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Aerodynamic and Ballistic Analysis of a 155 mm Rocket-Assisted Projectile

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Abstract

The interaction between the exhaust plume and the external supersonic flow in 155 mm Rocket-Assisted Projectiles (RAPs) generates complex aerodynamic phenomena that affect base pressure, wake structure, and drag, although experimental and numerical data on these effects remain limited. This work presents an integrated computational fluid dynamics (CFD) and ballistic investigation of a 155 mm RAP, focusing on propulsion-induced modifications to the base flow and their impact on projectile range. Reynolds-Averaged Navier-Stokes simulations were performed for propelled and non-propelled configurations over a Mach range from 0.7 to 2.5. Numerical uncertainties were quantified using the Grid Convergence Index methodology, and the results were validated against PRODAS data. The simulations show that the exhaust plume produces a more compact recirculation region and increases aerodynamic drag by approximately 70% to 90% relative to the non-propelled configuration, although this difference decreases at higher Mach numbers. The aerodynamic coefficients were incorporated into a ballistic solver simulating 3300 trajectories. Results indicate that plume effects can reduce maximum range by up to 720 m near optimal firing angles, with influence concentrated during the first 50 s of flight. The proposed framework supports ignition and grain optimization for performance enhancement in extended-range artillery systems.

Keywords: Rocket-Assisted Projectile (RAP), Exhaust Plume Interaction, CFD, GCI, external ballistics

1 Introduction

The growing complexity of modern warfare has reinforced the strategic importance of field artillery, particularly in operations involving mobile forces and counter-battery engagements. The integration of drones, radars, and digital fire-control systems has increased targeting speed and accuracy, making survivability and rapid repositioning essential as discussed by Gouveia and Freitas [1] and Oprean [2]. Consequently, extended-range artillery systems have become a strategic requirement, enabling deep fire support while reducing exposure to enemy counter-fire.

This demand has accelerated the modernization of 155 mm artillery systems, favored for their interoperability and compatibility with advanced munitions. Programs such as the U.S. ERCA and systems like the CAESAR, K9 Thunder, and PzH 2000 demonstrate the global focus on ranges exceeding 40 km with conventional ammunition and over 70 km with assisted projectiles.

Among range-extension technologies, Rocket-Assisted Projectiles (RAPs) stand out for combining increased range with compatibility with conventional guns and no need for barrel modifications, as discussed by Barcellos Filho [3] for base-bleed technologies. RAPs incorporate a solid rocket motor in the projectile base, providing additional thrust during flight at lower cost than guided or ramjet-powered munitions such as the Projectile Sceptre shown in Figure 1.



Fig. 1 External view of the Sceptre projectile. Source: Tiberius Aerospace Press and Media Kit. [4].

Operating under supersonic conditions, RAPs are subjected to complex flow phenomena involving shock-wave interactions, boundary-layer development, wake formation, and strong pressure gradients. In this regime, aerodynamic performance is highly dependent on the flow structures developing in the projectile afterbody and base region. Since base drag may represent a significant fraction of the total aerodynamic resistance, wake topology and pressure recovery mechanisms play a critical role in determining projectile efficiency, stability, and range.

The aerodynamic importance of the projectile wake has motivated extensive investigations of supersonic axisymmetric bodies. Numerical and experimental studies have shown that relatively small modifications in aft-body geometry can substantially alter vortex structures, pressure distributions, and drag characteristics. In particular, Ma et al. [5] demonstrated that boattail configurations strongly influence wake dynamics and aerodynamic coefficients through modifications of the trailing vortex system and surface pressure field. Similar studies on axisymmetric projectiles and bullets

have reported significant drag reductions associated with improved pressure recovery and weaker recirculation regions, highlighting the strong sensitivity of projectile performance to base-flow physics.

The complexity of these flow mechanisms has led to the widespread adoption of Computational Fluid Dynamics (CFD) for projectile aerodynamics. Advances in numerical methods have enabled increasingly accurate analyses of shock-dominated and highly three-dimensional flow fields that remain difficult and expensive to characterize experimentally. Obeid et al. [6] demonstrated the capability of modern CFD approaches to capture asymmetric separated flows around slender bodies, emphasizing the importance of high-fidelity numerical simulations for understanding complex wake phenomena. Likewise, CFD investigations of spinning and non-spinning projectiles have successfully reproduced aerodynamic coefficients, shock structures, and wake behavior across subsonic, transonic, and supersonic regimes.

Despite these advances, most available studies focus on conventional projectiles without propulsion. For Rocket-Assisted Projectiles, the interaction between the rocket exhaust plume and the external supersonic flow introduces additional physical mechanisms that can significantly modify the wake structure. The exhaust gases may increase base pressure, alter recirculation dynamics, modify shock-wave patterns, and reduce aerodynamic drag, directly affecting projectile range. Although these effects are recognized as important for extended-range ammunition, plume-flow interactions and their consequences for both aerodynamic and ballistic performance remain insufficiently explored in the open literature.

This work presents an integrated aerodynamic and ballistic investigation of a 155 mm RAP under supersonic flight conditions. Reynolds-Averaged Navier-Stokes simulations employing the SST $k-\omega$ turbulence model are used to evaluate propulsion effects on wake topology, pressure distribution, and drag coefficient for Mach numbers between 0.7 and 2.5. The resulting aerodynamic database is subsequently incorporated into a Modified Mass Point ballistic model to quantify the influence of propulsion-induced aerodynamic changes on projectile trajectory and maximum range. Numerical reliability is ensured through mesh convergence analysis, GCI evaluation, and validation against PRODAS reference data.

2 Methodology

2.1 Computational Model and Numerical Setup

The projectile geometry was reconstructed from the dimensions reported by Ferfour et al. [7], as seen in Table 1, with missing parameters estimated from the published schematic. A two-dimensional axisymmetric computational domain was adopted, extending upstream and downstream of the projectile to minimize boundary effects. The overall domain configuration is presented in Figure 2, while Figure 3 details the boundary-condition locations and the near-body region used in the simulations.

For the configuration with exhaust, an internal nozzle consisting of convergent, throat, and divergent sections was added to the projectile base, as shown by Figure 3. Since complete nozzle dimensions were not available in the original reference, the geometry was adjusted iteratively using standard rocket motor relations until the

Table 1 Dimensions for the Projectile. Adapted from data reported by Ferfour et al. [7]

Parameter	Ogive	Body	Boattail	Convergent	Nozzle	Divergent
Left Diameter	10 mm	155 mm	155 mm	20 mm	9.4 mm	9.4 mm
Right Diameter	155 mm	155 mm	144 mm	9.4 mm	9.4 mm	40 mm
Length	523 mm	262 mm	85 mm	9 mm	8 mm	48 mm
Radius	3200 mm	0 mm	0 mm	0 mm	0 mm	0 mm

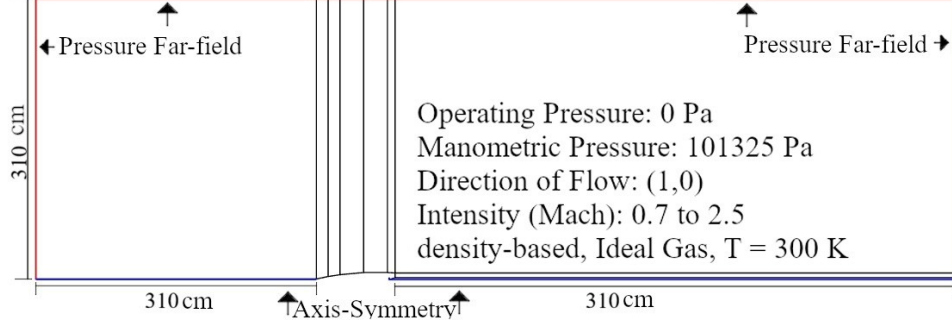


Fig. 2 Geometry for the domain and overall configuration.

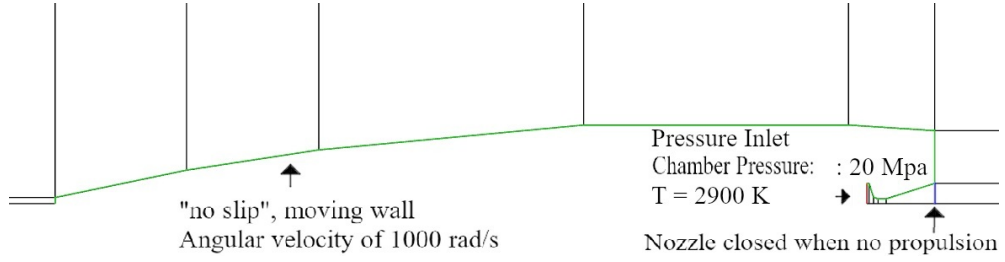


Fig. 3 Detail of the domain for the boundary conditions and configuration at the projectile geometry.

expected motor performance was reproduced. This procedure ensured consistency between the prescribed thrust profiles and the internal flow representation.

The rocket motor also follows the configuration reported by Ferfour et al. [7]. The grain configurations analysed was the Neutral defined by thrust evolution throughout burn duration in Table 2. Thrust curves were discretized using 100 points in simulations, although the neutral configuration has low variation in the value of thrust.

Table 2 Thrust values adapted from data reported by Ferfour et al. [7].

Burn Time (s)	0.04	0.68	1.01	1.37	1.68	2.04	2.65	3.00
Neutral Thrust (N)	2291.5	2175.3	2115.8	2151.7	2194.9	2240.2	2256.8	2051.9

Six computational meshes were generated: three for the configuration with exhaust and three for the configuration without, each comprising coarse, medium, and fine resolution levels. Cell clustering was applied near the projectile surface and in regions of interest, particularly along the base and aft section, where complex flow features such as recirculation and expansion waves are expected.

The flow field was solved using the compressible axisymmetric RANS equations with a density-based implicit solver. Air was modeled as a calorically and thermally perfect ideal gas, and turbulence effects were represented using the SST $k - \omega$ model. The energy equation was solved in its complete form, including viscous dissipation.

The pressure far-field boundary condition was applied to the external domain, covering Mach numbers between 0.7 to 2.5. All projectile and nozzle walls were treated as adiabatic no-slip surfaces. To account for projectile spin, the wall was assigned a rotational speed of 1000 rad/s about the symmetry axis. For propelled cases, chamber conditions were imposed through air pressure inlet located upstream of the nozzle throat, with a total pressure of 20 MPa and a total temperature of 2900 K.

The solution was initialized from free-stream conditions and advanced toward steady state using pseudo-time stepping with a Courant number of 1. Convergence was assumed when all residuals decreased below 1×10^{-6} or when the maximum iteration count of 20,000 iterations was reached.

2.2 Mesh Independence and Validation

A mesh independence assessment was performed using the three refinement levels generated for each configuration. The mesh strategy employed in the study is discussed in the section 2.1, where refinement was concentrated near the projectile surface, wake region, and exhaust plume interaction zone.

Numerical uncertainty was quantified through the Grid Convergence Index (GCI) methodology proposed by Roache [8] and Celik et al. [9]. A constant refinement ratio of 2 was maintained between successive mesh levels. The observed order of convergence was obtained from the coarse, medium, and fine mesh solutions, and Richardson extrapolation was used to estimate the grid-independent value. The resulting GCI of the finest mesh was adopted as the discretization uncertainty estimate.

Model validation was carried out using the unpropelled configuration. Drag coefficient predictions obtained with the finest mesh were compared against reference results generated with PRODAS [10] over the Mach range from 0.7 to 2.5. After validation, the same computational setup—including mesh strategy, turbulence model, solver settings, and boundary conditions—was applied to the propelled simulations without modification, except for the addition of the pressure inlet from the rocket motor. Consequently, any differences observed between the two configurations can be directly attributed to the aerodynamic effects of the rocket exhaust plume.

2.3 Trajectory Simulation Procedure

Ballistic trajectories were computed using the Modified Point-Mass model based on STANAG 4355 [11]. In this formulation, the projectile is represented by a material

point located at its center of gravity, while aerodynamic and gravitational effects are incorporated through semi-empirical force and moment models.

The complete STANAG formulation for rotating projectile was implemented, including drag, lift, Magnus force, gravity, Coriolis effects, spin damping, yaw-of-repose estimation, and rocket thrust. For propelled trajectories, the model additionally accounts for propellant consumption, thrust generation, center-of-gravity displacement, and variation of the axial moment of inertia during motor operation. The thrust history was prescribed from the motor performance data presented in Table 2. The projectile properties adopted in the simulations, including the transition from launch to burnout conditions, are summarized in Table 3.

Table 3 Projectile input data and firing conditions, adapted from Ferfour et al [7]

Projectile input data	
Caliber d [mm]	155
Length l [mm]	870
Before burnout	
Mass m_l [kg]	43
Center of gravity from nose x_{CGI} [mm]	548.7
Axial Moment of Inertia I_{xVI} [$kg \cdot m^2$]	0.14
Lateral Moment of Inertia $I_{yVI} = I_{zVI}$ [$kg \cdot m^2$]	1.78
After burnout	
Mass m_f [kg]	40
Center of gravity from nose x_{CGI} [mm]	540
Axial Moment of Inertia I_{xVI} [$kg \cdot m^2$]	0.13
Lateral Moment of Inertia $I_{yVI} = I_{zVI}$ [$kg \cdot m^2$]	1.67
Firing conditions	
Muzzle velocity V_0 [m/s]	565.4
Firing altitude Y_0 [m] (sea level)	0

The trajectory computation begins by defining the initial projectile state at the gun muzzle using the prescribed firing conditions, including muzzle velocity, launch elevation, azimuth, mass properties, and spin rate. Atmospheric properties are then calculated from the projectile altitude using the formulations presented by Carlucci and Jacobson [12] and McCoy [13]. Based on these conditions, the local Mach number and all aerodynamic, gravitational, and propulsion forces are evaluated.

The projectile equations of motion are subsequently integrated using a fourth-order Runge-Kutta (RK4) method to obtain the position, velocity, and rotational state at the next time step. The updated state becomes the starting point for the following iteration, and the process is repeated until the projectile reaches the ground. The resulting trajectory is then used to extract quantities of interest such as range, flight time, and impact velocity.

The aerodynamic coefficients obtained from the CFD analysis were incorporated into the modified point-mass solver to evaluate the influence of exhaust-plume effects on projectile performance. Three aerodynamic databases were considered:

- **PRODAS baseline:** 1100 trajectories using the reference drag coefficients from the PRODAS industrial software;
- **CFD no-plume:** 1100 trajectories using the drag coefficients from the CFD simulations of the unpropelled configuration (fine mesh solution);
- **CFD with plume:** 1100 trajectories using the drag coefficients from the CFD simulations of the propelled configuration (fine mesh solution).

A total of 3300 trajectories were generated, corresponding to 1100 launch elevations for each aerodynamic dataset. The elevation angle varied from 1 to 1100 mils in increments of 1 mil, covering the practical operating range of the projectile while maintaining the angular resolution typically used in artillery fire-control systems.

All sets of trajectories employed identical initial conditions, including muzzle velocity, projectile mass properties, atmospheric conditions, and launch azimuth. Since the objective of the present study is to quantify the influence of plume-induced drag variations, all aerodynamic coefficients, displayed in the Table 4, were obtained from the PRODAS database and kept unchanged throughout the analysis in all three cases, except drag, the first column. All other columns are used in the equations according to the model from the STANAG 4355 [11].

Table 4 Aerodynamic Coefficients generated by PRODAS [10].

Mach	CD ₀	CD ₂	CL _a	CL _{a3}	C _{ypa}	CL _p	CM _a	CM _{a3}
0.700	0.157	2.92	1.55	7.39	-0.77	-5.2	3.350	-4.0
0.800	0.158	3.02	1.55	7.14	-0.77	-5.2	3.500	-4.0
0.900	0.169	3.51	1.72	6.63	-0.86	-7.5	3.900	-4.0
0.950	0.209	5.76	1.81	6.27	-1.08	-9.9	4.200	-4.0
1.000	0.294	6.28	1.77	5.83	-0.99	-13.8	3.700	-4.0
1.050	0.332	6.86	1.82	5.34	-0.90	-13.4	3.500	-4.0
1.100	0.327	7.42	1.86	4.82	-0.86	-14.6	3.450	-4.0
1.200	0.314	7.96	1.90	4.32	-0.77	-15.8	3.400	-4.0
1.500	0.288	6.91	2.03	5.46	-0.77	-15.3	3.300	-4.0
2.000	0.246	5.99	2.26	6.56	-0.77	-15.3	3.100	-4.0
2.500	0.213	5.43	2.40	7.22	-0.77	-15.3	2.900	-4.0

For the CFD plume dataset, the drag coefficient was updated according to the motor operating condition. Prior to ignition, the projectile employed the drag coefficients obtained from the unpropelled CFD solution. At 7 s after launch, motor ignition was initiated and the plume-corrected drag coefficients were applied throughout the approximately 3 s burn period. After motor burnout, the drag coefficients reverted to the unpropelled values, reflecting the disappearance of the exhaust plume and the recovery of the base-flow structure.

This approach isolates the aerodynamic contribution of the exhaust plume from all other ballistic effects. Consequently, differences observed between the CFD plume and CFD no-plume trajectories can be directly attributed to the drag increase generated by plume-flow interaction during the powered phase.

3 Results

The mesh refinement study demonstrated consistent convergence for both the propelled and unpropelled configurations. The drag coefficient results for the unpropelled projectile are presented in Table 5 and Figure 4. As the mesh was refined, the numerical solution approached the PRODAS reference values over the entire Mach range, with the medium and fine meshes showing substantially smaller differences than the coarse mesh. This behavior indicates that the solution is generally within the asymptotic convergence range.

The corresponding GCI analysis confirms low discretization uncertainty for most operating conditions. For the unpropelled configuration, GCI values remained below 2% in nearly all cases, with only isolated transonic conditions exhibiting higher uncertainty.

Table 5 Results and GCI analysis for Drag Coefficient for the simulation without exhaust plume

Mach	Results			GCI Analysis			
	Coarse	Medium	Fine	Order of Convergence	Extrapol.	Error	GCI
0.70	0.175	0.158	0.157	4.760	0.157	0.004	0.02%
0.80	0.177	0.160	0.155	1.811	0.153	0.032	1.58%
0.90	0.192	0.177	0.175	2.734	0.175	0.012	0.27%
0.95	0.211	0.203	0.189	0.935	0.174	0.075	10.27%
1.00	0.362	0.347	0.340	1.039	0.333	0.022	2.56%
1.05	0.379	0.356	0.347	1.446	0.342	0.024	1.76%
1.10	0.376	0.348	0.342	2.148	0.340	0.019	0.68%
1.20	0.355	0.339	0.327	0.528	0.302	0.034	9.64%
1.50	0.315	0.300	0.295	1.406	0.291	0.019	1.43%
2.00	0.258	0.255	0.253	0.646	0.250	0.007	1.53%
2.50	0.224	0.216	0.215	3.390	0.215	0.004	0.05%

The anomalous behavior observed in Mach 0.95 and Mach 1.20 may be attributed to the strong nonlinear flow phenomena characteristic of the configuration, indicating that the asymptotic range was not fully reached for these points, requiring an even finer mesh or adaptive refinement to capture the unsteady flow structures.

A similar refinement study was performed for the propelled configuration (Table 6 and Figure 5). Although the subsonic cases exhibited higher uncertainty levels, convergence improved significantly above Mach 1.0, where most GCI values remained below 1%. These results indicate that the numerical methodology is sufficiently accurate to evaluate the aerodynamic influence of the exhaust plume on projectile performance.

The propulsion-related quantities showed even stronger convergence characteristics. Tables 7 indicate that Thrust remained nearly independent of mesh resolution, with GCI values close to 0.1% for all investigated Mach numbers. Consequently, the numerical uncertainty associated with the propulsion model is considered negligible compared with the aerodynamic uncertainties associated with the external flow.

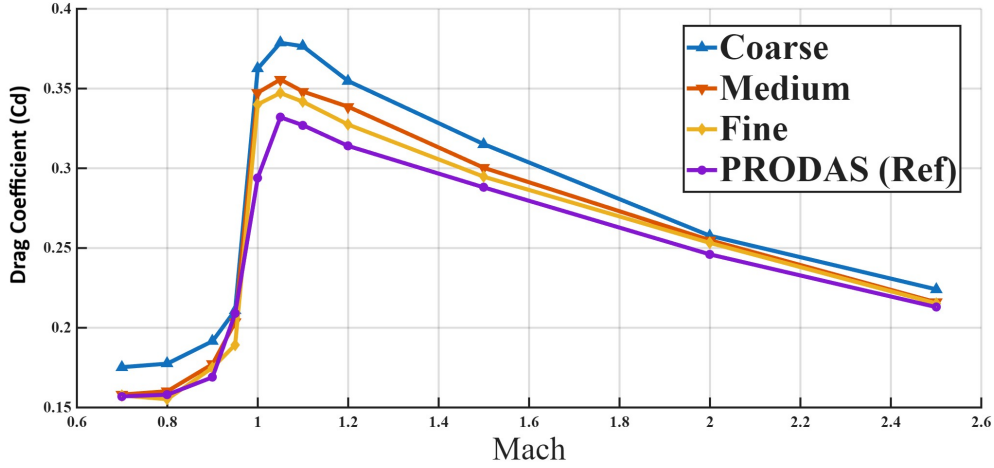


Fig. 4 Drag Coefficient curves resulting from the three meshes and the reference data

Table 6 Results and GCI analysis for Drag Coefficient for the simulation with exhaust plume

Mach	Results			GCI Analysis			
	Coarse	Medium	Fine	Order of convergence	Extrapolation	Error	GCI
0.70	0.4733	0.3711	0.3227	1.076	0.279	0.150	16.93%
0.80	0.4212	0.3349	0.3088	1.726	0.297	0.085	4.58%
0.90	0.3986	0.3326	0.3056	1.287	0.287	0.088	7.67%
0.95	0.4079	0.3588	0.3436	1.697	0.337	0.044	2.46%
1.00	0.6011	0.5627	0.5545	2.230	0.552	0.015	0.50%
1.05	0.5952	0.5681	0.5609	1.917	0.558	0.013	0.58%
1.10	0.5841	0.5505	0.5432	2.219	0.541	0.013	0.46%
1.20	0.5349	0.5250	0.5242	3.617	0.524	0.002	0.02%
1.50	0.4342	0.4374	0.4507	2.044	0.455	0.029	1.18%
2.00	0.3249	0.3252	0.3253	1.087	0.325	0.000	0.04%
2.50	0.2522	0.2484	0.2497	1.539	0.250	0.005	0.35%

The comparison between the drag coefficients obtained for the propelled and unpropelled configurations is shown in Figure 6. Across the entire Mach range, the presence of the exhaust plume increased the projectile drag coefficient substantially. The increase was particularly pronounced in the subsonic and transonic regimes, where the drag coefficient of the propelled configuration was approximately 70?90% higher than that of the baseline configuration.

As the Mach number increased, the difference between the two configurations progressively decreased. Although the plume remained present throughout the investigated range, its relative influence on the drag coefficient became less significant at higher flight velocities.

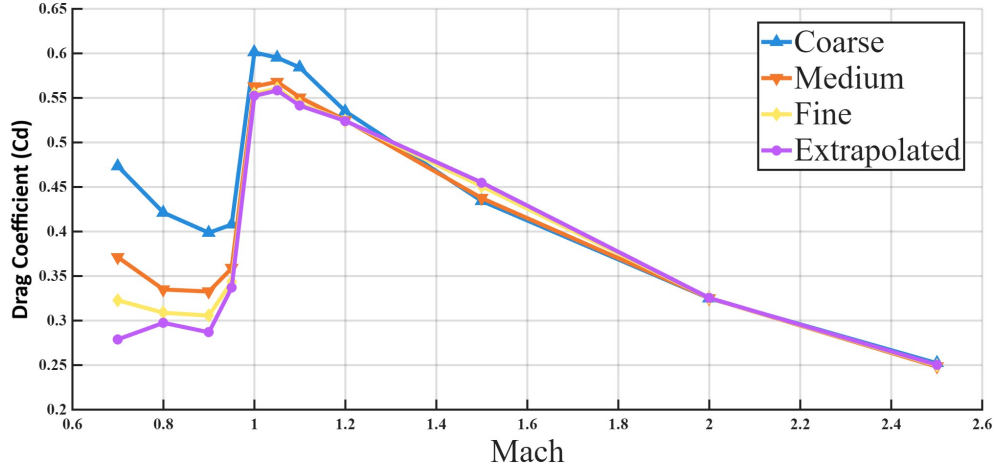


Fig. 5 Drag Coefficient curves resulting from the three meshes and the Extrapolated data

Table 7 Results and GCI analysis for the Thrust simulation

Mach	Results			GCI Analysis			
	Coarse	Medium	Fine	Order of convergence	Extrapolated	Error	GCI
0.70	2132.51	2134.19	2125.86	2.314	2123.77	0.004	0.12%
0.80	2132.59	2134.21	2126.67	2.223	2124.61	0.004	0.12%
0.90	2132.66	2134.25	2125.88	2.392	2123.92	0.004	0.12%
0.95	2132.69	2134.25	2124.95	2.568	2123.07	0.004	0.11%
1.00	2132.84	2134.25	2126.30	2.494	2124.59	0.004	0.10%
1.05	2132.83	2134.22	2124.67	2.778	2123.04	0.004	0.10%
1.10	2132.81	2134.17	2125.77	2.633	2124.16	0.004	0.09%
1.20	2132.79	2134.15	2126.57	2.481	2124.92	0.004	0.10%
1.50	2132.73	2134.19	2125.45	2.586	2123.70	0.004	0.10%
2.00	2132.76	2134.21	2126.27	2.449	2124.48	0.004	0.10%
2.50	2132.77	2134.23	2126.05	2.486	2124.27	0.004	0.10%

The pressure fields presented in Figures 7 to 10 provide insight into the physical mechanisms responsible for this behavior. For all investigated Mach numbers, the exhaust plume modifies the base-flow topology behind the projectile, reducing the pressure in the wake region and altering the recirculation structure. Compared with the unpropelled case, the plume produces a more compact wake and significantly changes the pressure distribution immediately behind the projectile.

The interaction between the exhaust gases and the external flow also alters the extent of the turbulent mixing region. The wake becomes noticeably shorter and more concentrated when propulsion is active, indicating a stronger coupling between the jet plume and the surrounding compressible flow.

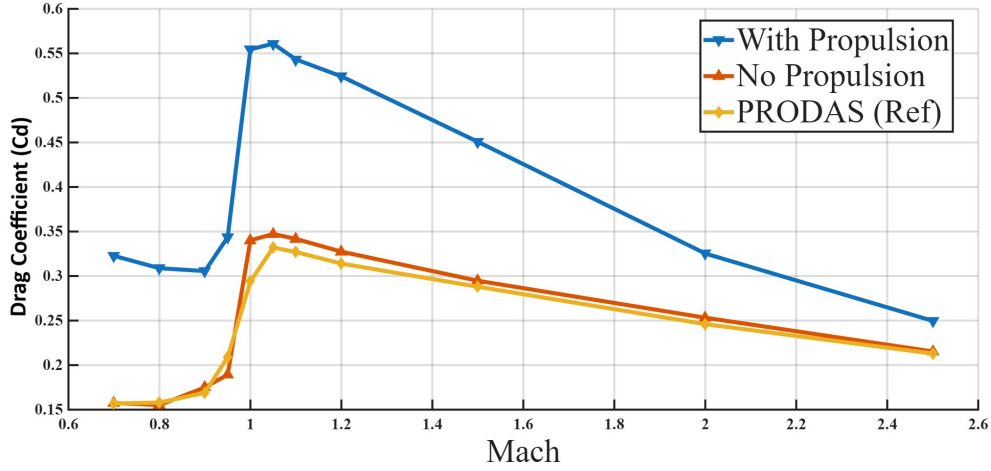


Fig. 6 Drag Coefficient curves resulting from the three meshes and the extrapolation for the simulation with exhaust plume

The reduction in drag difference observed at higher Mach numbers appears to be associated with the natural decrease in base pressure that already occurs in the unpropelled configuration. Without the exhaust, the pressure behind goes to barely below 1×10^5 for 0.7, to 8.5×10^4 for 1.0, to 6×10^4 for 1.5, and finally 4.5×10^4 for 2.5. With the exhaust, the pressure goes to from 9×10^4 for 0.7, to 6×10^4 for 1.0, to 3×10^4 for 1.5, and finally 1.5×10^4 for 2.5. Consequently, the additional pressure reduction produced by the plume represents a smaller relative change, causing the drag coefficients of the propelled and unpropelled configurations to move closer together.

Having established the numerical accuracy and convergence properties of the CFD simulations, this section evaluates the impact of the plume-induced aerodynamic modifications on the projectile trajectory. The aerodynamic databases obtained from CFD were incorporated into the modified point-mass trajectory model to quantify the ballistic consequences of the plume-induced drag increase. A total of 3300 trajectories were simulated, covering firing elevations between 1 and 1100 mils.

The median range values obtained for each elevation interval and standard deviation of the projectile are summarized in Table 8. For low-elevation trajectories up to 11.25° , the differences between the three aerodynamic datasets remain small because the projectile impacts the ground before motor ignition. As a result, plume-related aerodynamic effects have little opportunity to influence the flight.

From 11.30° onward, the differences become progressively larger. The trajectories generated using the CFD coefficients without plume effects remain relatively close to the PRODAS predictions, indicating that the aerodynamic discrepancies between the two datasets have only a limited influence on overall ballistic performance.

In contrast, the inclusion of plume effects produces a systematic reduction in projectile range. The range loss increases with elevation angle and approaches approximately 700 m in the highest firing intervals analyzed. However, the divergence tends

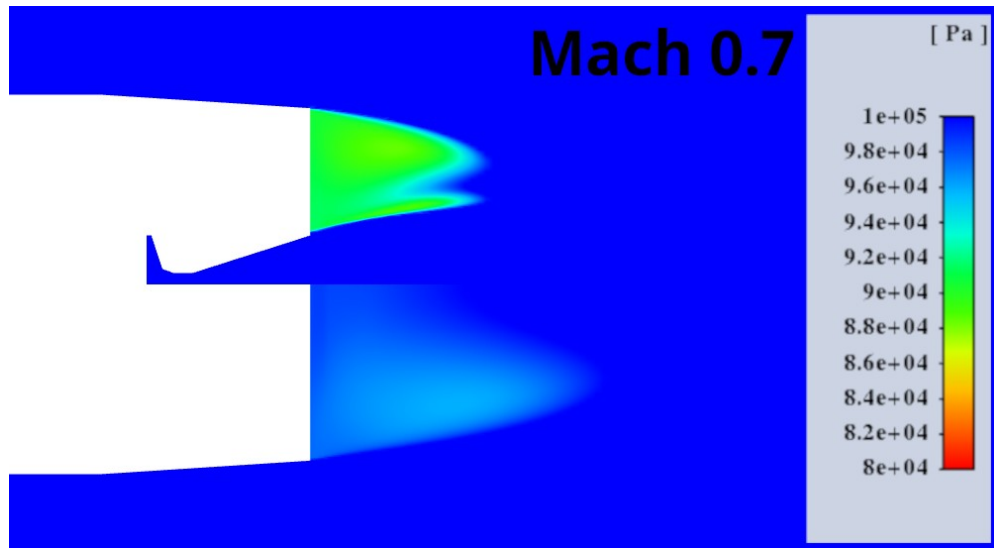


Fig. 7 Pressure field for the simulation with exhaust (upper side) and without (lower side) for Mach number equal to 0.7.

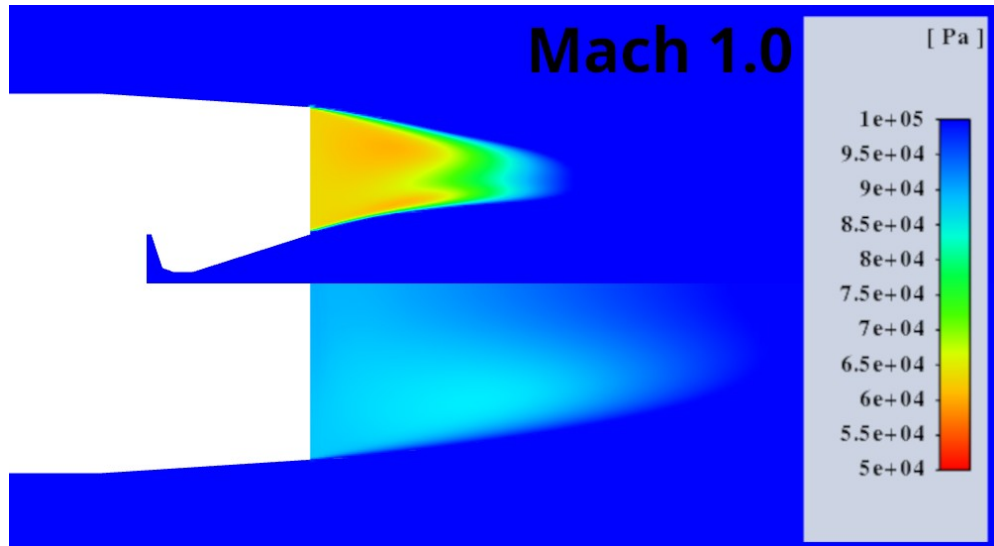


Fig. 8 Pressure field for the simulation with exhaust (upper side) and without (lower side) for Mach number equal to 1.0.

to stabilize at elevations higher than 39.43° , indicating that the additional drag generated during the propulsion phase accumulates primarily during motor operation. After

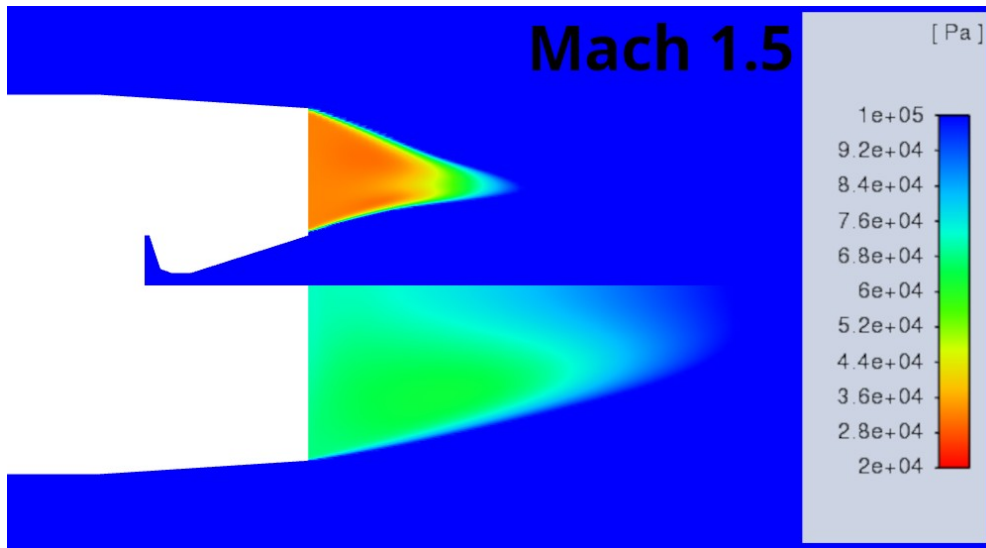


Fig. 9 Pressure field for the simulation with exhaust (upper side) and without (lower side) for Mach number equal to 1.5.

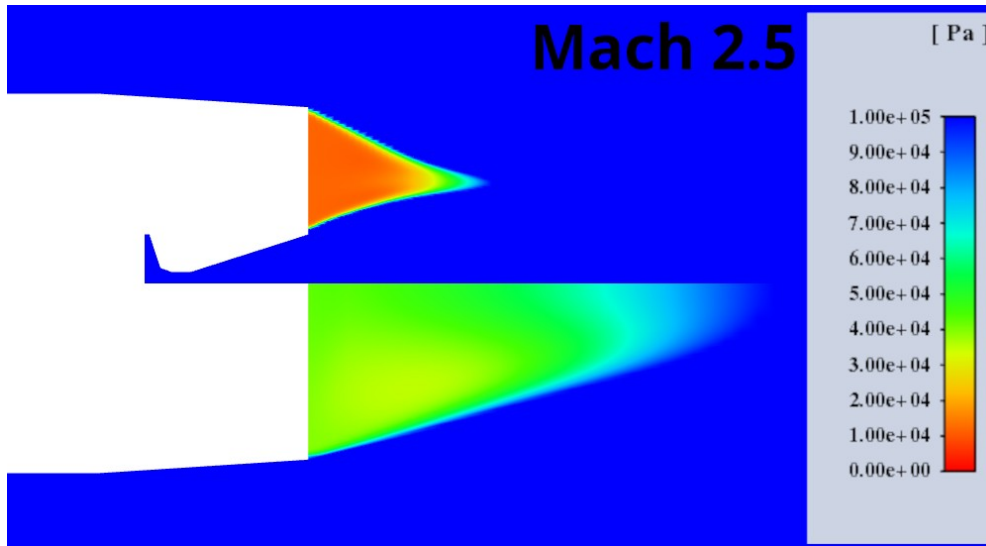


Fig. 10 Pressure field for the simulation with exhaust (upper side) and without (lower side) for Mach number equal to 2.5.

burnout, all trajectories experience nearly identical aerodynamic conditions, causing the range difference to approach a nearly constant value.

Table 8 Median range values and standard deviation for each elevation interval

Elevation Range (°)	Median Range Values (m)			Standard Deviation (m)		
	Sim. with PRODAS	Sim. with no Plume	Sim. with Plume	Sim. with PRODAS	Sim. with no Plume	Sim. with Plume
0.06-5.62	2720.43	2709.17	2706.84	1435.29	1426.29	1423.07
5.68-11.25	7372.52	7307.33	7155.26	1299.70	1279.72	1197.05
11.30-16.87	11191.29	11052.36	10658.37	919.91	898.84	848.30
16.93-22.5	13929.15	13735.32	13219.62	691.01	679.41	654.81
22.55-28.12	16065.04	15838.29	15254.72	554.93	546.60	530.74
28.18-33.75	17784.76	17529.50	16897.06	444.54	436.23	423.50
33.80-39.37	19123.88	18839.06	18166.35	331.06	323.03	312.15
39.43-45.00	20036.00	19728.20	19023.69	196.00	190.81	183.37
45.05-50.62	20431.34	20112.92	19389.49	38.04	37.40	34.00
50.68-56.25	20193.39	19873.33	19135.36	176.08	177.71	178.60
56.30-61.87	19196.37	18869.38	18143.71	409.18	410.61	402.27

This behavior is illustrated in Figures 11 and 12. The impact-point distribution shows that trajectory divergence begins shortly after motor ignition and increases progressively during the powered phase. Similarly, the velocity history demonstrates that the plume case experiences greater velocity loss while the motor is operating. After burnout, the velocity decay rates become nearly identical, confirming that the primary source of ballistic divergence is the drag increase associated with plume-flow interaction.

The range-dispersion results presented in Table 8 exhibit the same overall trend for all aerodynamic datasets. The standard deviation decreases with elevation angle until reaching a minimum near the optimum ballistic range and subsequently increases again for high-angle trajectories. Although the plume case generally presents slightly lower standard deviation values, this behavior is primarily a consequence of the reduced projectile range rather than an indication of improved ballistic stability. Since the plume produces shorter trajectories, the spacing between neighboring impact points is also reduced, naturally leading to lower absolute dispersion values.

Overall, the results demonstrate that the exhaust plume introduces a significant aerodynamic penalty during the powered phase of flight. While the propulsion system increases projectile energy, the associated modification of the base flow produces a substantial drag increase that partially offsets the expected ballistic gains. Therefore, accurate prediction of plume-induced aerodynamic effects appears essential for realistic performance assessment and trajectory prediction of rocket-assisted artillery projectiles.

4 Conclusion

This study evaluated the aerodynamic and ballistic effects of the exhaust plume of a 155 mm Rocket-Assisted Projectile using a coupled CFD and modified point-mass trajectory framework. The numerical methodology showed satisfactory convergence and

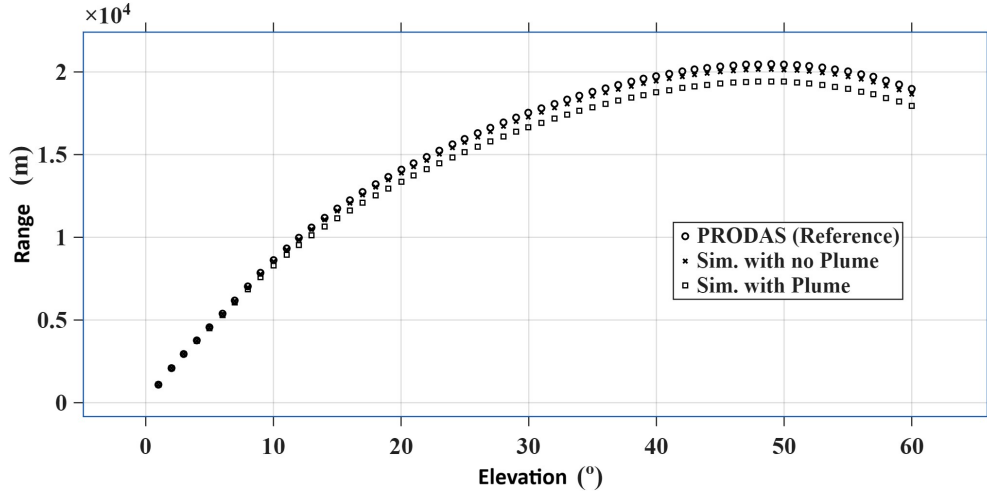


Fig. 11 Impact points for selected elevation angles between 1 °and 60 °, showing the progressive divergence caused by plume effects.

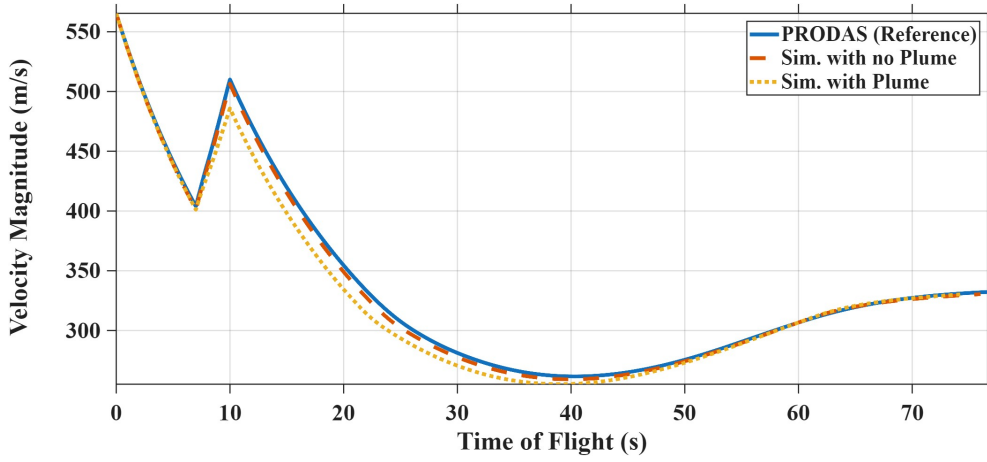


Fig. 12 Velocity magnitude as a function of time for the trajectory fired at 48°(853 mils).

good agreement with PRODAS reference data, supporting its use for the investigation of plume-flow interactions in artillery projectiles.

The results demonstrated that the exhaust plume significantly modifies the base-flow region, reducing base pressure and increasing aerodynamic drag throughout the investigated Mach range. The drag increase was most pronounced in the subsonic and transonic regimes, where the propelled configuration exhibited drag coefficients up to 90% higher than the corresponding unpropelled configuration. As the Mach number

increased, the relative influence of the plume decreased due to the naturally lower base pressure associated with high-speed flight.

When incorporated into the ballistic model, these aerodynamic differences produced measurable reductions in projectile range. For low-elevation trajectories, the plume had little influence because impact occurred before motor ignition. For higher firing angles, however, the additional drag generated during the propulsion phase accumulated throughout the flight, producing range reductions of up to approximately 720 m under the conditions investigated.

The results indicate that neglecting plume-induced drag may lead to an over-estimation of the ballistic performance of rocket-assisted projectiles. Therefore, the interaction between the exhaust plume and the external flow should be considered during aerodynamic characterization, trajectory prediction, and propulsion-system design. The proposed CFD-ballistic framework provides a practical tool for assessing these effects and may support future optimization studies involving nozzle geometry, ignition timing, and motor operating conditions.

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Declarations

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Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

Not applicable. This manuscript does not contain any individual person’s data in any form (including individual details, images, or videos).

Data availability

The data that support the findings of this study are not publicly available due to restrictions imposed by the Brazilian Army and/or the Instituto Militar de Engenharia

(IME) regarding the confidentiality of sensitive information. Data are available from the corresponding author upon reasonable request and with permission of the IME.

Materials availability

Not applicable. No new materials were developed or used in this study beyond those described in the methodology.

Code availability

The custom code developed for this study is not publicly available due to institutional restrictions. It is available from the corresponding author upon reasonable request and with permission of the Instituto Militar de Engenharia (IME).

Clinical trial registration

Not applicable. This study does not involve human participants or animals, is not a clinical trial, and therefore does not require clinical trial registration.

Author contribution

L.G.A. designed the methodology, performed the investigation, analyzed the data, and wrote the original draft. V.S.S. and A.L.T.R. were responsible for the initial conceptualization and delineation of the research scope, providing the overarching framework that guided the entire study. They also provided continuous scientific supervision, critically evaluated the intermediate findings, and rigorously revised the manuscript to enhance its theoretical and logical coherence. All authors reviewed and approved the final version and agree to be accountable for all aspects of the work.

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