Peer-Review

Hu, Roland. 2025. "Altitude-Dependent Performance Analysis of Bell, Aerospike and Expansion-Deflection Nozzles for Rotating Detonation Engines." *Journal of High School Science* 9 (4): 394–412. https://doi.org/10.64336/001c.154674

This is generally good work. Congratulations. My concerns have to do with robustness, statistical analysis, assumptions and sensitivity. I list these below.

1.Robustness: You do not report mesh-independence, solver sensitivity, turbulence-model sensitivity, or boundary-condition sensitivity. Results' sensitivity to geometry variations and inflow uncertainties remains unquantified. Consider: (1) 3D transient RDE–nozzle coupled simulations (URANS/LES/DES) to capture unsteadiness; (2) mesh-convergence and solver-sensitivity studies (GCI, residual targets, y+); (3) parameter sweeps of spike/pintle geometry, design pressures, and throat radii; (4) inclusion of wall heat-transfer, cooling load, and system mass penalties; (5) report Cf and Isp with uncertainties; (6) compare against experimental plume/pressure data for validation; (7) explore base-bleed and pintle angle effects to mitigate premature wake closure. Please report and include in the manuscript.

2.Assumptions: Key assumptions (2D axisymmetric, time-averaged inflow, ideal gas, frozen chemistry, constant mass flow) are stated and partially justified with literature; limitations are acknowledged, but the impact on thrust predictions is not quantified. Please do so in the manuscript.

3.Were simulations replicable and replicated? Please report uncertainty quantification, confidence intervals, or repeated runs; validation of assumptions for any comparative statistical test; report variability and CIs (e.g., via replicate runs or UQ) and consider non-parametric summaries for small n.

4.Normalization: Percent-of-ideal thrust is a useful normalization; also report normalized Cf and Isp for broader comparability across studies (also see point 1).

5.Experimental design: Computational setup is described (mesh counts, boundary conditions, SST k–ω), but lacks verification/validation, grid convergence, hardware/software reproducibility details, and thermal boundary modeling; define sources of error and add validation against experimental or high-fidelity benchmarks.

Dear Reviewer,

Thank you for your detailed and constructive feedback. We have carefully revised the manuscript to address all concerns regarding robustness, assumptions, uncertainty quantification, normalization, and experimental design.

1. Robustness

Comment:

"Robustness: You do not report mesh-independence, solver sensitivity, turbulence-model sensitivity, or boundary-condition sensitivity. Results' sensitivity to geometry variations and inflow uncertainties remains unquantified. Consider: (1) 3D transient RDE–nozzle coupled simulations (URANS/LES/DES) to capture unsteadiness; (2) mesh-convergence and solver-sensitivity studies (GCI, residual targets, y+); (3) parameter sweeps of spike/pintle geometry, design pressures, and throat radii; (4) inclusion of wall heat-transfer, cooling load, and system mass penalties; (5) report Cf and Isp with uncertainties; (6) compare against experimental plume/pressure data for validation; (7) explore base-bleed and pintle angle effects to mitigate premature wake closure. Please report and include in the manuscript."

Revision:

We have added a new section named 2.6 Validation and Uncertainty Quantification in the Methodology that reports all robustness-related analyses performed:

- **Mesh independence:** Each nozzle mesh was refined by ~2.5× (to ~250k elements). The change in thrust was <0.3% for all geometries, indicating that further mesh refinement produced negligible changes in thrust. (section 2.6)
- **Solver sensitivity:** Discretization order and residual targets were varied (1st–2nd order, tighter convergence) for a representative bell nozzle case. The largest thrust difference was 0.2%. (section 2.6)
- **Turbulence model sensitivity:** The ED nozzle at 10 kPa was re-simulated using k-ε and Spalart–Allmaras. Changes in thrust were ~0.9%. (section 2.6)
- **Boundary-condition sensitivity:** Variation in mass flow rate (<1.5% in literature) is discussed but not simulated as its effect on thrust averages to around 0. Inlet static pressure perturbation of 5% resulted in a 1% difference in thrust for a representative bell nozzle case. (section 2.6)
- **Geometry sensitivity:** Unconstrained geometry features (nozzle curvature and length) were varied by ~10%; thrust changed by only 0.4% for a representative bell nozzle case. (section 2.6)
- **3D transient simulations:** These were beyond the computational scope of this study, and has been deemed as future work in the discussion. (Discussion)
- **Heat-transfer modeling:** A representative fixed-wall-temperature case was run, producing ~1% change in thrust. The adiabatic assumption is now discussed as a source of error in the discussion. (Discussion)
- **Cf and Isp uncertainties:** Added to the Results table with propagated uncertainties. (Results)
- **Experimental validation:** Bell nozzle thrust at sea level matched NASA Marshall RDE test results within 3%, and aerospike Cf aligned with Harroun. Qualitative plume feature of the bell matched NASA testing. (section 2.6)
- **Base bleed / pintle angle:** Pintle angle was simulated in a preliminary simulation, but created shock losses without significant wake closure changes. This has been clarified in the ED Nozzle section of the Methodology. Base bleed is further elaborated in discussion and framed as future work, but was not simulated due to complexity. (*Expansion-Deflection* under 2.3, Discussion)

2. Assumptions and Their Quantified Impact

Comment*:*

"Assumptions: Key assumptions (2D axisymmetric, time-averaged inflow, ideal gas, frozen chemistry, constant mass flow) are stated and partially justified with literature; limitations are acknowledged, but the impact on thrust predictions is not quantified. Please do so in the manuscript."

Revision:

- **2D axisymmetry and steady inflow:** Literature indicates thrust deviations of a few percent for attached flows; ED nozzle deviations may be up to 10%. (2nd to last paragraph of Discussion)
- **Frozen chemistry:** Literature suggests that additional combustion in the nozzle can increase thrust for methalox engines by up to 6%. (2nd to last paragraph of Discussion)
- **Ideal gas assumption:** A real-gas model test was run, showing ~1–2% thrust decrease for the bell nozzle. (2nd to last paragraph of Discussion)
- **Adiabatic walls:** Fixed-wall-temperature test produced ~1% decrease. (2nd to last paragraph of Discussion)
- **Impact quantification:** These errors were not combined into a single quantity due to them being systematic biases, but their affects act in opposite directions, which may explain the small 3% difference in thrust compared to NASA testing. (section 2.6)

3. Replicability, Statistical Analysis, and Confidence Intervals

Comment:
"Were simulations replicable and replicated? Please report uncertainty quantification, confidence intervals, or repeated runs; validation of assumptions for any comparative statistical test; report variability and CIs (e.g., via replicate runs or UQ) and consider non-parametric summaries for small n."
Revision:
The Validation and Uncertainty Quantification in Methodology also addresses this.
- The bell nozzle at 50 kPa was repeated two more times, but variability between runs was <0.1%, so additional replicates were unlikely to alter performance. (section 2.6)
- Numerical uncertainties from mesh, solver, turbulence, and geometry factors were added in quadrature, yielding 1.5% numerical uncertainty, corresponding to ±3.0% at about 95% confidence. (section 2.6)
- All thrust, Cf, and Isp values in the Results table now include ±95% CI. (results)

4. Normalization of Cf and Isp
Comment:
"Normalization: Percent-of-ideal thrust is a useful normalization; also report normalized Cf and Isp for broader comparability across studies (also see point 1).
Revision:
The Results section now includes:
- Cf with 95% CI uncertainties discussed above
- Isp with 95% CI uncertainties discussed above

This addition appears in the performance tables in Results.

5. Experimental Design and Reproducibility
Comment:
"Experimental design: Computational setup is described (mesh counts, boundary conditions, SST k–ω), but lacks verification/validation, grid convergence, hardware/software reproducibility details, and thermal boundary modeling; define sources of error and add validation against experimental or high-fidelity benchmarks."
Revision:
2.4 Computational Setup section in Methodology has been expanded:
- Added solver settings (2nd-order schemes, residual target 1×10^{-4}, double-precision) and added workflow description (section 2.4)
- Verification and grid convergence has been addressed in comment 1 (section 2.6)
- Added hardware and detailed software description (2025 ANSYS Fluent Student R1) (section 2.4)
- The nozzle thermal boundaries were assumed adiabatic, which was shown to produce an overestimate of about 1% from comment 3. (2nd to last paragraph of discussion)
- Added validation against NASA Marshall RDE test data from comment 1 (section 2.6), and error sources have been addressed in comments 2 and 3 (2nd to last paragraph of discussion, section 2.6)

All reviewer concerns have now been addressed and incorporated into the revised manuscript. The robustness tests, uncertainty quantification, normalization improvements, validation additions, and expanded discussion significantly strengthen the manuscript.
We grateful to the reviewer and editor for the insightful comments, which have greatly improved the quality and clarity of the work.

Thank you for addressing my comments. Would you please address the remaining minor inconsistencies/deficiencies below.

1.Remove the word ‘ambient’ before the word ‘pressure’ in X-axis titles from figures.
2.Provide the propellent mass flow rate in the legend of Table 6 (and in other tables where specific impulse is mentioned). even though you have provided it at the start in Table 1.
3.If there are two performance downgrades at 50 and 101 kPa for ED, should there not be two slope transitions for 100 to 50 and then for 50 to 10 kPa? Instead, figure 4 shows no such duality in slopes. Why?
4.Suggest you change the sentence “….Furthermore, the lack of altitude compensation produced by the aerospike as well as the greater than expected losses of the ED nozzle demonstrate the challenges of nozzle integration with a pre-existing RDE combustion chamber.” to " Furthermore, the lack of altitude compensation produced by the aerospike as well as the greater than expected losses of the ED nozzle at > 50 kPa demonstrate the challenges of nozzle integration with a pre-existing RDE combustion chamber"
5.you state “…While there is an increase in total thrust due to increased pressure thrust, the nozzle performance is comparatively worse; the percent of ideal decreases relative to the performance at 50 kPa.” can you present ratio for [increased total thrust/percent of ideal (for nozzle)] for all three nozzle designs at lower pressures (say < 50 KPa)? Can you also present calculated total thrust at 100% ideal? Discuss the implications of forgoeing ideal nozzle-combustion chamber integrated design due to increased ratios for any particular nozzle. In other words, if the total thrust increases beyond that which would be achievable with a combustion-nozzle integrated design (even though nozzle utilization is < 100%), then why go/opt for an integrated design?
6.Provide a word document of your manuscript, 12 Times Roman font, single column with the Tables formatted as Tables (not figures or images).
7.Table 1, correct the mislabeled oxidizer and fuel rows.
8.Rewrite everything (as far as possible) in past perfect tense. For example, “…Multiple nozzle geometries with varying parameters will be tested using 2D computational fluid dynamics (CFD) simulations.” changes to “Multiple nozzle geometries with varying parameters were tested using 2D computational fluid dynamics (CFD) simulations.” Check the entire manuscript.
9.Instead of saying the metrics are “solely dependent on the total thrust”, say: “…the relative variation of these metrics depends solely on the total thrust.”

Dear Reviewer,
Thank you again for your careful review of the revised manuscript and for your additional comments. We have addressed each point below and believe these changes have improved the clarity and completeness of the paper.

1. **Remove the word ‘ambient’ before the word ‘pressure’ in X-axis titles from figures.**
   The term “ambient” has been removed from all X-axis titles, now using “Pressure [Pa]” in Figure 4(a) and 4(b).

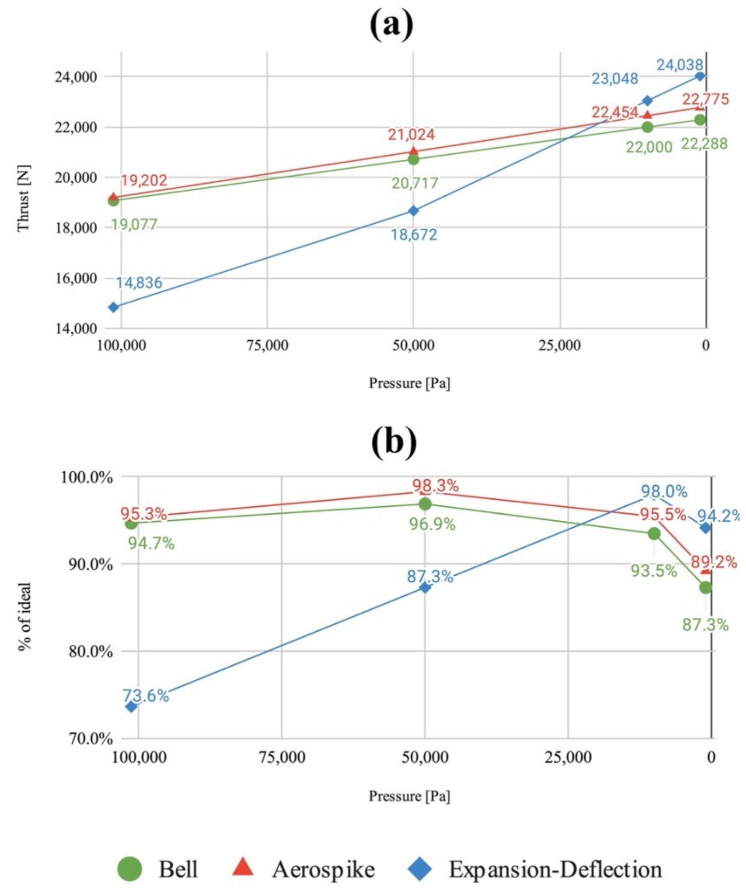

Figure 1: Performance of three different RDE nozzle types across a range of ambient pressures. The effects of ambient pressure on (a) the thrust and (b) the percentage of ideal thrust. Thrust was obtained from CFD simulations, while ideal thrust was calculated with isentropic flow equations.

2. **Provide the propellent mass flow rate in the legend of Table 6 (and in other tables where specific impulse is mentioned). even though you have provided it at the start in Table 1.**
   Propellant mass flow rate has now been provided in the results tables (tables 4, 5, 6).
   "$\dot{m}$ = 7.39 kg/s for all cases (see Table 1)."
3. **If there are two performance downgrades at 50 and 101 kPa for ED, should there not be two slope transitions for 100 to 50 and then for 50 to 10 kPa? Instead, figure 4 shows no such duality in slopes. Why?**
   The performance downgrades for the ED at 101 and 50 kPa are due to the low pressure recirculation zone at 101 kPa and lower-than-ambient exhaust due to premature wake closure at 50 kPa, causing a large negative contribution from pressure. However, total thrust and percent of ideal thrust still increase as pressure decreases because the exit pressure remained similar. As a result, decreasing ambient pressure contributes nearly linearly to both metrics, producing similar slopes between pressure points. A finer pressure sweep may resolve additional differences in slope, particularly near the wake transition. This clarification has been added to the Figure 4 caption.

   "The smooth trends reflect interpolation between points; however, a finer pressure sweep may reveal differences in the trends, particularly for the ED nozzle near wake transition."
4. **Suggest you change the sentence "….Furthermore, the lack of altitude compensation produced by the aerospike as well as the greater than expected losses of the ED nozzle demonstrate the challenges of nozzle integration with a pre-existing RDE combustion**

chamber." to " Furthermore, the lack of altitude compensation produced by the aerospike as well as the greater than expected losses of the ED nozzle at > 50 kPa demonstrate the challenges of nozzle integration with a pre-existing RDE combustion chamber"
The suggested change has been incorporated.

5. **you state "…While there is an increase in total thrust due to increased pressure thrust, the nozzle performance is comparatively worse; the percent of ideal decreases relative to the performance at 50 kPa." can you present ratio for [increased total thrust/percent of ideal (for nozzle)] for all three nozzle designs at lower pressures (say < 50 KPa)? Can you also present calculated total thrust at 100% ideal? Discuss the implications of forgoeing ideal nozzle-combustion chamber integrated design due to increased ratios for any particular nozzle. In other words, if the total thrust increases beyond that which would be achievable with a combustion-nozzle integrated design (even though nozzle utilization is < 100%), then why go/opt for an integrated design?**
The manuscript compares total thrust directly to the calculated ideal thrust at each ambient pressure. The calculated 100% ideal thrust is presented in Table 3 in section 2.5, which is where the % of ideal metric was calculated from: [measured thrust/ideal thrust]. This comparison represents the unrealized expansion that could have been gained with a more suitable nozzle. The revised manuscript clarifies that increases in total thrust at lower ambient pressure are caused by reduced back-pressure, and decreases in % of ideal thrust indicate incomplete use of the available exhaust expansion.
"This occurs because the reduction in ambient pressure increases pressure thrust even when the nozzle is not optimally expanded, and the decrease in percent of ideal thrust indicates that a larger fraction of the exhaust expansion occurs outside the nozzle" (Section 3.1).
The Discussion section has been revised to clarify the implications for integrated combustor–nozzle design. The manuscript now emphasizes that integrated designs would recover unused expansion, allowing both higher total thrust and a higher percentage of ideal thrust compared to the non-integrated configurations studied here.

"Development should focus on integrated combustor–nozzle systems rather than relying on theoretical altitude-compensating designs alone. An integrated design would allow a greater portion of the available exhaust at high altitudes to be converted into thrust rather than wasted expanding outside the nozzle. Even though thrust already increases with altitude in this study, integrated designs would allow for further increases and a higher percentage of ideal, enabling better-performing and more efficient RDE-powered launch vehicles in the future" (Discussion, last paragraph).

6. **Provide a word document of your manuscript, 12 Times Roman font, single column with the Tables formatted as Tables (not figures or images).**
The manuscript is in the format requested (12 pt Times New Roman, single column, tables formatted as tables), but an additional copy of the manuscript word document has now also been separately attached in the additional files.

7. **Table 1, correct the mislabeled oxidizer and fuel rows.**
The oxidizer and fuel labels in Table 1 have been corrected.

Fuel	gaseous methane (CH_4)
Oxidizer	gaseous oxygen (O_2)

8. **Rewrite everything (as far as possible) in past perfect tense. For example, "…Multiple nozzle geometries with varying parameters will be tested using 2D computational fluid dynamics (CFD) simulations." changes to "Multiple nozzle geometries with varying parameters were tested using 2D computational fluid dynamics (CFD) simulations." Check the entire manuscript.**

The manuscript has been re-read thoroughly to ensure past tense is used consistently throughout. Changes to past tense primarily occurred in the abstract, methodology, and results sections.

9. **Instead of saying the metrics are "solely dependent on the total thrust", say: "…the relative variation of these metrics depends solely on the total thrust."**
The phrasing has been revised based on your suggestion.

We appreciate the reviewer's time and constructive feedback, which helped improve the clarity and completeness of the manuscript.

Thank you for addressing my comments. Accept. Please check the highlighted text for accuracy in the galley proof.

Dear Dr. Apte,

Thank you for carefully proofing my paper. I have made several minor changes to grammar, phrasing, and errors, which I have highlighted in red in the attached PDF. Please note that the PDF formatting may differ slightly from the original proof.

I also noticed that the in-text equation referencing in section 2.3 and section 2.5 differ, as 2.3 uses parentheses (Eq #) while 2.5 does not: Eq. #.

I would also like to make the following changes:

Title change: I would like to update the title to "Altitude-dependent performance analysis of bell, aerospike, and expansion–deflection nozzles for Rotating Detonation Engines" as this more accurately reflects the scope and focus of the paper.
Keywords: I would like to add "Aerospace engineering" as one of the keywords.
Terminology: I have reverted instances of "applied pressure" back to "ambient pressure", as this is the standard terminology in aerospace engineering and is consistent with similar experiments reported in the literature.
Thank you for your time and consideration. Please let me know if you need any additional information.

Best regards,
Roland Hu

Finally, I would also like to replace Figure 4 with an updated version. No content was changed; I have made the figure using nicer tools, and made it horizontally laid out to take full advantage of available space. Thanks for your consideration.

Done. Shireesh Apte