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A Survey of Challenges in Aerodynamic Exhaust Nozzle Technology for Aerospace Propulsion Applications

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Abstract
The current paper discusses aerodynamic exhaust nozzle technology challenges for aircraft and space propulsion systems. Technology advances in computational and experimental methods have led to more accurate design and analysis tools, but many major challenges continue to exist in nozzle performance, jet noise and weight reduction. New generations of aircraft and space vehicle concepts dictate that exhaust nozzles have optimum performance, low weight and acceptable noise signatures. Numerous innovative nozzle concepts have been proposed for advanced subsonic, supersonic and hypersonic vehicle configurations such as ejector, mixer-ejector, plug, single expansion ramp, altitude compensating, lobed and chevron nozzles. This paper will discuss the technology barriers that exist for exhaust nozzles as well as current research efforts in place to address the barriers.

Introduction

Today's aerospace vehicles are designed to meet two important constraints: economic viability and environmental impact. Due to the previously mentioned constraints, propulsion systems designed for these aerospace vehicles must have robust technology in order to meet mission requirements. Advances in computational and experimental methods have led to more robust design and analysis tools, but many major challenges continue to exist in propulsion systems especially with the exhaust nozzle. The exhaust nozzle is the 'business' end of the propulsion system and so its performance is key. New generations of aircraft and space vehicles will dictate that the propulsion system and airframe be highly integrated for high performance, low noise and sonic boom mitigation. This is of significant concern for supersonic and hypersonic flight. Exhaust nozzles incorporating advanced technology will play major roles in achieving high performance, low weight and environmentally friendly propulsion systems. This paper will attempt to characterize the technology challenges inherent in the aerodynamic design of exhaust nozzles for subsonic, supersonic and hypersonic propulsion systems. With the advent of faster and faster computing platforms, computational nozzle design and analysis techniques have improved tremendously over the last ten years. Advanced turbulence modeling techniques such as two-equation models, algebraic stress models, large eddy simulation and direct numerical simulation have allowed more accurate analysis of complex flow phenomena within the nozzle.

Exhaust Nozzles

The primary function of a propulsion system nozzle is to expand the gases exhausted from the engine at a condition of low speed with high temperature and pressure to a high velocity in order to obtain maximum thrust. Nozzles designed for subsonic, supersonic and hypersonic flight include numerous innovative advanced concepts such as ejector, mixer-ejector, plug, single expansion ramp, altitude compensating, chevron, lobed and tabbed nozzles, etc. Stitt discusses the benefits of these types of nozzles and their performance characteristics in reference 1. These types of nozzles have been developed in order to meet subsonic, supersonic and hypersonic vehicle mission requirements as well as meeting economic and environmental constraints.

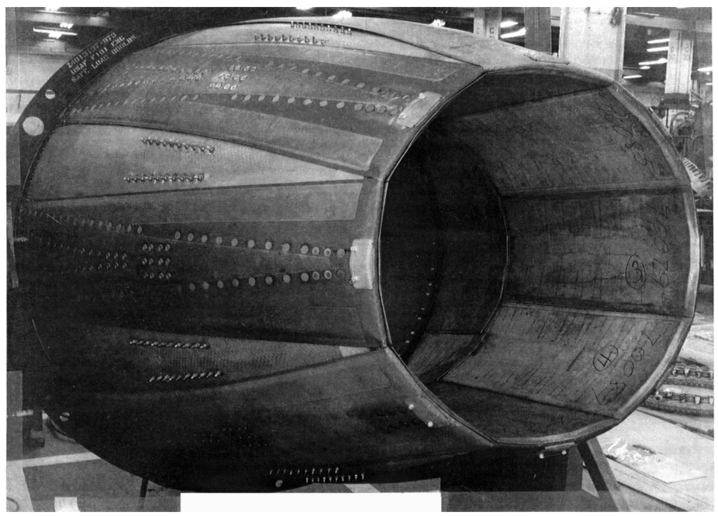

Figure 1 Photograph of a General Electric F101 subsonic exhaust nozzle

Subsonic Flight

In recent years, the majority of the research on exhaust nozzles for subsonic (exhaust velocities less than the speed of sound) vehicle applications has focused on economically and environmentally friendly technology. Aircraft noise has become a barrier to the growth of air traffic and this has significant global implications. Aircraft noise translates into an economics issue as airlines are constrained in new flight offerings as a result of increased number of daily flights. International airports are denying airlines landing privileges or charge them increased landing fees if their aircraft do not meet stringent noise regulations. Increased landing fee charges adversely impact airlines' operating costs and these increased costs are then passed along to the flying public via higher air fares. The net impact of increased landing fees and airline operating costs is a tendency to reduce passenger counts which may lead to constrained growth of the air travel system. NASA, aircraft engine and airframe manufacturers have looked at new propulsion and airframe system configurations including novel exhaust nozzle concepts to help address the noise issue. Ejector, mixer-ejector, chevron, lobed and tabbed nozzles have been investigated with varying degrees of success. These types of nozzles have been designed to enhance mixing within the jet emanating from a nozzle with minimal or zero attendant performance loss. Mixing enhancement is the primary method of jet noise reduction and these nozzles achieve noise reduction by the introduction of vorticity into the flow field. A lobed nozzle tested experimentally by Zaman (ref. 2) is shown in figure 2. These types of nozzles introduce vorticity by mechanical means, which may add weight, mechanical complexity and increased costs to the design and manufacturing processes. Many of the aforementioned technologies have been or are being currently incorporated into exhaust nozzles for noise reduction by many aircraft manufacturers.

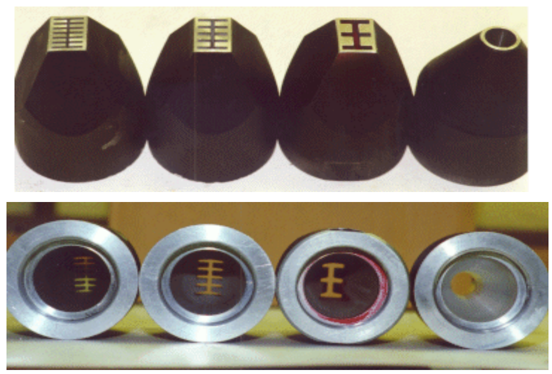

Figure 2 Photographs of subsonic 14, 10, 6 lobed and circular nozzles

Non-mechanical means of mixing enhancement are being investigated in order to reduce mechanical complexity and manufacturing costs. Fluidic injection utilizing air, water and plasma are currently being investigated by researchers to understand its potential for replacing mechanical concepts for mixing enhancement. Detailed computational and experimental evaluations are being performed to assess the viability of fluidic injection including system studies examining the trade-offs between nozzle performance, noise and weight. Additionally, fluidic injection is being studied as a replacement for mechanical thrust vectoring nozzles shown such as the nozzles pictured on a NASA F-15 flight research vehicle shown in figure 3. Fluidic injection for thrust vector control offers reduced weight, cost and mechanical complexity as advantages, but disadvantages such as complex control systems and plumbing schemes may over-shadow any attendant benefits.

Figure 3 Photograph of thrust vectoring nozzles on F-15 flight research vehicle at Dryden at NASA Dryden Flight Research Center

<u>Supersonic Flight</u>

Overland supersonic cruise flight requirements present significant barriers to the aircraft and especially the propulsion system. Continuous supersonic flight requires sonic boom mitigation, adaptive cycles for the propulsion system, advanced materials and structures for the propulsion system and airframe, as well as analysis of the impact of continuous afterburning in the exhaust nozzle. Additionally, computational analysis of the flow field exhausting from a supersonic nozzle presents significant difficulty for many computational methods. In order to capture the mixing effectiveness of the nozzle, computer codes must be able to accurately compute the mixing characteristics of the flow field including shock waves, shear layers, plume and freestream interaction. Due to the advent of faster and more efficient computing platforms, computational nozzle design and analysis techniques have improved tremendously over the last twenty years. Advanced turbulence modeling techniques such as two-equation models, algebraic stress models, large eddy simulation and direct numerical simulation has allowed more accurate analysis of complex flow phenomena including mixing within the nozzle. Technology gaps still exist in our current suite of turbulence model methods due to limited accuracy of the empirical models and enormous computing resources required for large eddy and direct numerical simulation. Additionally, unsteady phenomena in supersonic propulsion systems, pulse detonation engines, etc. require time accurate computational methods such large eddy simulation due to the highly unsteady nature of the flows. Figure 4 shows a plot of instantaneous and time-averaged axial velocity contours emanating from a supersonic circular jet and computed by a large eddy simulation computational method. DeBonis (ref. 3) provides a detailed discussion of his large eddy simulation computations for a supersonic circular jet in reference 3. Many of the computational modeling technology gaps should be closed as computing power continues to increase in the years to come. Likewise, recent advances in experimental methods especially with optically based non-intrusive measurement techniques will provide turbulence modelers with enhanced quantitative and qualitative data as well as detailed physics of nozzle flow fields.

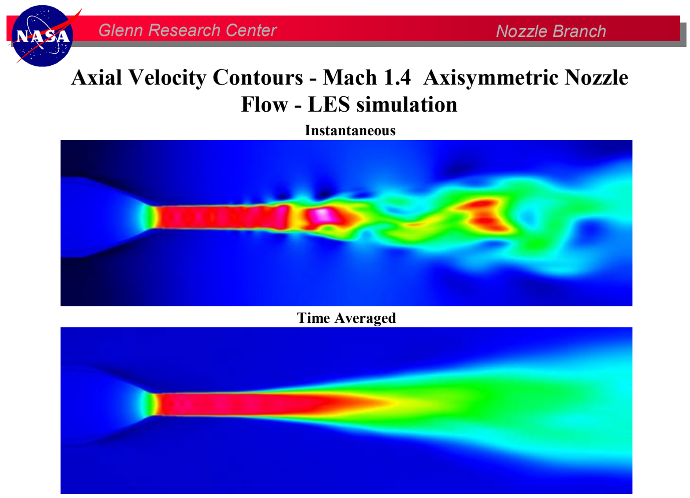

Figure 4 Axial velocity contours from large eddy simulation computational analysis, Mach 1.4, supersonic axisymmetric nozzle

Hypersonic Flight

Airbreathing propulsion systems for hypersonic aerospace applications including reusable launch, transatmospheric and missile vehicles will be highly integrated with the airframe of the vehicle. For this class of vehicles, it is likely that the entire undercarriage of the vehicle downstream of the internal portion of the propulsion system will function as the exhaust nozzle. The design of a hypersonic nozzle is based on high Mach number condition, but the nozzle must also function over the vehicle's operating range which includes take-off, subsonic, transonic, supersonic and hypersonic cruise operating conditions. Figure 5 provides an illustration of a hypersonic single expansion ramp nozzle (SERN) and highlights some of the numerous technical challenges a SERN presents. These challenges include base drag, flow separation, chemical kinetics, shock waves, shear layer stability, etc. Nozzle base drag and pitch moment control are particularly acute problems for a SERN, especially during transonic flight conditions as the propulsion system is operating at extreme off-design conditions. Carboni et al. (ref. 4) and Trefny et al. (ref. 5) present cold and hot jet experimental data detailing the performance characteristics of SERNs. Base drag reduction techniques such as external burning discussed in reference 5 may be used to minimize the performance degradation due to severe off-design operating conditions. Materials and structures also present significant problems for a hypersonic nozzle due to the high heating loads generated by the vehicle in flight. High strength, low weight materials and structures will be required and robust cooling schemes must be used to in order to maintain the structural integrity of the vehicle especially in the nozzle.

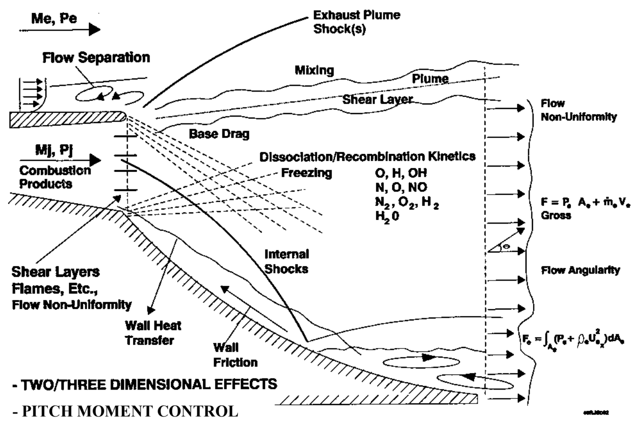

Figure 5 Schematic of Hypersonic Single Expansion Ramp Nozzle

Future Directions

Numerous advancements in "smart" technology including control systems, instrumentation and materials will allow propulsion systems to perform optimally throughout the entire operating envelope. "Smart" technology will enable nozzles to change shape in order to optimize its performance throughout the vehicle's entire flight trajectory. These types of propulsion system advances are discussed in reference 6, the NASA Aeronautics Blueprint. Nozzles will be able to change their shape through the use of shape memory alloys, high temperature instrumentation and robust, fast control systems controlled and monitored by high-speed on-board computer systems.

Summary

Many nozzle concepts have been proposed for applications to subsonic, supersonic and hypersonic propulsion systems. Numerous technical challenges in aerodynamic exhaust nozzle technologies exist for all of the aforementioned speed regimes and nozzle concepts. The advent of "smart" engine technology will allow nozzles to change shape to optimize its performance over the vehicle's entire flight trajectory. Major research activities are currently in place within academia, government research laboratories and industry to address these technology challenges as dictated by the global marketplace.

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