JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Numerical flow investigation approach during off-trimming of missiles mounted under a fighter jet aircraft wing.

A CFD-Based Analysis of Aerodynamic Asymmetry and Trim Stability in Missile-Carrying Fighter Aircraft Configurations

[1]**Abhishek Kanaje**, [2]**Aasmi Gupta**, [3]**Aditya Shankarnarayanan,** [4]**Smit Shinde,** [5]**Tanvee Shah,** [6]**Nikhil Gangamkote**

[1,3,4]Aerospace Engineer, [2,5]Aeronautical Engineer
[1,2,3,4,5]Propulsion,
[1,2,3,4,5]Prime Toolings, Bangalore, India

Abstract: This study presents a comprehensive computational fluid dynamics (CFD) investigation into the aerodynamic behavior of an open missile bay integrated into a delta wing platform under supersonic flow conditions. The primary objective is to analyze the internal flow structures, pressure distribution, and aerodynamic stability in configurations with and without internal missile stores. Using ANSYS Fluent, steady-state, density-based simulations were performed employing the SST (Shear Stress Transport) k-ε (k-epsilon) turbulence model to resolve complex shock interactions and recirculating flow features within the missile bay cavity.

Two configurations were analyzed: one featuring a clean bay (without missiles) and another incorporating vertically aligned cylindrical missiles. The clean configuration exhibited a stable shear layer over the bay opening, a large coherent vortex structure within the cavity, and a symmetric pressure distribution — indicating minimal impact on structural loading and aircraft trim. In contrast, the inclusion of missiles significantly disrupted the internal flowfield, resulting in asymmetric vortex fragmentation, increased turbulence intensity, high-pressure stagnation zones, and complex wake interactions that elevated the drag and trim imbalance.

Furthermore, various missile mounting positions on the delta wing were studied to determine their effect on aerodynamic performance and stability. The analysis showed that missiles mounted closer to the wing root introduced more substantial trim disturbances and central wake formation, while wingtip-mounted missiles exhibited more localized flow disruption and manageable aerodynamic penalties. The dual-missile configuration, though symmetrical, increased parasitic drag.

Overall, the study provides valuable insights into missile bay aerodynamics and the strategic deployment of stores to optimize flight performance. These findings have critical implications for the design of stealth and high-speed aircraft, where minimizing acoustic signatures and preserving aerodynamic balance are paramount. Future work will focus on unsteady simulations, store separation modeling, and experimental validation to further refine deployment strategies and enhance design accuracy.

IndexTerms **- Delta wing, missile deployment, CFD, wake interaction, trim balance, pressure distribution, path line, missile store ejection**

1. AIM

TO INVESTIGATE THE AERODYNAMIC EFFECTS OF MISSILE BAY CONFIGURATIONS WITH AND WITHOUT INTERNAL MISSILE STORES ON A DELTA WING PLATFORM UNDER SUPERSONIC FLOW CONDITIONS USING COMPUTATIONAL FLUID DYNAMICS (CFD), AND TO DEVELOP AN OPTIMIZED MISSILE DEPLOYMENT STRATEGY BASED ON FLOW BEHAVIOR, PRESSURE DISTRIBUTION, AND STABILITY CONSIDERATIONS.

2. OBJECTIVES

1. ***To model and simulate*** *a supersonic missile bay cavity using ANSYS Fluent under steady-state conditions for both clean (empty) and missile-loaded configurations.*
2. ***To analyze*** *the impact of internal missile presence on cavity flow structures, including shear layer dynamics, vortex behavior, and pressure fields.*
3. ***To evaluate*** *the aerodynamic consequences of mounting missiles at different locations (inner, outer, and dual) on a delta wing in terms of trim balance, wake formation, and drag.*
4. ***To compare*** *pressure distribution and flow symmetry across all configurations and quantify aerodynamic penalties (e.g., increased drag or control surface deflection).*
5. ***To propose*** *a missile deployment strategy that ensures flight stability, minimizes aerodynamic disturbance, and supports efficient operational sequencing.*
6. ***To identify*** *critical aerodynamic risks associated with asymmetric store configurations and recommend corrective strategies for trim control.*
7. ***To suggest*** *future research directions such as unsteady simulations, store separation modeling, and experimental validation.*

3. INTRODUCTION:

Modern high-speed and stealth aircraft frequently employ internal weapon bays to reduce radar cross-section and aerodynamic drag. While these recessed bays are effective in preserving the external profile of the aircraft, they introduce a range of complex aerodynamic and aeroacoustics phenomena—particularly under supersonic flow conditions. The presence of an open cavity within a high-speed external flow disrupts boundary layer stability, generates unsteady shear layers, and leads to the formation of large-scale recirculating vortices within the bay. These flow dynamics can induce significant structural loading, pressure oscillations, and acoustic resonance, collectively referred to as ***cavity flow oscillations****.*

When internal stores such as missiles are housed within these bays, the flow field complexity increases further. The presence of these stores introduces physical obstructions that interfere with the natural development of shear layers and internal vortices. This can result in asymmetric pressure fields, increased turbulence, and strong wake interactions—all of which pose a threat to aerodynamic stability, store ejection performance, and the structural integrity of the bay and surrounding airframe.

Understanding these interactions is essential for optimizing both the design and deployment strategy of missile systems, particularly in next-generation fighter jets and unmanned combat aerial vehicles (UCAVs), where ***low observability, maneuverability, and high-speed operation*** *are critical.*

This study employs CFD simulations to investigate the internal flow characteristics of a delta wing missile bay under supersonic freestream conditions. The research focuses on two primary configurations:

Case A*: An empty missile bay (clean configuration), serving as a baseline.*

Case B*: A missile bay loaded with vertically mounted cylindrical missiles.*

By comparing these two cases, the study aims to:

Identify how internal missiles alter the flow structure within the cavity.

Quantify changes in pressure distribution, vortex dynamics, and shear layer behavior.

Assess the implications for aircraft trim, drag, and missile deployment safety.

Recommend optimal missile mounting and deployment strategies for aerodynamic efficiency and stability.

The CFD analysis also extends to the behavior of missiles mounted externally on a delta wing platform, evaluating how different missile positions (inner, outer, and both) influence flow symmetry, trim effects, and overall aerodynamic performance.

This research contributes valuable insights to the ongoing effort to improve the integration of weapons systems in advanced combat aircraft. It emphasizes the necessity of coupling aerodynamic analysis with systems engineering to ensure that stealth, control, and performance are not compromised during weapons carriage or deployment.

4. METHODOLOGY:

The aerodynamic behavior of an open missile bay under supersonic external flow was investigated using Computational Fluid Dynamics (CFD) simulations. The analysis was conducted using ANSYS Fluent, with particular focus on flow characteristics such as shear layer development, vortex structures, pressure distribution, and wake interactions. Two geometric configurations were studied to capture the aerodynamic impact of internal missile storage:

Case A: Empty missile bay (no internal stores)

Case B: Missile bay with vertically mounted cylindrical missiles

4.1 Geometry and Physical Domain

The physical model consisted of a simplified missile bay cavity integrated into a delta wing platform. Two versions of the geometry were prepared:

- *Empty Bay (Case A): A clean cavity with no internal obstruction.*
- *Missile-loaded Bay (Case B): Same cavity, now containing cylindrical missile bodies placed vertically within the bay.*

For external flow analysis, missile-mounted wing configurations were also created to assess aerodynamic impact at different missile positions:

i. *Inner missile only*
ii. *Outer missile only*
iii. *Both missiles mounted symmetrically*

The geometries were created and meshed in ANSYS Design Modeler and Mehing modules.

4.2 Meshing Strategy

A structured / unstructured hybrid mesh approach was used.

Local mesh refinement was applied near critical flow regions such as:

- *Cavity edges*
- *Missile surfaces*
- *Shear layer zones*
- *Leading/trailing edges*

Inflation layers were added near solid walls to capture boundary layer effects.

The mesh quality ensured a Y+ value < 30 to maintain turbulence model accuracy.

Grid independence was assumed based on refinement zones and residual trends, though a full grid convergence study was not explicitly reported.

4.3 Solver and Numerical Scheme

The CFD simulations were conducted using the following settings:

i. *Solver Type: Density-based solver*
ii. *Flow Regime: Steady-state, compressible, supersonic flow*
iii. *Turbulence Model: Shear Stress Transport (SST) k-ε (k-epsilon), selected for its robustness in resolving flow separation and boundary layers.*
iv. *Spatial Discretization: Second-order upwind for momentum and turbulence equations*
v. *Pressure-Velocity Coupling: Implicit formulation for better convergence stability*

4.4 Boundary Conditions

Boundary conditions were defined to replicate a high-speed external environment typical of supersonic cruise or attack flight regimes:

i. *Inlet:*

Type: Pressure Far Field or Velocity Inlet

Mach Number: 0.8

Static Temperature: 300 K

ii. Outlet:

Type: Pressure Outlet

Gauge Pressure: 0 Pa (ambient condition)

Wall Conditions:

Type: Adiabatic (no heat transfer), no-slip condition

Assumption: Wall friction included; heat flux neglected for simplification

4.5 Convergence Criteria

Convergence was monitored through:

Residuals for continuity, momentum, energy, and turbulence (targeted < 10^{-4})

Mass imbalance at inlet and outlet boundaries

Stability of integral quantities such as lift, drag, and moment coefficients

Simulations were run until a quasi-steady state was reached, with negligible variation in solution variables over additional iterations.

4.6 Post-processing

Flow visualization and quantitative analysis were performed using ANSYS Fluent post-processing tools.

Outputs analyzed included:

Velocity vectors and pathlines

Static pressure contours

Shear layer profiles and vortex structures

Wake formations and flow separation zones

Comparative plots were generated for each case to assess the aerodynamic impact of internal missiles and external mounting configurations.

5. CAD DIMENSIONS AND DESIGNS:

- Wing Dimensions (for all 4 cases)

Wing Root – 600mm

Wing semispan- 550mm

1st Missile Mount distance (from root) = 145mm

2nd Missile Mount distance (from root) = 315mm

- Missile Dimension (for all 4 cases)

Length – 4410mm

Diameter – 1220.08mm

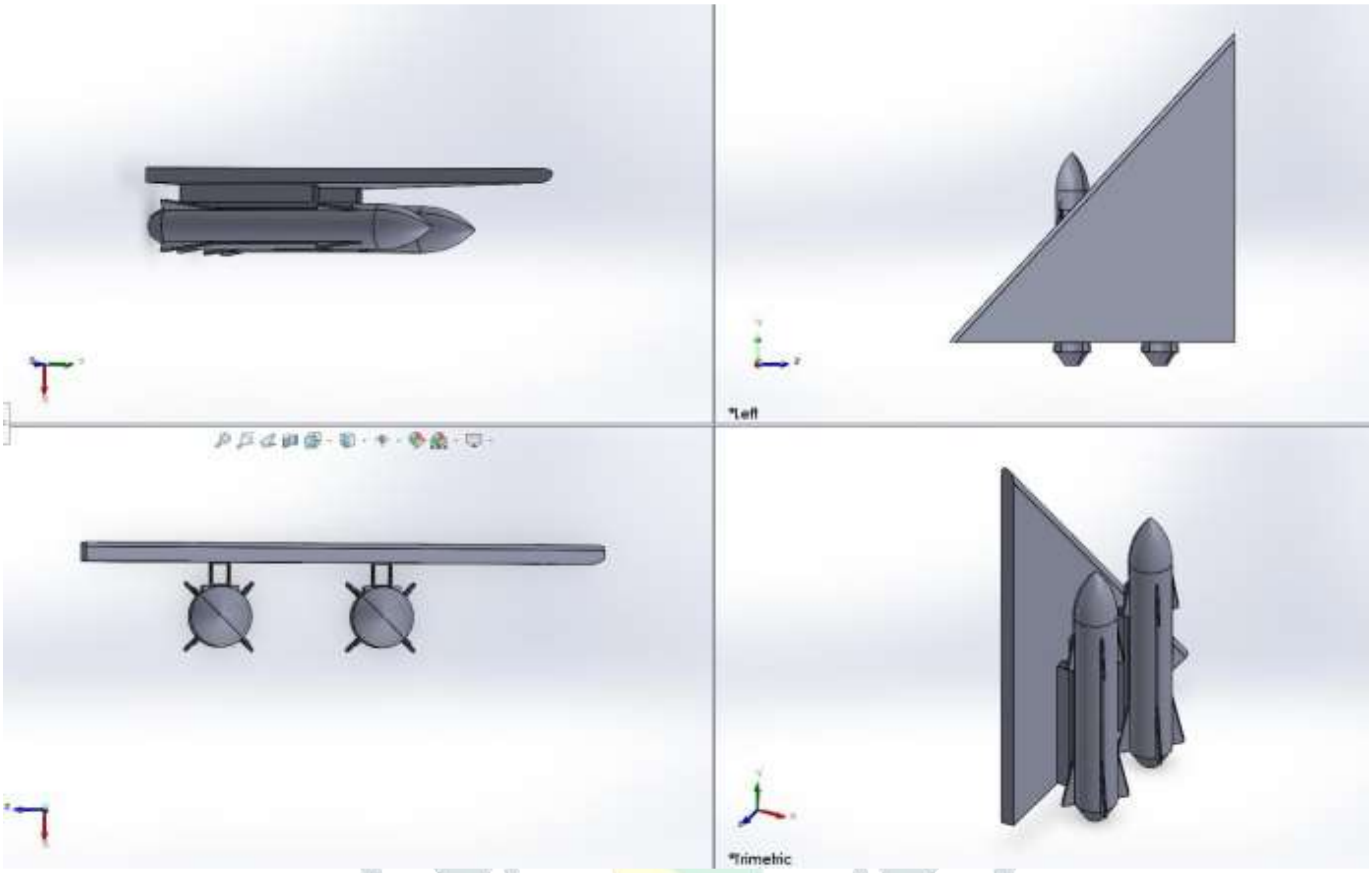

Fig1. Both Missiles mounted under the wing

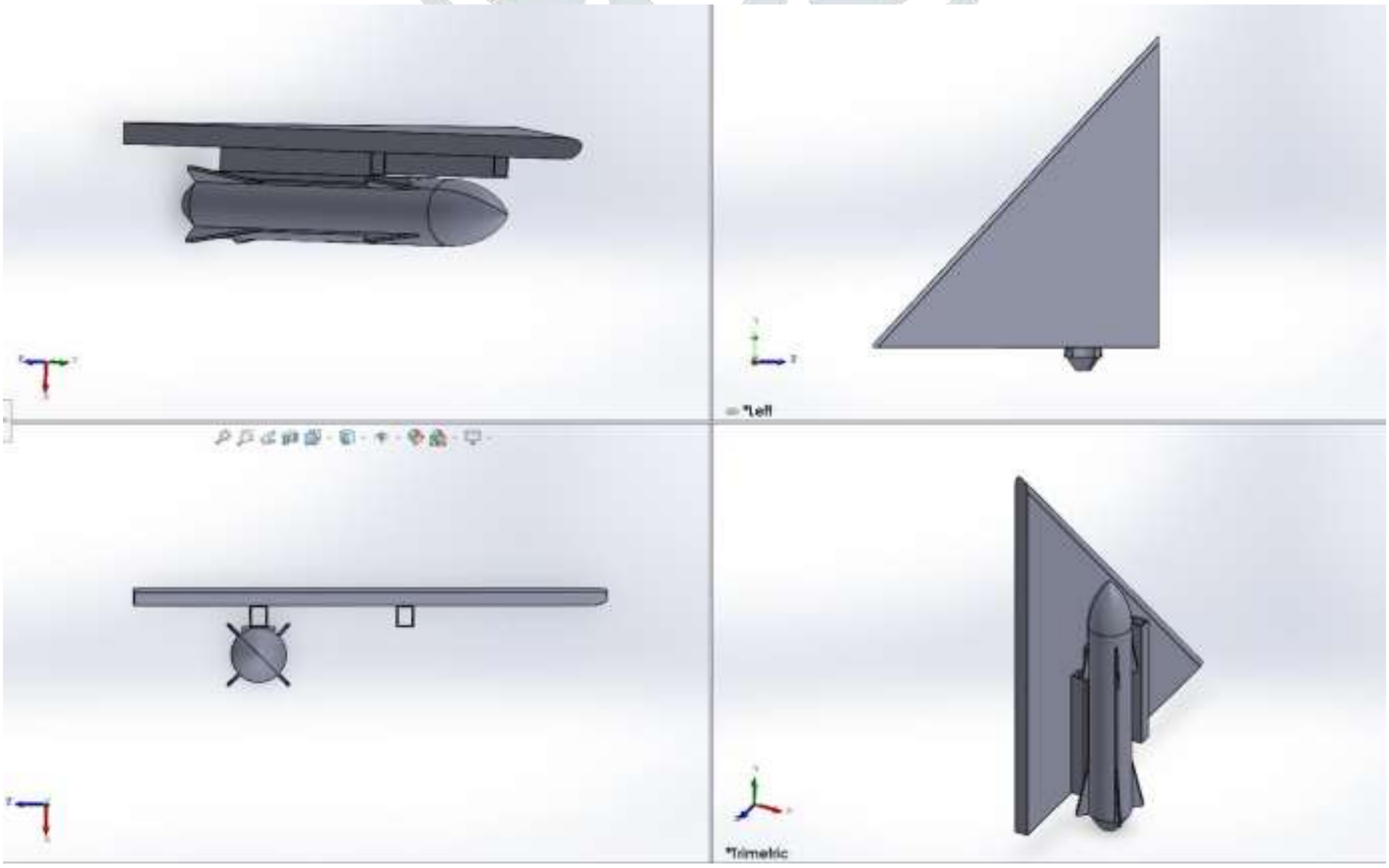

Fig2. Outer Missile Deployed

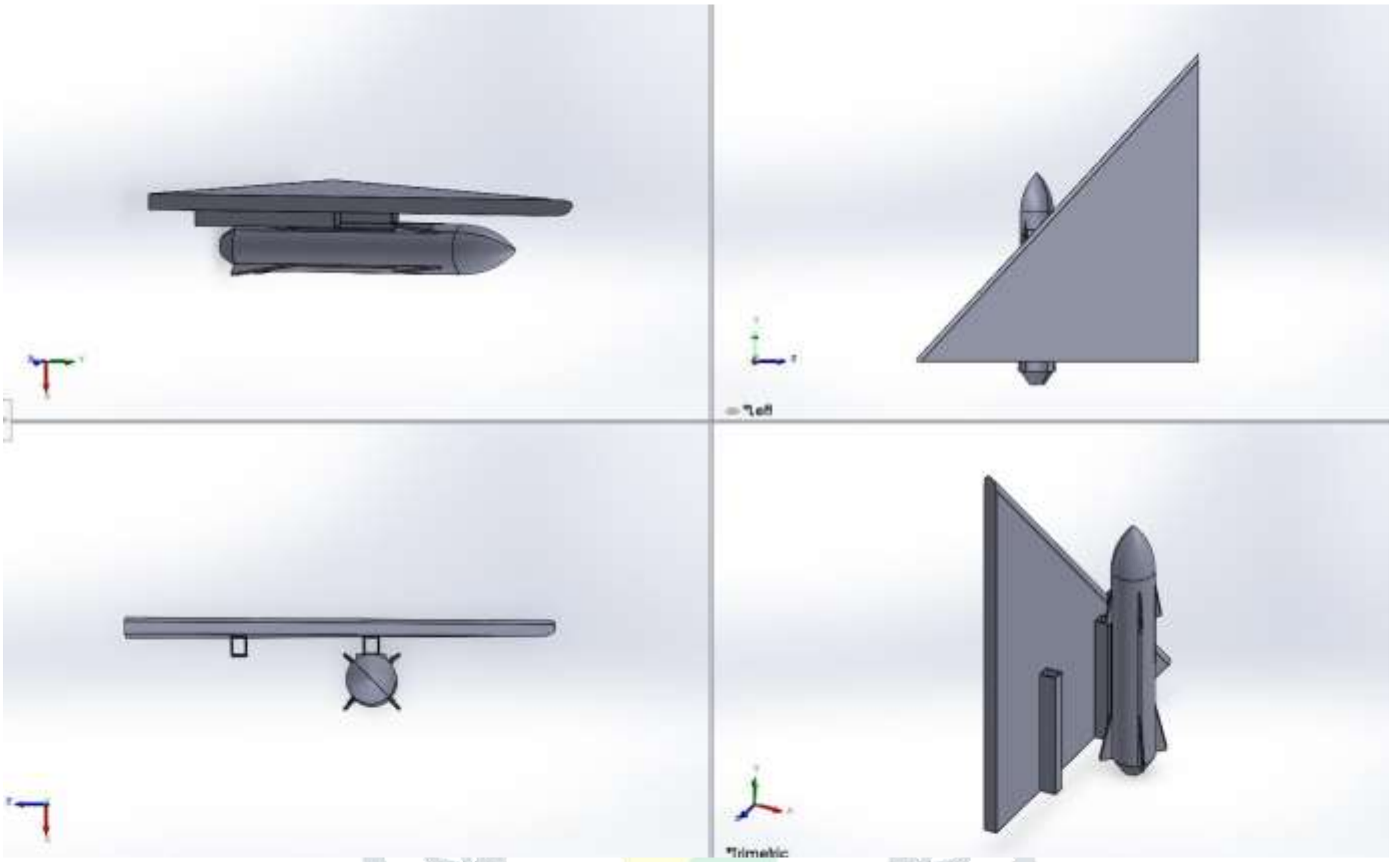

Fig3. Inner Missile Deployed

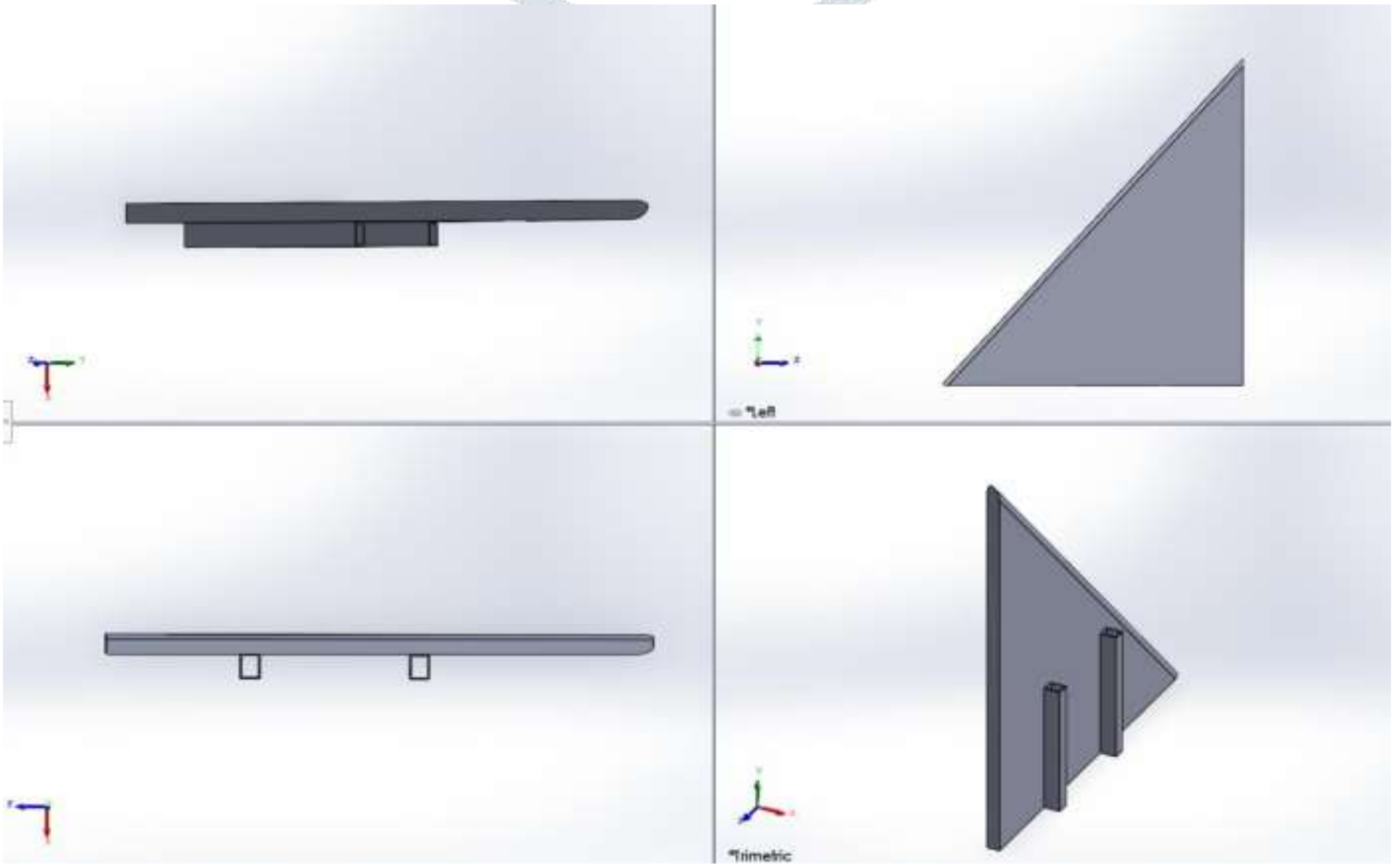

Fig 4. Both Missiles Deployed

6. DISCUSSION:

The CFD analysis yielded insight into the aerodynamic behavior of the missile bay in two primary configurations — Case A (Empty Bay) and Case B (Missile-loaded Bay) — under supersonic flow conditions. Additionally, results were examined for missiles mounted externally on a delta wing, in different configurations (inner, outer, both). Velocity and pressure fields were evaluated to interpret shear layer development, vortex formation, pressure asymmetry, trim effects, and aerodynamic penalties.

6.1 CASE A – EMPTY MISSILE BAY (CLEAN CONFIGURATION)

Velocity Field Analysis:

A well-defined shear layer spans the cavity opening, isolating the high-speed external flow from the low-speed recirculating zone within the bay.

A large, coherent vortex forms along the floor and rear wall of the cavity, rotating in the direction of the freestream.

Flow reattaches smoothly at the aft wall of the cavity, producing a focused high-velocity impingement region.

The flow pattern is largely two-dimensional and stable, with minimal fluctuation across the span.

Pressure Distribution:

Low-pressure zones develop near the cavity floor, coinciding with the vortex core.

A stagnation region forms at the rear wall due to reattachment, generating a localized high-pressure zone.

The pressure distribution is symmetrical across the span of the cavity, suggesting minimal lateral forces and no impact on aircraft trim.

6.2 CASE B – MISSILE BAY WITH VERTICALLY ORIENTED MISSILES

Velocity Field Analysis:

The presence of missiles disrupts the otherwise stable cavity flow.

High-speed jets form between the missile surfaces and cavity sidewalls due to constricted flow paths.

The primary vortex observed in Case A is broken into multiple smaller vortices, due to flow interference from missile bodies.

Wake shedding is observed behind the missiles, increasing local turbulence and instability.

Flow reattachment becomes disorganized, indicating a rise in unsteady flow behavior and vortex fragmentation.

Pressure Distribution:

High-pressure zones occur at the front face of missiles due to direct stagnation from the incoming flow.

Pronounced low-pressure wakes trail behind each missile, extending toward the rear wall.

The overall pressure field becomes asymmetric, especially in cases where missile alignment is not perfectly centered, introducing side forces and potential yaw or roll moments.

The increased unsteadiness and asymmetry lead to greater structural loading and possible aeroacoustic resonance risks.

6.3 MISSILE EFFECTS ON DELTA WING AERODYNAMICS

The influence of missile mounting on a delta wing platform was analyzed in four configurations. Results were presented in terms of flow symmetry, wake behavior, trim effects, and aerodynamic drag.

- *No Missile (Clean Wing – Baseline)*

Velocity Field: Smooth, uninterrupted flow with no vortex shedding or flow separation.

Pressure Contour: Symmetric across the centerline; no pressure imbalance.

Trim: Trim-neutral, no additional control surface deflection required.

Drag: Minimal; serves as a benchmark for comparison.

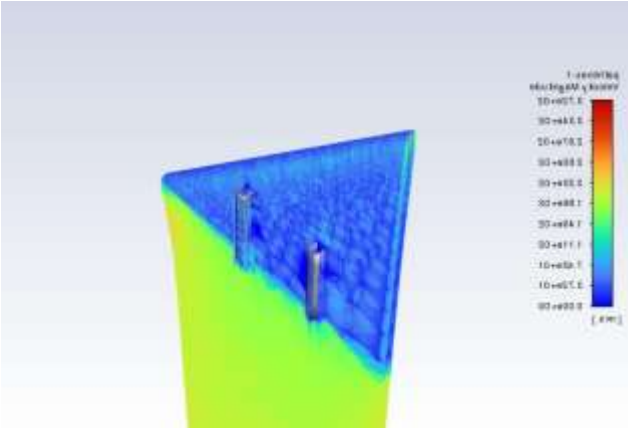

Fig 5. No missile velocity pathlines (isometric)

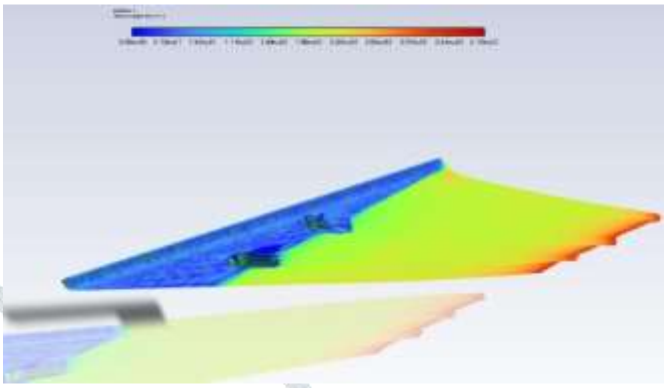

Fig 6. No missile velocity pathlines (side view)

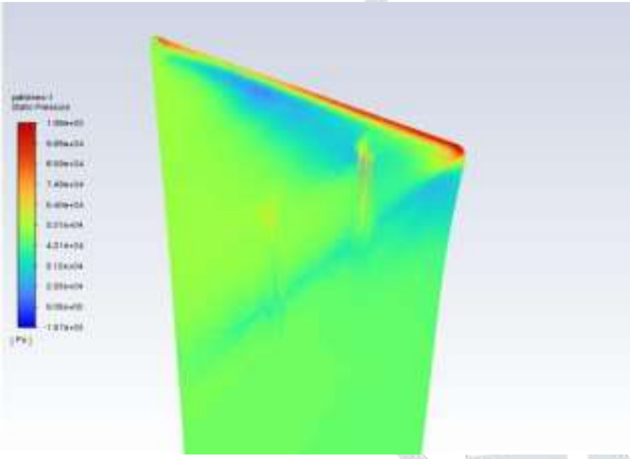

Fig 7. No missile pressure pathlines (isometric)

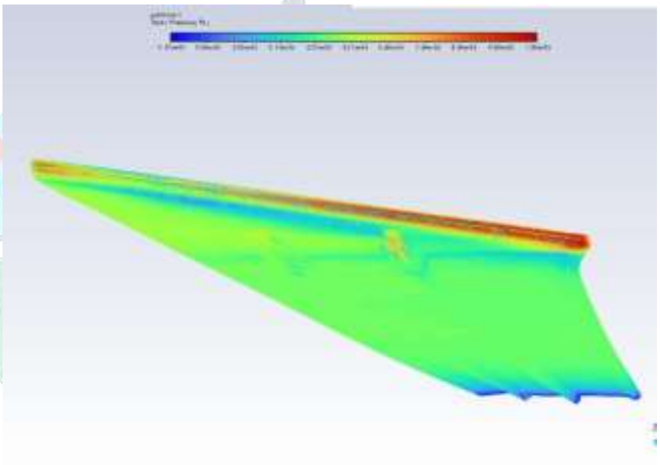

Fig 8. No missile pressure pathlines (side view)

- *Inner Missile Only (Near Wing Root)*

Velocity Field: Strong disruption near the wing root; wake spreads laterally.

Pressure Contour: High pressure at missile nose; low pressure in wake region.

Trim: Major pitch and yaw offset due to asymmetric pressure distribution.

Drag: Moderate, with added induced drag from disrupted wing surface flow.

Comment: Requires significant trim correction; undesirable for isolated inner missile carriage.

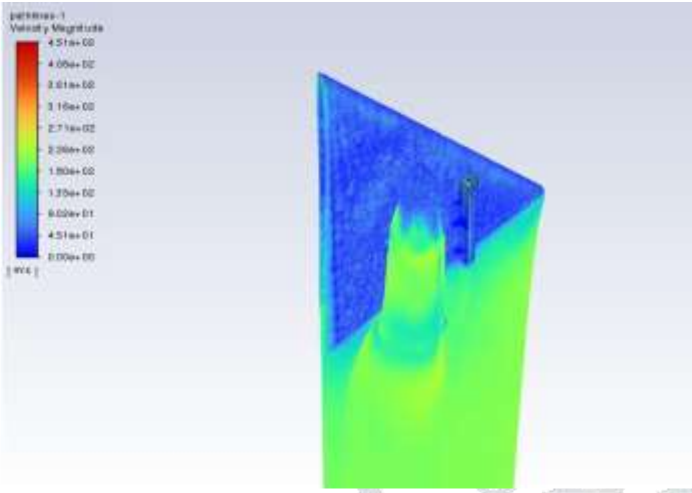

Fig 9. Inner missile velocity pathlines (isometric)

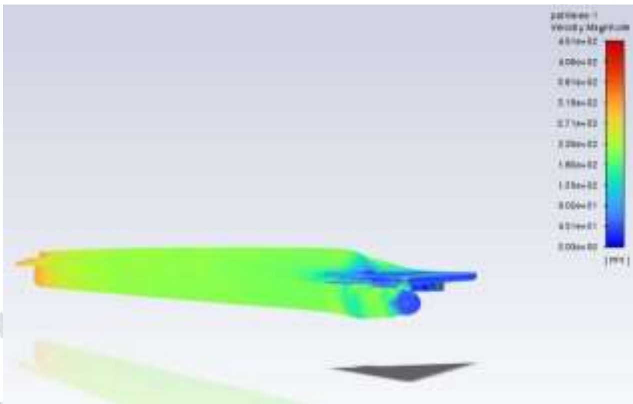

Fig 10. Inner missile velocity pathlines (side view)

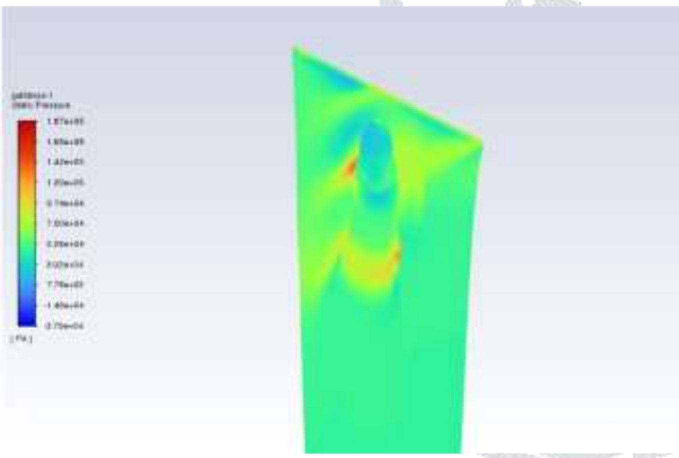

Fig 11. Inner missile pressure pathlines (isometric)

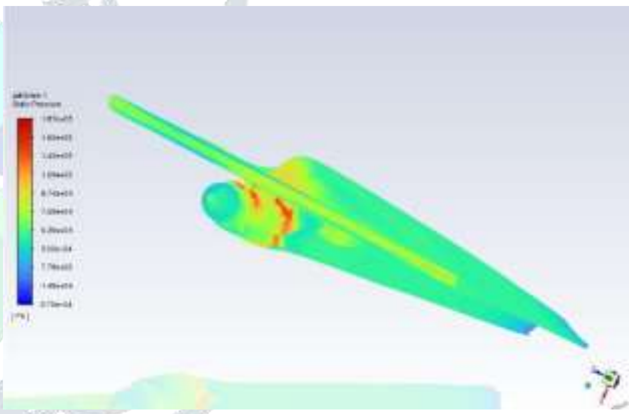

Fig 12. Inner missile pressure pathlines (side view)

- *Outer Missile Only (Near Wing Tip)*

Velocity Field: Localized disruption near the tip; central flow mostly unaffected.

Pressure Contour: Slight asymmetry, but manageable.

Trim: Minor rolling moment; easily compensated.

Drag: Moderate; better than inner missile due to less central flow disturbance.

Comment: Favorable for single missile deployment.

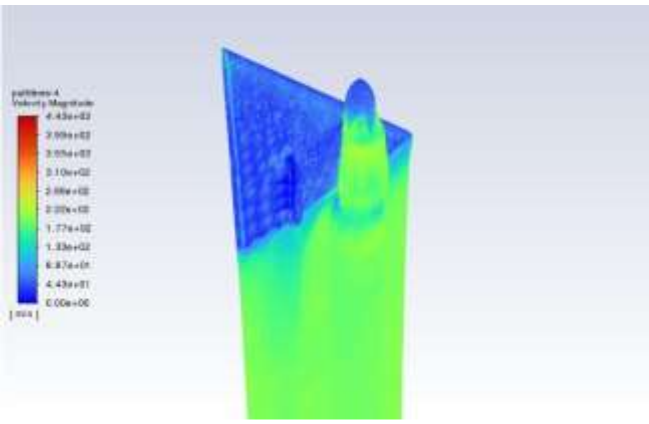

Fig 13. Outer missile velocity pathlines (isometric)

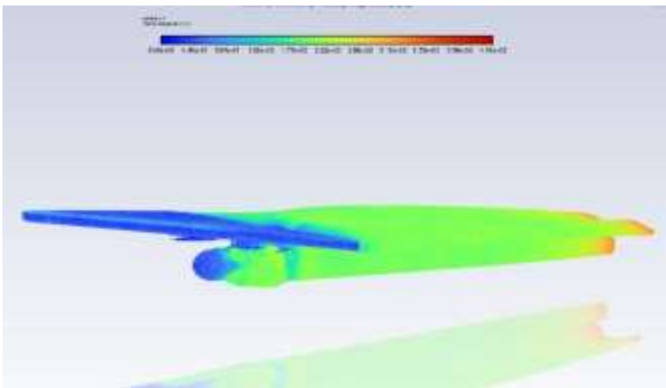

Fig 14. Outer missile pathlines (side view)

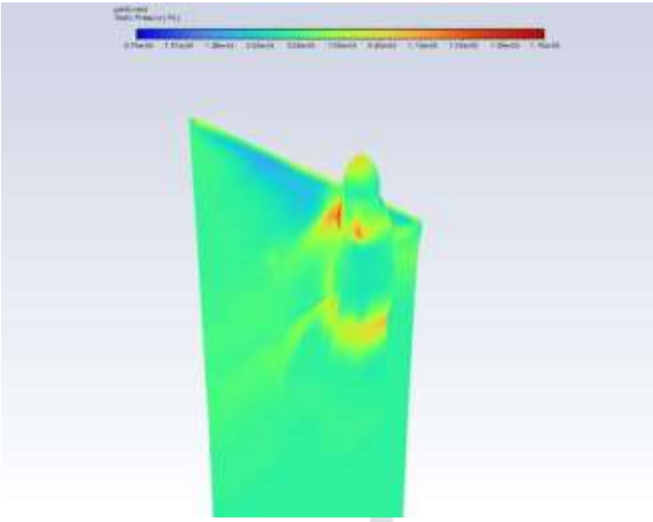

Fig 15. Outer missile pressure pathlines (isometric)

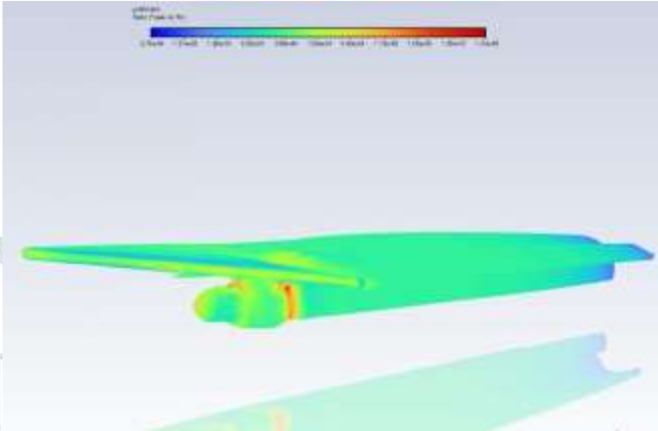

Fig 16. Outer missile pressure pathlines (side view)

- <u>*Both Missiles Mounted Symmetrically*</u>

Velocity Field: Balanced and symmetrical flow disruption; strong wakes behind both missiles.

Pressure Contour: Symmetrical, though net pressure is elevated.

Trim: Centered; no net yaw or roll moment.

Drag: Highest due to doubled frontal area and parasitic drag.

Comment: Best for balanced flight, but at a drag cost.

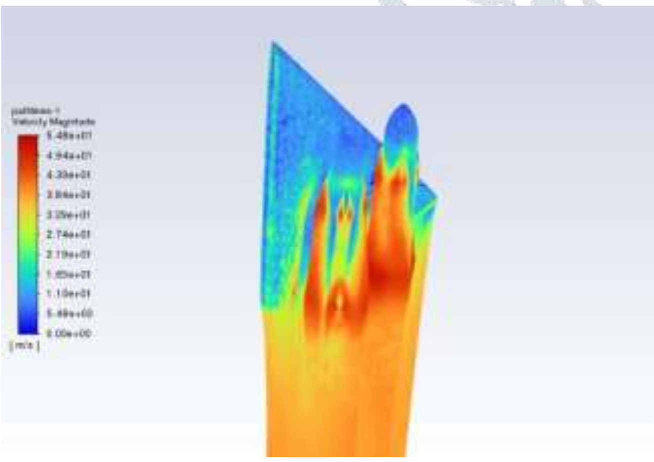

Fig 17. Both missile velocity pathlines (isometric)

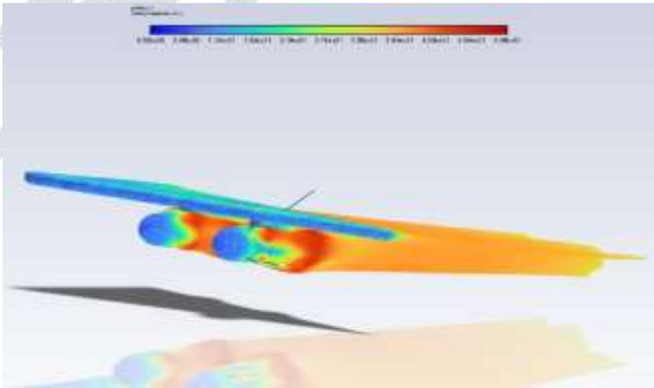

Fig 18. Both missile velocity pathlines (side view)

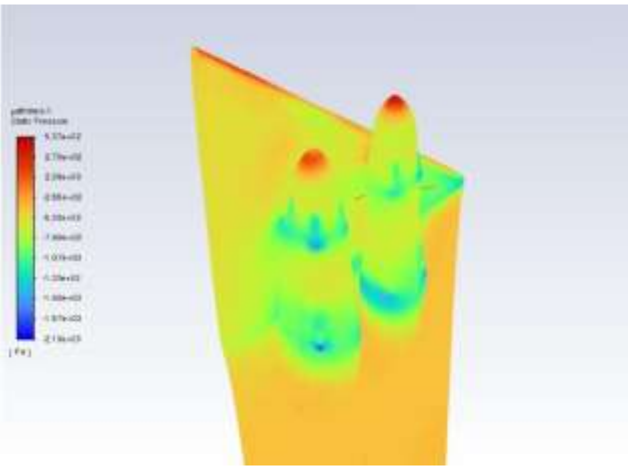

Fig 19. Both missile pressure pathlines (isometric)

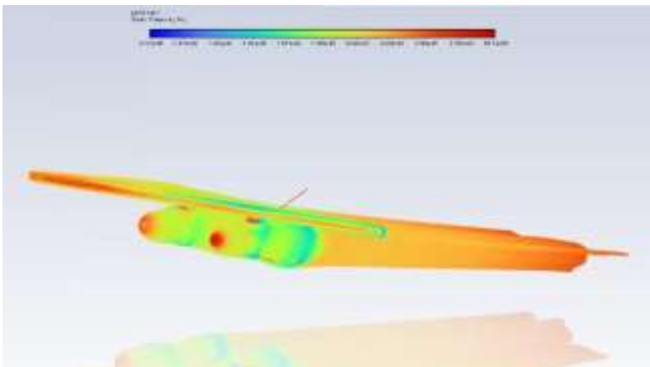

Fig 20. Both missile pressure pathlines (side view)

7. *CFD METHODOLOGY:*

The aerodynamic behavior of the missile bay cavity under supersonic flow conditions was investigated using Computational Fluid Dynamics (CFD) simulations performed in **ANSYS Fluent**. The methodology involved rigorous preprocessing, solver configuration, and post-processing stages to ensure physically accurate representation of flow characteristics such as shear layer dynamics, vortex formation, pressure gradients, and aerodynamic forces. The simulation strategy was designed to analyze both internal bay configurations (with and without missiles) and external missile placements on a delta wing.

7.1 Geometry and Domain Setup

Two primary 3D geometrical configurations were modeled:

Case A – Empty Bay: An open rectangular cavity embedded within a simplified delta wing profile, devoid of internal stores.

Case B – Missile-Loaded Bay: Same cavity, containing vertically oriented cylindrical missile bodies centrally mounted within the bay.

Additional external missile configurations were modeled to study their effects on wing flow:

Inner missile (near wing root),

Outer missile (near wing tip),

Dual symmetric missiles.

The physical domain extended sufficiently upstream, downstream, and laterally to avoid boundary-induced interference in flow solutions.

7.2 Mesh Generation

Mesh generation was carried out in **ANSYS Meshing**, using a **structured/unstructured hybrid approach**:

Unstructured mesh in the far-field and outer domain

Structured or swept mesh near the missile bodies and cavity walls to capture flow gradients accurately

Mesh Refinement Techniques:

Inflation layers near solid walls to resolve boundary layer effects, with first layer height computed to maintain **Y+ < 30**

Local refinement zones around:

Cavity leading/trailing edges

Missile surfaces

Flow separation regions

Mesh quality metrics such as orthogonality, skewness, and aspect ratio were carefully monitored to ensure numerical stability and convergence.

7.3 Solver and Physical Models

The simulations were conducted using a **density-based steady-state solver**, appropriate for high-speed compressible flows. Key solver settings include:

Setting	**Value/Selection**
Solver Type	Density-based, Steady-State
Flow Regime	Compressible, Supersonic
Turbulence Model	SST (Shear Stress Transport) k-ε (k-epsilon)
Discretization (Momentum)	Second-Order Upwind solution
Pressure-Velocity Coupling	Implicit formulation
Energy Equation	Activated (for temperature-linked compressibility)
Gas Model	Ideal gas (1.225 Kg/m3)

Table:1

Offers robust near-wall resolution

Captures boundary layer separation and shock interactions effectively

Blends the advantages of k–ε in the far field with k–ω near walls

7.4 Boundary Conditions

The boundary conditions were set to replicate typical supersonic flight conditions at Mach 0.8:

Boundary	Condition Type	Details
Inlet	Velocity Inlet or Pressure Far-Field	Mach 0.8, T = 300 K
Outlet	Pressure Outlet	Gauge Pressure = 0 Pa (ambient)
Walls	Adiabatic No-Slip	Heat flux neglected, viscous effects included
Symmetry	Applied where relevant	Reduces computational cost

Table:2

The pressure far-field condition was preferred for outer boundaries in some simulations to better represent supersonic inflow behavior and shock formation.

7.5 Solution Control and Convergence

To ensure numerical accuracy, the following **solution control settings** and convergence criteria were adopted:

Under-relaxation factors were optimized for stability

Residual convergence criteria:

Continuity and momentum: $< 1\times10^{-4}$

Turbulence equations: $< 1\times10^{-4}$

Mass imbalance between inlet and outlet maintained under 1%

Monitored **surface integrals**: drag coefficient, pressure forces, and moment coefficients to ensure steady solution

7.6 Post-processing

Post-processing was conducted within **ANSYS Fluent** and further enhanced using CFD-Post tools. Key outputs analyzed include:

- **Static Pressure Contours**: to identify stagnation zones, wake formation, and asymmetry
- **Velocity Pathlines and Vectors**: to visualize shear layers, vortex dynamics, and jet effects
- **Wall Shear Stress**: to examine boundary layer behavior and separation regions
- **Turbulence Intensity Fields**: to assess areas of high fluctuation and flow unsteadiness

Comparative visualizations and plots were generated for each configuration to understand the aerodynamic implications of missile presence and placement.

7.7 Assumptions and Limitations

- **Steady-state flow assumption**: Time-averaged analysis; transient effects like resonance or buffeting not captured
- **No heat transfer (adiabatic walls)**: Simplified thermal model; radiative and convective effects ignored
- **Ideal gas behavior**: Sufficient for Mach 0.8 regime; real gas effects not modeled
- **No store separation modeling**: Static missiles assumed; dynamic ejection not simulated
- **No control surface deflection**: Trim corrections were inferred from flow imbalance, not dynamically modeled

8. Results and Discussion

8.1 Condition 1: Clean Configuration (No Missiles Mounted)

i. Velocity Field:

Streamlines remain smooth and attached along the delta wing surface.

No evidence of flow separation, wake formation, or trailing edge vortices.

The flow exhibits uniform spanwise behavior and minimal vertical disturbance.

ii. Pressure Distribution:

Pressure contours are symmetric about the longitudinal centerline.

No stagnation points or pressure spikes due to obstructions.

Balanced pressure recovery across the upper and lower surfaces of the wing.

iii. Trim and Stability:

Aerodynamically neutral; no pitching, rolling, or yawing moments generated.

No control surface deflection required for flight trim.

iv. Drag Characteristics:

Baseline (lowest) drag observed.

Serves as reference for evaluating aerodynamic penalties in other cases.

8.2 Condition 2: Inner Missile Mounted (Root Proximity)

i. Velocity Field:

Significant flow disruption observed near the wing root.

A strong wake forms behind the missile, extending laterally toward the centerline.

Flow separation evident along the wing surface downstream of the missile body.

ii. Pressure Distribution:

High stagnation pressure forms on the missile's nose.

Low-pressure wake persists behind the missile, causing pressure asymmetry between the left and right wing halves.

The missile creates a blockage effect, altering local pressure gradients.

iii. Trim and Stability:

Asymmetric pressure leads to a ***pitching and yawing moment****.*

Requires ***active trim correction*** *via rudder and elevon deflections.*

Undesirable for isolated inner missile deployment.

iv. Drag Characteristics:

Moderate drag increases due to large frontal area and wake.

Overall aerodynamic efficiency is reduced significantly compared to the clean case.

8.3 Condition 3: Outer Missile Mounted (Near Wing Tip)

i. Velocity Field:

Localized flow disturbance near the wingtip region.

Wake formation is confined to outboard sections and doesn't affect centerline flow.

Minimal flow separation observed compared to inner missile case.

ii. Pressure Distribution:

Moderate stagnation pressure at the missile nose.

Wake behind missile causes localized low-pressure zone.

The overall pressure field retains ***quasi-symmetry****, especially inboard of the missile.*

iii. *Trim and Stability:*

*Minor **rolling moment** induced due to outboard asymmetry.*

Easily corrected using aileron or differential elevon control.

More stable than inner missile configuration.

iv. *Drag Characteristics:*

*Moderate drag penalty, but **lower than inner missile case**.*

Favorable trade-off between trim stability and drag for single missile deployments.

8.4 Condition 4: Dual Missiles Mounted Symmetrically

i. *Velocity Field:*

Balanced, symmetric wakes generated by both missiles.

Wake interaction remains stable and predictable across the span.

Flow remains attached outside wake zones, but total wake volume increases.

ii. *Pressure Distribution:*

Symmetrical stagnation zones in front of both missiles.

Equal low-pressure wake regions behind each missile.

*No net rolling or yawing moment — **trim remains centered**.*

iii. *Trim and Stability:*

Best case for balanced flight during multi-missile carriage.

Minimal control surface deflection required to maintain flight attitude.

Ideal for missions requiring simultaneous multi-store deployment.

iv. *Drag Characteristics:*

***Highest total drag** due to increased frontal area and combined wake effects.*

Acceptable for short-term weapon deployment but less efficient for long-range cruising.

9. MISSILE DEPLOYMENT STRATEGY

Based on aerodynamic response, the following sequence is optimal:

→ Deploy outer missile first: Ensures minimal trim disturbance and better roll balance.
→ Retain inner missile until final phase or follow outer missile release with trim correction.
→ Avoid solo inner missile deployment due to its proximity to wing root and resulting asymmetric loads.

10. CONCLUSION

The CFD analysis validates that missile position significantly alters the flow characteristics of a delta wing configuration. Inner missile deployment leads to higher flow disruption and trim offset due to central wake development and pressure asymmetry. Outer missile deployment results in more manageable aerodynamic disturbances, while the symmetric dual-missile configuration provides optimal stability with increased drag. These findings support a strategic deployment sequence beg...
Further work should include:
- Unsteady RANS/LES simulations to evaluate transient effects and buffet onset
- Store separation trajectory modeling
- Experimental validation in wind tunnel setups

11. *REFERENCE:*

- OpenAI. (2024). ChatGPT: Advanced language model for research and analysis.
- Prime Toolings Company- Precision engineering and design specifications for aerospace applications.
- Xue, R., & Choi, S. (2005). Numerical Investigation of Open Cavity Flowfields for Supersonic Flight. AIAA Journal, 43(7), 1553–1563.
- Rhoads, T. R., & Jumper, E. J. (1996). Unsteady Flow in a Rectangular Cavity with and without Flow Control. AIAA

Journal, 34(3), 489–494.
■ Radespiel, R., & Heinze, W. (2013). CFD Applications in Aircraft Design: From Conceptual to Detailed Design. Aerospace Science and Technology, 28(1), 4–17.
■ Anderson, J. D. (2010). Fundamentals of Aerodynamics (5th ed.). McGraw-Hill Education.
■ Chyczewski, T. S., & MacLean, M. (2015). Store Release in Supersonic Flow: Simulations and Analysis Using CFD. AIAA SciTech Forum, AIAA 2015-0221.