Proposed Flight Research of a Dual-Bell Rocket Nozzle Using the NASA F-15 Airplane

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Outline

• The Conventional-Bell (CB) Nozzle
• The Dual-Bell Nozzle
• Flight-Research Campaign, Objectives, and Captive-Carry Rationale
• The Flight-Testbed Capability
• Conclusion
The Convergent-Divergent nozzle was developed by Carl G. P. de Laval

- Utilized within his single-stage steam turbine, which was displayed at the 1893 World Columbian Exposition in Chicago, Illinois

Robert H. Goddard was the first to utilize the de Laval nozzle with early rocket experiments, in 1915

- Demonstrated a significant efficiency improvement in converting the fuel’s chemical energy into the kinetic energy of the rocket

The CB nozzle is still the gold standard of all rocket nozzles

- Used within the architecture of virtually all rockets

The CB nozzle is very efficient at converting the high pressure and temperature gases within a rocket’s combustion chamber into thrust

- Problem: The CB nozzle can only be optimized at one specific altitude within the rocket’s entire trajectory
During a rocket’s trajectory, a CB nozzle has three distinct phases of nozzle flow:

- At sea level / low altitude: Flow is over-expanded, and inefficient
- At its design altitude: Flow is near-optimal
- At high altitude: Flow is under-expanded, and inefficient

With a CB nozzle, significant performance inefficiencies exist throughout most of the rocket’s trajectory.
The thrust coefficient \((C_f)\) is used to evaluate nozzle performance

- The thrust coefficient is related to the thrust \((F)\), chamber pressure \((P_C)\), and area at the throat of the nozzle \((A^\ast)\):

\[
C_f = \frac{F}{P_C A^\ast}
\]

- The performance of the nozzle is crucial to the performance of any rocket

- The figures show the performance of three different CB nozzles (with a fixed area ratio) during a rocket trajectory

- A CB nozzle experiences performance losses through most of its trajectory
Several Altitude-Compensating Nozzle (ACN) concepts have been proposed over the years
- Goal: Reduce nozzle performance losses
- The dual-bell rocket nozzle is one type of ACN

Dual-bell nozzle development has been slow, despite the performance benefits that have been predicted
- 1949: The concept first appeared in literature (JPL)
- 1993: First publication on static testing (Rocketdyne)
- 2013: Still requires testing in a relevant flight environment

Performance predictions on the dual-bell nozzle continue to show advantages over the CB nozzle
- The dual-bell nozzle has been analytically studied worldwide
- Some organizations have complemented their analytical effort with static tests, to verify their performance predictions
The NASA Marshall Space Flight Center (MSFC) has conducted research on several types of ACN concepts, including the dual-bell nozzle.

- Analytical predictions were complemented by and verified against static test data.
- The dual-bell nozzle was proven to offer a performance benefit over the CB nozzle.

![Nozzle testing in the MSFC Nozzle Test Facility (NTF)](image)

Dual-bell nozzle testing  CB nozzle testing
Flight-research campaign, with NASA F-15:
- Phase I: Flights to quantify the local flow-field conditions near the nozzle exit plane
- Phase II: Flights while operating cold flow through various test articles
- Phase III: Flights while operating reacting flow through various test articles

Overarching Objective:
- To advance the technology readiness level (TRL) of the dual-bell rocket nozzle

Technical Objectives:
- Develop methods to reliably control dual-bell internal flow behavior, and demonstrate those methods in a relevant environment
- Develop and validate the design and analysis tools required for dual-bell nozzles
- Develop the F-15 captive-carry flight testbed and the flight-test techniques required for advanced rocket nozzles
- Develop dual-bell performance databases, and databases of flight research with advanced nozzles
• Dual-bell nozzle flight research with a free-flying rocket should be conducted in the future, after captive-carry flight research
  ▪ Flight research with a free-flying rocket is the most relevant flight environment
  ▪ Captive-carry flight research will more accurately answer the fundamental questions

• Captive-Carry Flight Rationale:
  ▪ Enables utilization of cold-flow propellant, allowing the existing MSFC NTF test data to be leveraged as much as possible
  ▪ Permits a closer examination into the plume behavior and flow physics, with more control of the flight-test conditions
  ▪ Enables an isolated performance assessment of the nozzle, as opposed to the combined performance assessment of the integrated rocket vehicle
  ▪ Permits the propulsion assets to be better protected for future testing
  ▪ Permits a rapid flight turn around, and assessment of nozzle performance with different nozzles at the same flight-test conditions
The Flight-Testbed Capability
The NASA DFRC F-15 Airplanes

- The NASA Dryden Flight Research Center (DFRC) has a long history of rocket propulsion flight research, and captive-carried flight research
- DFRC’s fleet of airplanes includes an F-15B and three F-15D airplanes
  - Proposal: To utilize one of the NASA DFRC F-15 airplanes as a testbed to conduct captive-carry flight research with a dual-bell rocket nozzle
• DFRC’s background and expertise led to the creation of the PFTF
• DFRC led the design and development of the PFTF, and then integrated the PFTF with the centerline pylon of the F-15B airplane
  - F-15B/PFTF initial expansion flights were completed in 2001 and 2002
  - Flights included the Cone Drag Experiment (CDE), mated underneath the PFTF, and was utilized to spatially and inertially simulate a large propulsion test experiment
  - The F-15B/PFTF has been utilized to develop advanced technologies since 2002
The Flight-Testbed Capability
The Propulsion Flight Test Fixture (PFTF)

- **PFTF design and limitations**
  - Fabricated from a solid billet of aluminum, 107 inches x 19 inches x 10 inches
  - Main structure is divided into three bays: forward-bay, mid-bay, and aft-bay
  - PFTF internal volume is intended to contain components such as propellant tanks, control valves, propellant feed system plumbing, and instrumentation
  - Includes a six-degree-of-freedom in-flight force measurement capability, with an axial force limitation of 2,000 lbf
- **The design was flight-proven during F-15B/PFTF envelope expansion flights**
The Flight-Testbed Capability
The Propulsion Flight Test Fixture (PFTF)

- **PFTF flight envelope**
  - Altitude limit: 60,000 ft
  - Mach limit: 2.0
  - Dynamic pressure limit: 1,100 psf

- **Preliminary plans for dual-bell nozzle operation within flight envelope:**
  - Phase I: All test points that encapsulate nozzle operation during Phase II & Phase III
  - Phase II: Low-altitude test points (perhaps ~25 kft) and high-altitude test points (perhaps ~50 kft) will be identified for nozzle operation that is optimized in each nozzle mode, as well as intermediate altitudes to research the mode transition
  - Phase III: In addition to the altitude test points (in Phase II), high dynamic pressure test points (perhaps ~1,000 psf) will be included to simulate a rocket trajectory
The dual-bell nozzle is predicted to have greater performance than a CB nozzle over a rocket’s integrated trajectory to low-Earth orbit
  - The performance benefit has been predicted analytically and through static test data

This predicted performance benefit warrants investigation of dual-bell nozzle performance in a relevant flight environment
  - If the predictions are accurate, this performance advantage could result in delivering higher mass payloads to low-Earth orbit (thus, lowering the cost)

The NASA DFRC F-15/PFTF has been proposed as the flight testbed
  - The F-15/PFTF was specifically developed and flight-proven for the purpose of advancing propulsion-focused technologies through captive-carry flight research
  - The F-15/PFTF has the potential to advance the TRL of the dual-bell rocket nozzle

NASA DFRC and NASA MSFC have formed a collaborative effort to advance the TRL of the dual-bell nozzle, through flight research