Variable Exhaust Gas Geometry (VEGGie)

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Introduction

The U.S. Air Force Research Laboratory's Aerospace Propulsion Outreach Program sponsors an intercollegiate competition that provides undergraduate students the opportunity to modify a JetCat P100Rx turbojet engine. The objective for the 2024-2025 competition is to develop a working, actuating variable nozzle system for the JetCat P100 that changes the exhaust exit area to achieve a maximal thrust range. There are 4 main criteria:

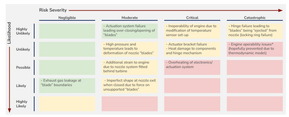
- Deliver >19 lbf of maximum thrust with the variable nozzle
- Maximize thrust range (over 8 lbf) at 80% corrected engine speed
- Minimize weight (under 4 lbf)
- Minimize radial and forward/ rear axial distance of additional hardware on engine

Solution Development

Alternative design solutions considered: rectangular nozzle, iris (thrust negator), tri-flap, ejector shroud

Criteria for our design selection:

1. Feasibility (can it meet the objectives?)
2. Manufacturability
3. Potential Risk
4. Simplicity
5. Creativity



System Risk Matrix

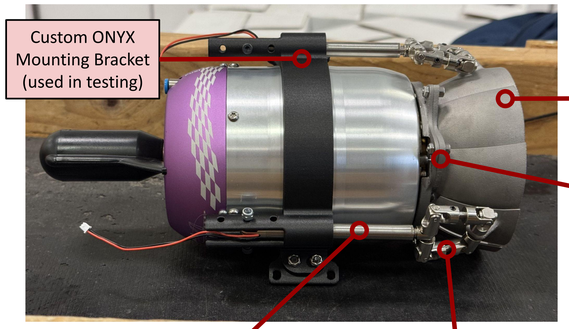
VEGGie Solution Design Evaluation:

+ : theoretically meets specified thrust targets
+ : simple, creative flap mechanism, built-in hinges
+ : 0.73” radial distance, 2” axial distance
+ : (relatively) circular aperture in closed config.
+/- : modern manufacturing techniques (DMLS), 100% additive, but expensive to produce
- : weight compromise of battery for actuators
- : potential gas leakage between flap seams

Our Solution

We designed a nozzle with 9 overlapping concave Inconel 718 flaps, 3 of which are pushed and pulled via linear electric actuators. The flaps’ overlap allow the 3 flaps with protrusions to push and pull the rest of the flaps, creating a simple and efficient design that eliminates unnecessary moving parts and saves both weight and space. The 9 flaps are connected to the base with a built-in pins and shoulders mechanism, as well as a locking ring that attaches around the flaps, allowing them to hinge smoothly without tight tolerances or extra pieces. The inner cone is held with guide vanes, which also provide slight counter-rotational guidance for the exhaust gasses. The concave flaps are angled 36 degrees at the base and 72 degrees at the tip of the flap so that they close to create the “ideal” nozzle shape (and achieve max thrust), and open to heavily decrease thrust, effectively maximizing the potential thrust range.

The actuation system is built upon 3 linear electric actuators. These actuators connect to the flaps via 2-sided linkages (for redundancy) and provide 9kg combined push/pull force of reliable output, with the added advantage of being both lightweight and precise. The actuators are held in place by a custom 3D-printed ULTEM 9085 mounting bracket.



Materials

Flaps, base and locking brackets: Inconel 718 (previously SS 316)

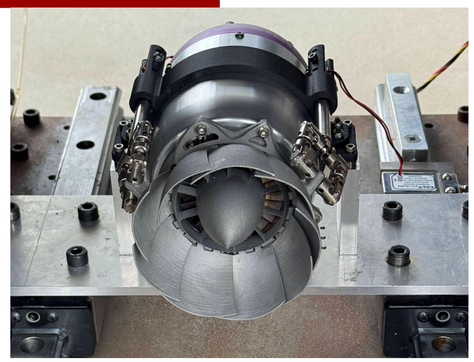
- Using DMLS to manufacture the complex geometries of our hardware, we produced 2 iterations of metal 3D printed pieces- the first prototype with Stainless Steel 316, followed by the final iteration with Inconel 718
- Conducted hand-calculations to ensure parts would not thermally expand past the built in 0.020” tolerance at a max temperature of 1000 C

Mounting bracket: ULTEM 9085 (previously ONYX)

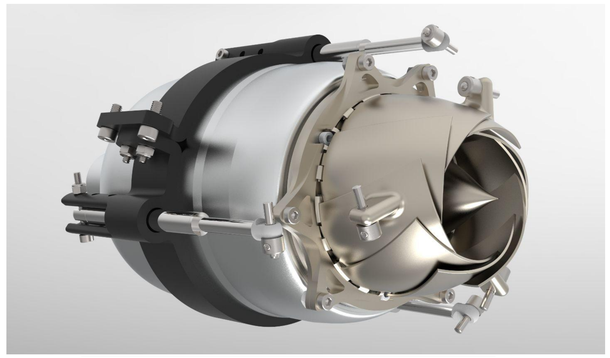
- To save cost and weight, we reconsidered the conventional metal mounting bracket for the engine. Our thermodynamic model predicted a T2 (where the bracket sits) of 174 C inside the engine, meaning the outside temperature would be verifiably less, which we verified by running the engine to max thrust (for a prolonged period with a stock configuration), which yielded a max temperature of 150 C. Then, we tested it with our configuration and an ONYX bracket (Tg @ 150 C), and are using an ULTEM 9085 (Tg @ 171 C) for our final iteration

All hardware: SS 316

- Every piece of hot-side hardware exposed to the extreme exhaust temperatures, either via convection or conduction, is made of SS 316 or an equivalent temperature-resistant metal. These pieces have been verified via their datasheets and direct testing of the apparatus



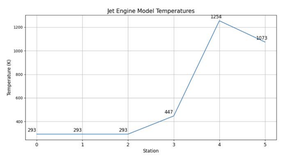
Variable Nozzle mounted on the engine for hot testing in our Containment Testing System (CTS)

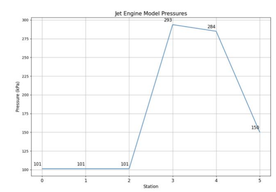


Render of full assembly (with different linkage style)

Simulations

Using Python, we created a thermodynamic model of the engine - predicting both temperature and pressure at each stage of the micro turbojet engine. Exhaust gas temperature (1073K) was predicted as being slightly higher than the 753-993K range given on JetCat specifications. This is likely due to uncertainty in efficiencies at each stage as well as using maximized fuel rate data. We know, from basic thermodynamics, that nozzle efficiency is given by the change in enthalpy divided by the isentropic change in enthalpy. After integrating a nozzle efficiency variable into the model, we were able to run the thermodynamic model based on our newly designed nozzle with data gathered from CFD simulations (to varying degrees of success - still in development). From this we were able to predict the thermodynamic impact of the nozzle on the engine in the absolute worst case - ensuring that our solution would not damage the engine even when running at full thrust.





Station
0 - atmospheric air
1 - inlet entry
2 - post inlet
3 - post compressor
4 - post combustor
5 - post turbine

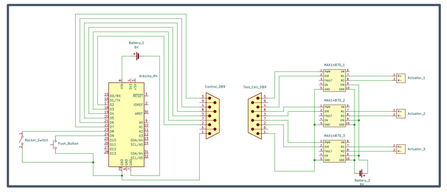
Numerical Analysis

We used hand calculations and order-of-magnitude estimates to verify the impacts of the thermal environment on both the materials and electronics throughout our system.

We determined the fins and base would not expand more than 0.020” in the most extreme case, which informed our tolerancing decisions in the joint design. Similarly, we calculated a negligible expansion of the locking bracket (because of a relatively small dT).

We also considered the loads and forces imparted on the flaps and actuators in the most strenuous scenario (max thrust + nozzle fully closed). Hand calculations using the known exit velocity and pressure of the nozzle revealed a force of 11.1N on the flaps, which did not come near to the holding power of our electrical actuators. We chose our electrical actuators to be so strong that they could push the entire engine at full thrust.

Electronics



The nozzle actuation mechanism is controlled by three linear actuators, each driven by a MAX14870 motor driver module, which receives PWM and direction signals from an Arduino R4. The Arduino is powered via 6V battery and receives user input through a push button and toggle switch, allowing finite directional control. A DB9 cable transmits six control signals (three PWM and three direction lines) and a shared ground from the control room to the test cell. On the test cell side, a second 6V battery powers the actuators through the MAX14870 drivers, with a shared ground to ensure consistent logic levels.

Testing & Validation

Within the development timeframe, the team was able to successfully demonstrate full operation of the variable nozzle over one hot test. The nozzle was able to successfully actuate to a fully open position and a fully closed position within the given test profile, however a malfunction in the calibration of our load cell prevented us from gathering the max thrust data. At 70% throttle (restricted by thermal concerns), we demonstrated a ~20% thrust range. The nozzle also successfully withstood the high temperatures and pressures without any detectable deformation. At our WPAFB test, the exhaust reached supersonic speeds, effectively becoming a diverging nozzle, making 18.4 lbf max thrust and a thrust range of ~5% (due to unexpected supersonic effects).

Conclusion & Future Work

VEGGie provides a novel way of maximizing thrust across a wide range of conditions by dynamically adjusting the nozzle geometry, enabling an engine to maintain efficient performance under a range of conditions. **Future iterations should address the following:**

- Optimization for supersonic exhaust (contours, diverging nozzle?)
- Reduced tolerance between flaps and further optimized flap contour to eliminate exhaust gas leaks and improve thrust figures
- Increased number of flaps to facilitate hinge movement and move towards a perfectly circular contour
- Varying the number of actuators to find an optimized balance between holding force and system weight