Design And Analysis of Ramjet Engine For Supersonic Flight

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Abstract- *The increasing demand for high-speed aircraft and missile systems has led to the development of propulsion systems capable of operating efficiently at supersonic speeds. This study focuses on the design and computational analysis of a ramjet engine inlet for supersonic flight applications, specifically examining the influence of cone angle on pressure recovery performance. Three inlet cone angles (43°, 44°, and 45°) were modeled using SolidWorks and subjected to cold-flow analysis in ANSYS Fluent at Mach numbers 2, 2.5, and 3. The k-epsilon turbulence model was employed with density-based solver settings under steady-state conditions. Results indicate that a 45° cone angle achieves maximum pressure recovery at Mach 3, producing an exit pressure of 1,585,917.50 Pa and generating a shock-train configuration favorable for pre-combustion conditions. The 44° cone angle demonstrates the highest absolute exit pressure (2,806,599.25 Pa) at Mach 3 but requires supercritical inlet conditions. The findings provide design guidance for artillery ramjet inlet geometry optimization and contribute to the broader understanding of supersonic air-breathing propulsion systems.*

Keywords: Ramjet engine; supersonic inlet; pressure recovery; cone angle; ANSYS Fluent; CFD; oblique shock; Mach number; air-breathing propulsion

I. INTRODUCTION

Air-breathing propulsion systems utilize atmospheric oxygen as the oxidizer for combustion, offering significant advantages over rocket-based systems by eliminating the need to carry onboard oxidizer. This results in improved payload capacity, operational endurance, and thermodynamic efficiency. Such systems broadly fall into two categories: mechanically compressed engines (turbojets, turbofans) and aerodynamically compressed engines (ramjets, scramjets).

The ramjet engine represents the simplest class of air-breathing propulsion devices, containing no rotating components. It relies entirely on the kinetic energy of the incoming airstream — captured through the inlet — to compress air before combustion. This mechanical simplicity makes the ramjet highly attractive for high-speed missile applications, where it offers excellent thrust-to-weight ratios in the Mach 2 to Mach 5 flight regime.

The inlet system is the most critical sub-component of the ramjet engine. Its primary function is to capture and decelerate supersonic freestream air to subsonic conditions suitable for stable combustion. The quality of this process, commonly expressed as pressure recovery (ratio of stagnation pressure at the inlet exit to freestream stagnation pressure), directly governs the combustion efficiency and net thrust of the engine.

Inlet pressure recovery is strongly influenced by the geometry of the compression spike, particularly the cone angle, which determines the structure and position of oblique shock waves. Incorrect cone geometry can result in bow shock detachment, significant total pressure loss, and subcritical or supercritical inlet behavior all of which are detrimental to engine performance.

This paper investigates the effect of inlet cone angle (43°, 44°, 45°) on pressure recovery for an artillery-type ramjet operating at Mach 2, 2.5, and 3. Computational simulations are carried out using ANSYS Fluent with appropriate turbulence modeling. The optimal cone angle configuration is identified based on exit pressure and Mach number at the inlet plane.

II. LITERATURE REVIEW

The design and analysis of supersonic ramjet inlets has been an active area of research due to their critical role in propulsion system performance. Several prior studies provide context for the present work.

Vnuchkov et altested solid fuel ramjet (SFRJ) configurations in aerodynamic facilities, using an eight-stream air admission system with an inlet diameter of 80 mm and cowl diameter of 122 mm. Their experiments at Mach 2–4 established baseline thrust measurement methodologies applicable to artillery ramjet design.

Gubba and Krishnan demonstrated that incorporating a solid-fuel ramjet into a 155 mm gun-launched projectile could extend range beyond 40 km. Their design used a 45°

cone angle with an annular gap of 6.5 mm and throat diameter of 85 mm — dimensions adopted in the present study.

Kermani and Akbarzadehnumerically compared single, double, and triple wedge inlets using Roe and MacCormack schemes, finding that triple-wedge configurations offer superior total pressure recovery by staging oblique shocks. Their cowl drag analysis confirmed that increasing the number of compression surfaces reduces stagnation pressure losses.

Das and Prasadstudied cowl deflection angle effects at Mach 2.2, showing that small cowl deflection angles (≈2°) improve inlet performance under backpressure conditions. Ran and Mavris proposed a systematic methodology for 2D supersonic inlet design to maximize total pressure recovery using double-wedge configurations with shock-on-lip conditions.

Kumar et al.analyzed ramjet inlet cones with angles of 30°–34° and found that a 33° cone with a modified flow hole achieved superior pressure recovery by converting oblique shocks to normal shocks along the cone length. These findings motivated extending the cone angle range in the present study.

III. PROBLEM STATEMENT AND OBJECTIVES

Maximum pressure recovery at the inlet exit directly enables stable combustion and improved thrust generation in artillery ramjet engines. Pressure recovery depends critically on the inlet spike geometry, specifically the cone angle, which governs shock wave structure and total pressure losses. The present study addresses the following objectives:

- Design the inlet cone of an artillery ramjet engine with three different cone angles — 43°, 44°, and 45° — using SolidWorks CAD software.
- Perform cold-flow computational analysis of each inlet design at Mach 2, 2.5, and 3 using ANSYS Fluent.
- Evaluate static pressure distributions and Mach number contours at the inlet exit for each configuration.
- Identify the optimal cone angle that yields maximum pressure recovery suitable for artillery ramjet operation.

IV. GEOMETRY AND COMPUTATIONAL MODELING

A. Inlet Geometry Dimensions

The geometry of the ramjet inlet was derived from the artillery ramjet specifications reported in the literature. The following principal dimensions were used across all three cone angle configurations:

Parameter	Value
Total Inlet Height	155 mm
Inlet Length	310 mm
Annular Gap	6.5 mm
Inner Cowl Length	267.36 mm
Outer Cowl Length	284.25 mm
Cone Spike Length	206.93 mm
Cowl Angles	28°, 31°

Table 1. Inlet geometry dimensions used for all three cone angle configurations.

B. CAD Modeling in SolidWorks

Two-dimensional cross-sectional profiles of the inlet were modeled in SolidWorks using the dimensions listed in Table 1. For each of the three cone angles, the following steps were performed: the front (XY) plane was selected; lines were drawn using the Line command with appropriate dimensional constraints; the cowl membranes were traced using Spline commands; the geometry was mirrored about the axis of symmetry; and a rectangular computational domain was added and converted to a planar surface using the Planar Surface command. Final geometries were exported in IGES/STEP format for import into ANSYS Workbench.

C. Mesh Generation

The 2D planar geometry was imported into ANSYS Meshing. Face meshing was applied to convert the default unstructured mesh into a structured quadrilateral mesh. Edge-based sizing was applied to improve resolution near the cone and cowl walls. Boundary edges were labeled as: Pressure Far-Field (inlet domain), Spike (wall), Cowl (wall), and Pressure Outlet. The mesh statistics for the final configurations are summarized below:

Parameter	Value	Unit
Element Size	1.0	mm
Nodes	1,082,424	—
Elements	107,227	—
Avg. Surface Area	15,684	mm²

Table 2. Mesh parameters for the computational domain.

V. COMPUTATIONAL METHODOLOGY

A. Solver Configuration

ANSYS Fluent 2D double-precision mode was used for all simulations. A density-based solver was selected to properly resolve the compressibility effects and shock-wave structures present in supersonic flow. Steady-state formulation was assumed. The energy equation was enabled to account for compressible flow thermodynamics.

B. Turbulence Model

The two-equation k-epsilon turbulence model was employed for its balance of computational efficiency and accuracy in capturing separated flows and shock-boundary layer interactions at supersonic Mach numbers. Sutherland's law was used for dynamic viscosity to account for temperature-dependent viscous effects.

C. Fluid Properties

Air was treated as an ideal gas with the following properties: molecular weight of 28.966 kg/kmol, specific heat capacity of 1006.43 J/(kg·K), and Sutherland's viscosity law. These settings are standard for compressible air simulations in the Mach 2–3 range.

D. Boundary Conditions

Pressure far-field boundary conditions were applied at the inlet domain, specifying freestream Mach number and a static temperature of 300 K for all cases. The operating pressure was set to zero so that gauge and absolute pressures are equivalent. Gauge total pressure of 101,325 Pa (sea level) was used. Pressure outlet conditions were applied at the exit boundary. All solid surfaces (spike and cowl) were treated as stationary, adiabatic, no-slip walls.

E. Convergence Criteria

A convergence criterion of 1×10^{-4} (residual monitor set to absolute) was applied for all flow variables: continuity, x-velocity, y-velocity, energy, turbulent kinetic energy (k), and turbulent dissipation rate (epsilon). Approximately 5,000 iterations were required for convergence on a Core i5 (9th generation) workstation with 8 GB RAM. Standard initialization was performed from far-field inlet conditions.

VI. RESULTS AND DISCUSSION

A. Cone Angle 43° — Pressure and Mach Number Analysis

Simulations for the 43° cone angle revealed that at Mach 2, the spike generates a bow shock that detaches from the cowl lip and propagates outward, resulting in degraded internal flow conditions. The exit static pressure was 672,217.31 Pa. At Mach 2.5, bow shock detachment decreased, yielding a higher exit pressure of 788,811.63 Pa. At Mach 3, the bow shock is further suppressed, producing a maximum exit pressure of 944,460.25 Pa.

The Mach number at the inlet exit was 0.9 for Mach 2 inflow — indicating near-sonic flow that is not ideal for stable subsonic combustion. For Mach 2.5 and 3, the exit Mach numbers were 1.29 and 1.25 respectively, confirming that the 43° cone fails to decelerate the flow to subsonic conditions. This makes the 43° cone angle unsuitable for the artillery ramjet application.

B. Cone Angle 44° — Pressure and Mach Number Analysis

The 44° cone angle produced subcritical inlet conditions at all three Mach numbers, with a normal shock forming in front of the cowl lip. Exit static pressures were 1,115,871 Pa, 1,661,877.75 Pa, and 2,002,445.50 Pa at Mach 2, 2.5, and 3 respectively, with peak internal pressures reaching 2,806,599.25 Pa at Mach 3.

The Mach number at the inlet exit achieved fully subsonic values: 0.75 at Mach 2, 0.63 at Mach 2.5, and 0.59 at Mach 3. The progressive reduction in exit Mach number with increasing inlet Mach number confirms effective compression. The 44° configuration is aerodynamically stable and appropriate for the intended operating range.

C. Cone Angle 45° — Pressure and Mach Number Analysis

The 45° cone angle exhibited subcritical behavior at Mach 2 and 2.5. At Mach 3, the inlet transitioned to supercritical condition, with the normal shock forming inside the inlet duct. Reflecting oblique shocks created a characteristic 'shock train' extending through the duct, providing excellent pre-combustion compression conditions. Exit pressures were 670,812.94 Pa, 1,581,222.13 Pa, and 925,419.06 Pa at Mach 2, 2.5, and 3 respectively, with internal peak pressures reaching 2,274,227.50 Pa (Mach 2.5) and 1,585,917.50 Pa (Mach 3).

The exit Mach numbers were 0.66, 0.92, and 0.40 at Mach 2, 2.5, and 3 respectively. The lowest exit Mach number of 0.40 at Mach 3 represents the most effective compression of the three configurations tested, indicating that at the design Mach number, the 45° cone angle provides superior flow deceleration and pre-combustion conditioning.

D. Comparative Analysis

Table 3 summarizes the key performance parameters across all cone angle and Mach number combinations, enabling direct comparison of pressure recovery and exit flow conditions.

Cone Angle	Mach No.	Exit Pressure (Pa)	Peak Pressure (Pa)	Exit Mach No.
43°	2	672,217	—	0.90
43°	2.5	788,812	—	1.29
43°	3	944,460	—	1.25
44°	2	1,115,871	—	0.75
44°	2.5	1,661,878	2,062,754	0.63
44°	3	2,002,446	2,806,599	0.59
45°	2	670,813	937,370	0.66
45°	2.5	1,581,222	2,274,228	0.92
45°	3	925,419	1,585,918	0.40

Table 3. Summary of exit static pressure and Mach number for all configurations.

The comparison plots reveal that the 44° cone achieves the highest absolute exit pressure at Mach 3. However, the 45° cone at Mach 3 uniquely achieves both the lowest exit Mach number (0.40) and the shock-train formation associated with supercritical operation. This combination is particularly desirable for ramjet combustion initiation, as it ensures sufficient static pressure rise and flow deceleration to support stable flame-holding.

VII. CONCLUSION

This study conducted a systematic computational investigation of the effect of inlet cone angle on pressure recovery in an artillery-type ramjet engine operating at supersonic Mach numbers. The following conclusions are drawn:

- The 43° cone angle is unsuitable for the artillery ramjet application across all tested Mach numbers, as it fails to achieve subsonic conditions at the inlet exit due to bow shock detachment.
- The 44° cone angle effectively decelerates the flow to subsonic conditions at all Mach numbers and achieves the highest absolute exit pressure (2,806,599.25 Pa) at Mach 3, making it a viable design for broad operational range.
- The 45° cone angle is identified as the optimal configuration for operation at Mach 3, achieving the lowest exit Mach number of 0.40 and generating a shock-train structure within the inlet that provides favorable pre-combustion conditions.
- Greater pressure recovery is achievable at higher Mach numbers by increasing the cone angle, consistent with theoretical predictions for oblique shock compression.

These findings provide actionable design guidance for artillery ramjet inlet geometry optimization. The 45° cone angle at Mach 3 is recommended as the baseline for further combustion analysis and missile integration studies.

VIII. FUTURE SCOPE

The present work establishes a foundation for more detailed design studies. Future extensions include:

- Evaluation of stepped or multi-stage cone configurations (double and triple cone designs) to further improve mass flow capture and pressure recovery.
- Parametric analysis of cone axial position within the engine duct to assess flow uniformity at the combustion chamber face.
- High-altitude simulations to study inlet performance across a range of atmospheric conditions and angles of attack.
- Reacting flow (combustion) analysis coupled with the optimized inlet geometry to evaluate end-to-end engine thrust and specific impulse.
- Experimental validation using scaled wind-tunnel models for the 44° and 45° cone configurations at the identified design Mach numbers.

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REFERENCES

[1] D. A. Vnuchkov, V. I. Zvegintsev, D. G. Nalivaicheo, V. I. Smolyaga, and A. V. Stepanov, "Testing of solid fuel ramjet with measurement of thrust characteristics in aerodynamic facilities," Thermophysics and Aeromechanics, vol. 25, 2018.

[2] S. R. Gubba and S. Krishnan, "Solid-Fuel Ramjet Assisted Gun-Launched Projectiles," in Proceedings of Workshop on Combustion in Aerospace Propulsion Systems, Hyderabad, India, Nov. 2001.

[3] M. Akbarzadeh and M. J. Kermani, "Numerical Computation of Supersonic-Subsonic Ramjet Inlets; a Design Procedure," 15th Annual Conference, 2017.

[4] Y. Yao, D. Rincon, and Y. Zheng, "Shock Induced Separating Flows in Scramjet Intakes," International Journal of Modern Physics: Conference Series, vol. 19, pp. 73–82, 2012.

[5] G. Dinesh Kumar, D. Gowri Shankar, and C. Suresh, "Numerical Analysis of Ramjet Spike with Various Cone Angles," International Journal of Pure and Applied Mathematics, Chennai, 2018.

[6] B. R. Giorgi, "Experimental and Computational Analysis of a Miniature Ramjet at Mach 4.0," M.S. Thesis, Naval Postgraduate School, Monterey, California, 2013.

[7] M. Akbarzadeh and M. J. Kermani, "Numerical Simulations of Inviscid Airflows in Ramjet Inlets," Aug. 2008.

[8] S. Das and J. K. Prasad, "Cowl Deflection Angle in a Supersonic Air Intake," Defense Science Journal, vol. 59, no. 2, pp. 99–105, Mar. 2009.

[9] H. Ran and D. Mavris, "Preliminary Design of a 2D Supersonic Inlet to Maximize Total Pressure Recovery," AIAA 5th Aviation, Technology, Integration, and Operations Conference, vol. 5, Sep. 2005.

[10] V. Yogeshkumar, N. Rathi, and P. A. Ramakrishna, "Solid Fuel-rich Propellant Development for use in a Ramjet to Propel an Artillery Shell," Indian Institute of Technology Madras, Chennai.

[11] M. N. Karanikolov, N. S. Veselinov, and D. M. Mladenov, "Supersonic Ramjet Engine Inlet for Jovian Flight."

[12] S. Krishnan, P. George, and S. Sathyan, "Design and Control of Solid-Fuel Ramjet for Pseudovacuum Trajectories," Journal of Propulsion and Power, vol. 16, no. 5, Sep.–Oct. 2000.

[13] K. M. Ferguson, "Design and Cold Flow Evaluation of a Miniature Mach 4 Ramjet," Naval Postgraduate School, Monterey, California.