the gains provided by an aerospike design, the aerospike lacks in experimental testing [4]. This lack in experimental data, in combination with the incredibly high cost associated with the iterative design process of rocket engines, has prevented aerospikes from flying. With improved nozzle efficiency, flight costs will drop further and new technologies, and even humans, will have even greater access to space.

Existing aerospike research has focused on hot-fires, neglecting the influences of external flow on plume formation at the nozzle exit [5,6,7,8,9,10]. It is my goal to fill in this knowledge gap with my research. I will do this by imaging cold flows through different nozzles in a supersonic wind tunnel using Schlieren optical techniques and by examining nozzle efficiency [13].

I will begin by designing two cold flow test articles, one rocket with a bell nozzle and one with an aerospike nozzle, to be tested in a Mach 3 blowdown tunnel at Princeton's Gas Dynamics Laboratory. The wind tunnel has an 8" x 8" test section with room for extension. The two articles will be designed for the same design altitude. The bell nozzle will be designed using Rao's method of characteristics for a bell nozzle [11] and the aerospike nozzle using Angelino's approximation to the method of characteristics for an aerospike nozzle [12]. The test articles will be designed in proportionality to the NASA Dryden Test rocket, a solid-fueled aerospike test rocket flown in 2004. The scaling of the rocket will be difficult in terms of matching parameters. The Reynolds number will be of highest priority, as I will be focusing on the interaction of the external slipstream with the exhaust plume. Once designed, the machining of the test articles will be outsourced, as the required tolerances are outside of not only my, but also the university machine shop's capabilities.

The cold flow through the test articles will simulate the rockets' ascents. Rather than varying atmospheric pressure as is done naturally in launch, I will vary the stagnation pressure of the cold flow. The lab has ownership of an existing cold flow system for a smaller pilot tunnel, which I plan to move to the larger 8" x 8" Mach 3 wind tunnel. Together, the wind tunnel, test articles, and cold flow system form a majority of the experimental setup. The remainder of the setup are the diagnostics. I will be visualizing the flow using Schlieren imaging with a high-speed camera and measuring the exhaust force with strain gauges mounted to the nozzle stings. The imaging will provide insight into the plume formation in different ascent conditions. There is presently no other research focusing on these plume formations and slipstream effects to my knowledge. The forces measured by the strain gauges can be used to calculate thrust, from which specific impulse can later be calculated. This specific impulse is effectively the rocket efficiency. The results of this first experiment will guide further explorations into aerospike nozzle design. Pending successful results, I would like to transition to hypersonic testing in the lab's hypersonic Mach 8 wind tunnel and to study the interactions of different fuselage and fin geometries on plumes. I am also interested in exploring the effects of aerospike truncation lengths and base bleeds on both slipstream effects and thrust generation.

Imaging cold flows through different nozzles in a supersonic wind tunnel using Schlieren optical techniques and examining nozzle efficiency will bring the aerospace industry one step closer to the implementation of improved rocket nozzles. By understanding how alternative nozzles' plumes are affected during ascent, the geometry of the nozzles can be refined until an ideal alternative is designed.

The data generated in these experiments demonstrating the relative efficiency of the aerospike will benefit the aerospace industry regardless of whether or not the data supports the aerospike. In the scenario that the data does indicate an increased efficiency, there is a greater chance that rocket companies will take the financial risk in building and flying this technology, and that new space technologies will then see the gains as the fiscal barrier can be further reduced. By lowering the entry cost to space, people around the globe will be directly impacted. For some this may be through improved wireless communication and for others the dream of space tourism will become a reality. If the aerospike is not shown to be an efficient alternative to the bell, the research holds the potential of inspiring other alternatives including, but not limited to, expansion-deflection nozzles and dual-bell nozzles. Focusing research on this crucially overlooked engine component is one of, if not the, most effective ways to improve engine efficiency, cut flight costs, and increase access to space.

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