CFD Analyses of the Aerodynamic Characteristics of a 30 mm AP-T Projectile

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***Abstract*—The present study is based on CFD (Computational Fluid Dynamics) numerical simulation of the aerodynamic characteristics (Drag Coefficient - C_D and the position of Centre of Pressure - CoP) for two geometrical configurations of a 30mm AP-T projectile. The differences between configurations appear at the nose of the ballistic cap, where for the first configuration a square geometry was proposed and for the second one a rounded shape. Numerical simulations were performed in Solid Work's Flow Simulation Module, with the main purpose of comparing the aerodynamic performances of both configurations and choosing the best geometrical shape from the proposed forms of ballistic caps.**

***Index Terms*—AP-T, CFD, projectile, Drag Coefficient, Center of Pressure.**

I. Introduction

A projectile moving in the air on its trajectory performs a general movement (with six degrees of freedom) which is composed of:

- a translational movement that is created by the variations of the three coordinates of the center of mass;
- a rotational movement of the body around the center of mass which is generated by the variation of three angles that define the orientation of the projectile towards a fixed point.

Due to the interaction with the fluid environment, the projectile is subjected on its path to the action of aerodynamic forces and torques. The aerodynamic forces have a predominant effect in breaking the projectile movement and at the same time they tend to move the projectile in a normal direction to the trajectory. Aerodynamic torques are continuously changing the motion of the projectile around the center of mass along the trajectory. [1]

The aerodynamic forces and torques depend, among other things, on the speed of the center of mass of the projectile and on the orientation of its axis in relation to the tangent to the trajectory. [2]

The behavior of air around a projectile depends on the speed of the air flow, the geometric characteristics and the orientation of the projectile towards the air stream.

Flowing around the projectile, the air current changes its speed and thermodynamic parameters. Thus, the change in velocity entails the change in pressure, and under certain conditions, significant variations in air density and temperature may occur if the air velocity increases above certain values. [1] Also, due to the relative motion between the body and the gas, an aerodynamic force is exerted by the air on the projectile. The aerodynamic force is composed by two elements: [3]

- the normal force due to the pressure on the surface of the body;
- the shear force due to the viscosity of the gas, also known as skin friction.

Pressure acts normal to the surface, and shear force acts parallel to the surface. Both forces act locally. The net aerodynamic force on the body is equal to the pressure and shear forces integrated over the body's total exposed area [4].

This aerodynamic force is commonly resolved into two components, both acting through the center of pressure: [5]

- drag is the force component parallel to the direction of relative motion;
- lift is the force component perpendicular to the direction of relative motion.

A number of CFD numerical simulations are conducted in order to investigate the differences between two configurations of 30 mm armor-piercing projectiles in terms of essential aerodynamic characteristics such as the value of the drag coefficient (C_D) and the location of the center of pressure (CoP) on the longitudinal axis of the projectile. For this paper, the CFD analyzes are implemented in Solid Work's Flow Simulation Module. This approach simplifies the determination of coefficients that classic literature usually either refers to tabulated data, or requires a significant number of experimental firings.

Although the mathematical models used in CFD numerical simulations are quite complex and continuously improving, they could deliver only a simple conclusion over a phenomenon and not a completely reliable solution. Based on this, the most reliable method of establishing the necessary projectiles aerodynamic characteristics in order to describe with exactitude the flight trajectories is still by empirical measurement.

II. Projectiles CAD Configuration

The 3D models of projectiles used for simulation in this study are made in SolidWorks CAD software. Two projectiles with different ballistic cap geometrical configurations are chosen for this study and they are presented in longitudinal section view as it follows:

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- Projectile equipped with square nose ballistic CAP (Fig. 1);

Figure 1. CAD model for projectile equipped with square nose ballistic CAP (section view)

- Projectile equipped with round nose ballistic cap (Fig. 2);

Figure 2. CAD model for projectile equipped with round nose ballistic cap (section view)

Both 30 mm armor-piercing projectiles models are designed in such manner that the only significant difference is the nose shape of the ballistic cap. The general characteristics for both forms of projectiles used in simulations are described in Table I.

TABLE I. GENERAL CHARACTERISTICS OF PROJECTILES

Characteristic	Value
Caliber	30 mm
Maximum Cross Section Diameter	31.10 mm
Length	140.50 mm
Mass	405 g
Type	AP-T
Muzzle velocity	890 m/s

III. DRAG COEFFICIENT (C_D) CFD SIMULATION SET-UP

In fluid dynamics, drag (sometimes called air resistance, a type of friction, or fluid resistance, another type of friction or fluid friction) is a vector oriented by the tangent to the trajectory in the opposite direction to the velocity vector of the center of mass of the projectile (in the opposite direction to the movement of the projectile). The effect of the resistance over the movement is to decrease the speed of the projectile and, implicitly, to increase the curvature of the trajectory.

In aerodynamics, the drag force (R) is expressed with (1), where ρ is the mass density of the fluid, V is the projectile center of mass velocity relative to fluid, S is the reference area (usually the maximum value of cross section of the projectile) and C_D is the drag coefficient – a dimensionless coefficient related to the object's geometry and taking into account both skin friction and form drag [4]

$$R = \frac{1}{2}\rho v^2 S C_D. \qquad (1)$$

The simulations consist in two Solid Work's Flow Simulation CFD on which the presented geometrical forms are analyzed. The main objective of these simulations is to study the values of the drag coefficient (C_D) and its variation depending on the change of the fluid's Mach number.

A. *CFD analysis of C_D for projectile equipped with square nose ballistic cap*

The CFD drag coefficient (C_D) simulation geometry for projectile equipped with square nose ballistic cap is presented in Fig. 3. For this analysis was used the CAD model of projectile presented in Fig. 1.

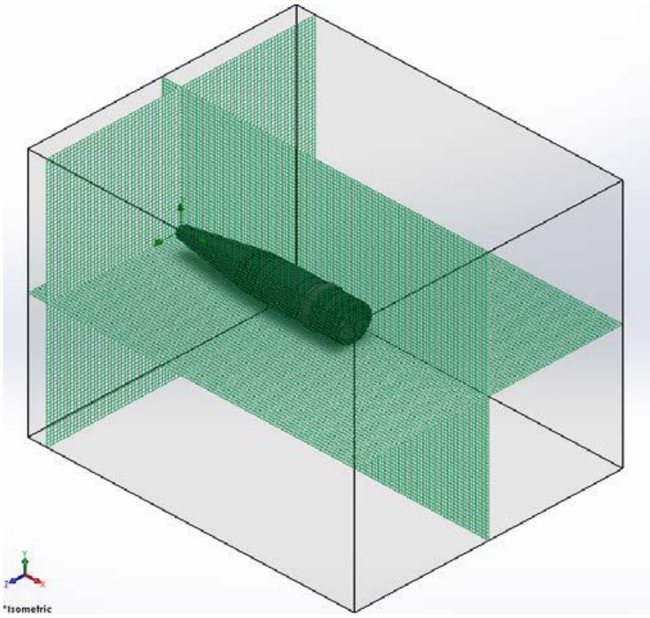

Figure 3. Discretization in finite elements of the computational domain for C_D analysis – square nose ballistic cap

In Table II are presented the Simulation settings and characteristics.

TABLE II. CHARACTERISTICS OF C_D SIMULATION - SQUARE NOSE BALLISTIC CAP CONFIGURATION

Characteristic	Value
Number of cells	X: 160
	Y: 80
	Z: 80
Total Number of Cells	1.024.000
Dimensions of computational domain	400×200×200 mm
Type of fluid	Air
Analyses type	External with excluded internal space
Thermodynamic parameters	Pressure: 101325 Pa
	Temperature: 20°C
Angle of attack	0°
Air density	1.2047 kg/m^3
Type of study	Parametric – 11 Scenarios
Simulation parameter	Velocity in X direction

B. *CFD analysis of C_D for projectile equipped with round nose ballistic cap*

The CFD drag coefficient (C_D) simulation geometry for projectile equipped with round nose ballistic cap is presented in Fig. 4. For this analysis was used the CAD model of projectile presented in Fig. 2.

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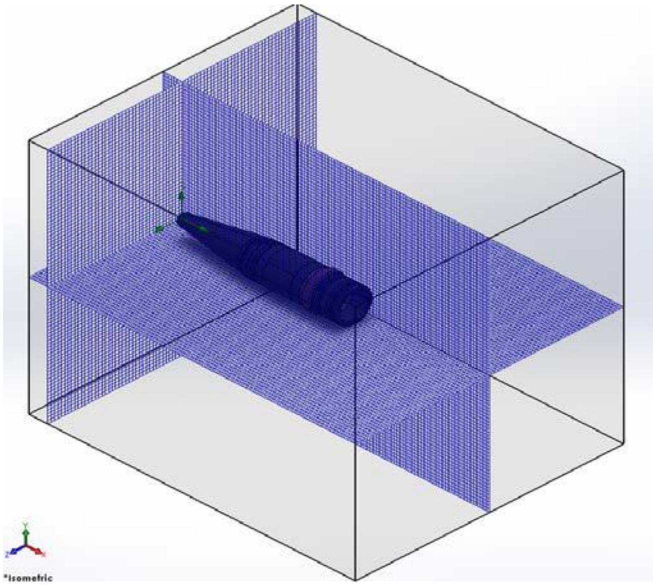

Figure 4. Discretization in finite elements of the computational domain for C_D analysis – round nose ballistic cap

In Table III are presented the Simulation settings and characteristics.

TABLE III. CHARACTERISTICS OF C_D SIMULATION - ROUND NOSE BALLISTIC CAP CONFIGURATION

Characteristic	Value
Number of cells	X: 160
	Y: 80
	Z: 80
Total Number of Cells	1.024.000
Dimensions of computational domain	400×200×200 mm
Type of fluid	Air
Analyses type	External with excluded internal space
Thermodynamic parameters	Pressure: 101325 Pa
	Temperature: 20°C
Angle of attack	0°
Air density	1.2047 kg/m^3
Type of study	Parametric – 11 Scenarios
Simulation parameter	Velocity in X direction

IV. CENTER OF PRESSURE (COP) CFD SIMULATION SET-UP

According to [6] the center of pressure is the point where the total sum of a pressure field acts on a body, causing a force to act through that point. The total force vector acting at the center of pressure is the value of the integrated vectorial pressure field. The resultant force and center of pressure location produce equivalent force and moment on the body as the original pressure field. Pressure fields occur in both static and dynamic fluid mechanics. Specification of the center of pressure, the reference point from which the center of pressure is referenced, and the associated force vector allows the moment generated about any point to be computed by a translation from the reference point to the desired new point. It is common for the center of pressure to be located on the body, but in fluid flows it is possible for the pressure field to exert a moment on the object of such magnitude that the center of pressure is located outside the shape of the body.

Determining the center of pressure (CoP) is a very difficult practice for the reason that the fluid's pressure changes around the exterior of projectile. In order to determine the center of pressure the use of calculus and information is required, regarding the pressure distribution around the body.

There are a few simplified methods to calculate the location of Center of Pressure in static mode, but they do not reflect the real phenomena because it does not include the distribution of pressure around the projectile. In order to obtain a more precise solution for the location of CoP, a CFD simulation is used.

The simulations consist in two Solid Work's Flow Simulation CFD analyses on which the presented geometrical forms (Fig. 1 and Fig. 2) are analyzed. The main objective of these simulations is to study the values of the position of Center of Pressure (CoP) and its variation depending on the change of the fluid's Mach number.

A. CFD analysis of CoP for projectile equipped with square nose ballistic cap

The CFD Center of Pressure (CoP) simulation geometry for projectile equipped with square nose ballistic cap is presented in Fig. 5. For this analysis was used the CAD model of projectile presented in Fig. 1.

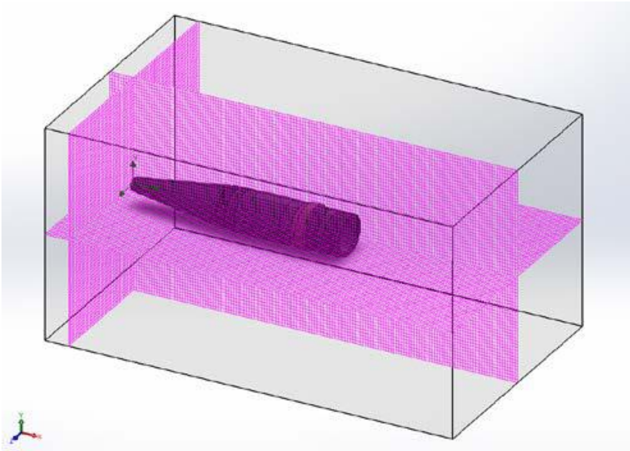

Figure 5. Discretization in finite elements of the computational domain for CoP analysis – square nose ballistic cap

In Table IV are presented the Simulation settings and characteristics.

TABLE IV. CHARACTERISTICS OF COP SIMULATION - SQUARE NOSE BALLISTIC CAP CONFIGURATION

Characteristic	Value
Number of cells	X: 170
	Y: 66
	Z: 66
Total Number of Cells	740.520
Dimensions of computational domain	450×180×180 mm
Type of fluid	Air
Analyses type	External with excluded internal space
Thermodynamic parameters	Pressure: 101325 Pa
	Temperature: 20°C
Angle of attack	2.5°
Air density	1.2047 kg/m^3
Type of study	Parametric – 11 Simulation Design Points
Simulation parameter	Velocity in X direction

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B. CFD analysis of CoP for projectile equipped with round nose ballistic cap

The CFD Center of Pressure (CoP) simulation geometry for projectile equipped with square nose ballistic cap is presented in Fig. 6. For this analysis was used the CAD model of projectile presented in Fig. 2.

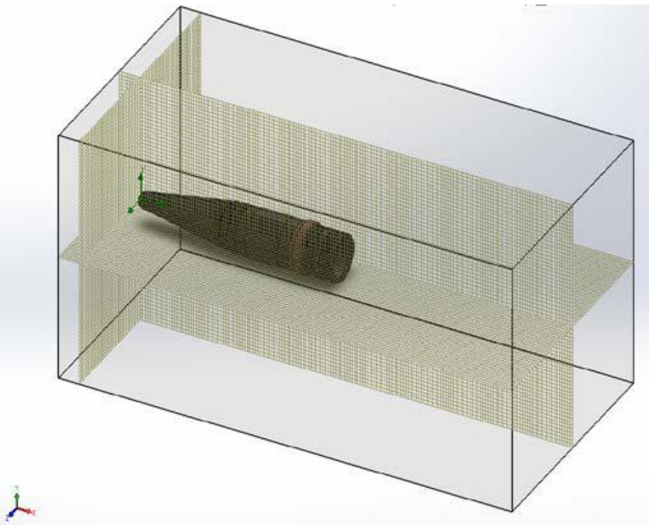

Figure 6. Discretization in finite elements of the computational domain for CoP analysis – round nose ballistic cap

In Table V are presented the Simulation settings and characteristics.

TABLE V. CHARACTERISTICS OF COP SIMULATION - ROUND NOSE BALLISTIC CAP CONFIGURATION

Characteristic	Value
Number of cells	X: 170
	Y: 66
	Z: 66
Total Number of Cells	740.520
Dimensions of computational domain	450×180×180 mm
Type of fluid	Air
Analyses type	External with excluded internal space
Thermodynamic parameters	Pressure: 101325 Pa
	Temperature: 20°C
Angle of attack	2.5°
Air density	1.2047 kg/m^3
Type of study	Parametric – 11 Simulation Design Points
Simulation parameter	Velocity in X direction

V. C_D SIMULATIONS RESULTS

A. Results of C_D CFD analysis for projectile equipped with square nose ballistic cap

In Table VI are presented the C_D CFD analysis results for projectile equipped with square nose ballistic cap.

TABLE VI. C_D CFD ANALYSIS RESULTS FOR PROJECTILE EQUIPPED WITH SQUARE NOSE BALLISTIC CAP

Simulation Design Point	Fluid Velocity (m/s)	Mach Number	C_D
1	65	0,189	0,220
2	126	0.367	0.229
3	248	0.723	0.252
4	343	1	0.277
5	425	1.239	0.405
6	499	1.454	0.437
7	568	1.655	0.367
8	686	2	0.329
9	743	2.166	0.319
10	810	2.361	0.309
11	890	2.594	0.301

In Fig. 7 is presented the evolution of the drag coefficient C_D over the variation of Mach number for the projectile equipped with square nose ballistic cap.

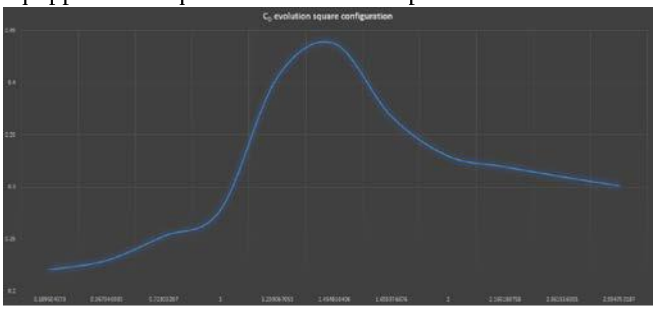

Figure 7. Drag coefficient evolution on variation of Mach number for the projectile equipped with square nose ballistic cap

In Fig. 8 is presented the distribution of pressure around the projectile equipped with square nose ballistic cap at Mach number value of 2.594.

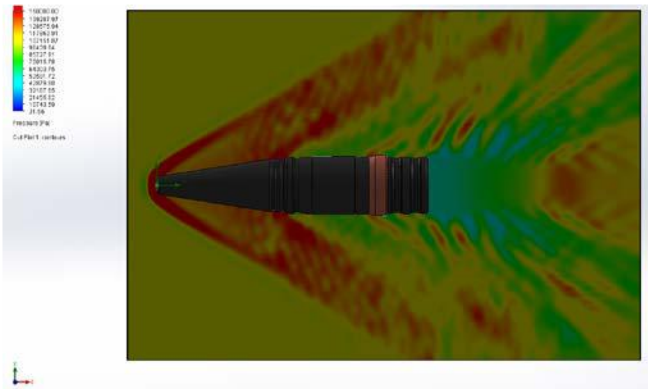

Figure 8. Distribution of pressure around the projectile equipped with square nose ballistic cap at Mach number value of 2.594

In Fig. 9 is presented the distribution of Mach number around the projectile equipped with square nose ballistic cap at Mach number value of 2.594.

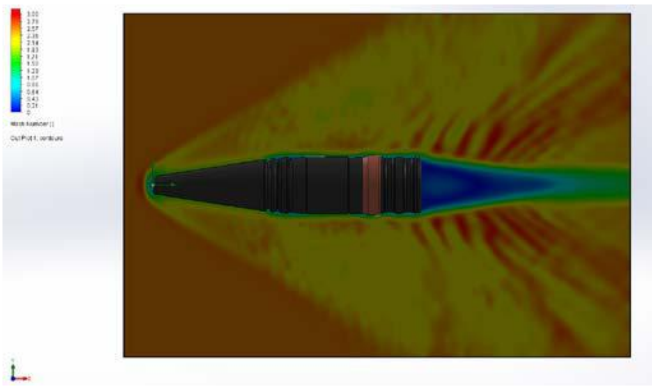

Figure 9. Distribution of Mach number around the projectile equipped with square nose ballistic cap at Mach number value of 2.594

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B. Results of C_D CFD analysis for projectile equipped with round nose ballistic cap

In Table VII are presented the C_D CFD analysis results for projectile equipped with round nose ballistic cap.

TABLE VII. C_D CFD ANALYSIS RESULTS FOR PROJECTILE EQUIPPED WITH ROUND NOSE BALLISTIC CAP

Simulation Design Point	Fluid Velocity (m/s)	Mach Number	C_D
1	65	0,189	0,205
2	126	0.367	0.215
3	248	0.723	0.237
4	343	1	0.265
5	425	1.239	0.418
6	499	1.454	0.391
7	568	1.655	0.380
8	686	2	0.349
9	743	2.166	0.329
10	810	2.361	0.306
11	890	2.594	0.283

In Fig. 10 is presented the evolution of the drag coefficient C_D over the variation of Mach number for the projectile equipped with round nose ballistic cap.

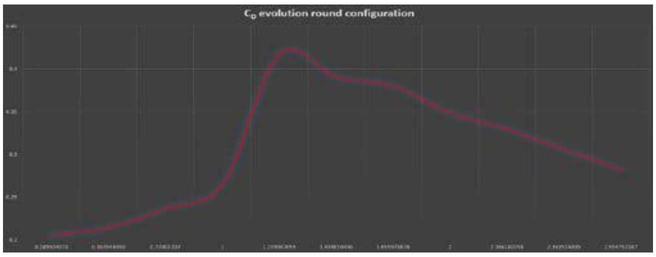

Figure 10. Drag coefficient evolution on variation of Mach number for the projectile equipped with round nose ballistic cap

In Fig. 11 is presented the distribution of pressure around the projectile equipped with round nose ballistic cap at Mach number value of 2.594.

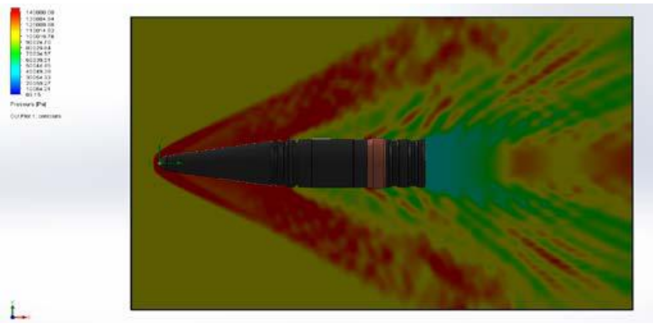

Figure 11. Distribution of pressure around the projectile equipped with round nose ballistic cap at Mach number value of 2.594

In Fig. 12 is presented the distribution of Mach number around the projectile equipped with round nose ballistic cap at Mach number value of 2.594.

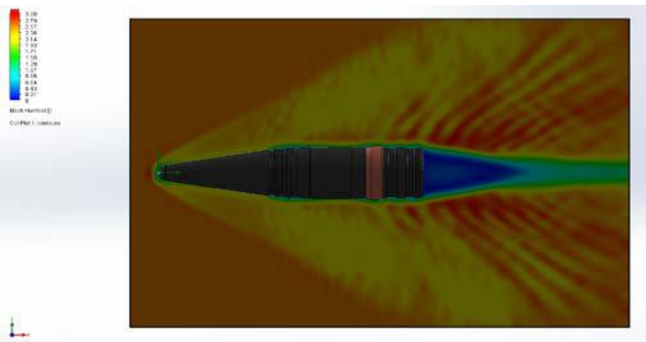

Figure 12. Distribution of Mach number around the projectile equipped with round nose ballistic cap at Mach number value of 2.594

VI. COP SIMULATIONS RESULTS

A. Results of CoP CFD analysis for projectile equipped with square nose ballistic cap

In Table VIII are presented the CoP CFD analysis results for projectile equipped with square nose ballistic cap.

TABLE VIII. COP CFD ANALYSIS RESULTS FOR PROJECTILE EQUIPPED WITH SQUARE NOSE BALLISTIC CAP

Simulation Design Point	Fluid Velocity (m/s)	Mach Number	CoP (mm)
1	65	0,189	57,797
2	126	0.367	59.381
3	248	0.723	58.033
4	343	1	40.899
5	425	1.239	80.860
6	499	1.454	62.128
7	568	1.655	61.214
8	686	2	62.347
9	743	2.166	61.978
10	810	2.361	65.960
11	890	2.594	68.331

In Fig. 13 is presented the evolution of the position of CoP over the variation of Mach number for the projectile equipped with square nose ballistic cap.

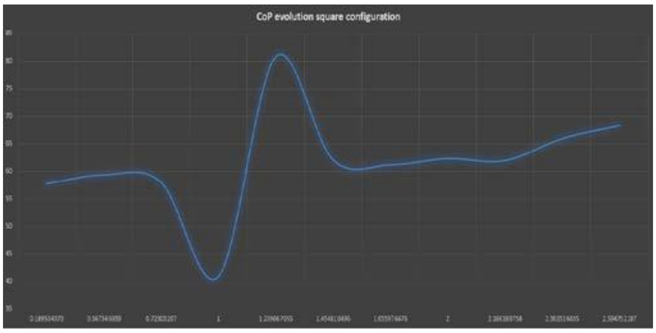

Figure 13. Center of Pressure position evolution on variation of Mach number for the projectile equipped with square nose ballistic cap

B. Results of CoP CFD analysis for projectile equipped with round nose ballistic cap

In Table IX are presented the CoP CFD analysis results for projectile equipped with round nose ballistic cap.

TABLE IX. COP CFD ANALYSIS RESULTS FOR PROJECTILE EQUIPPED WITH ROUND NOSE BALLISTIC CAP

Simulation Design Point	Fluid Velocity (m/s)	Mach Number	CoP (mm)
1	65	0,189	59.149
2	126	0.367	61.814
3	248	0.723	59.315
4	343	1	41.508
5	425	1.239	83.609
6	499	1.454	62.912
7	568	1.655	62.762
8	686	2	62.431
9	743	2.166	66.078
10	810	2.361	66.879
11	890	2.594	62.645

In Fig. 14 is presented the evolution of the position of CoP over the variation of Mach number for the projectile equipped with round nose ballistic cap.

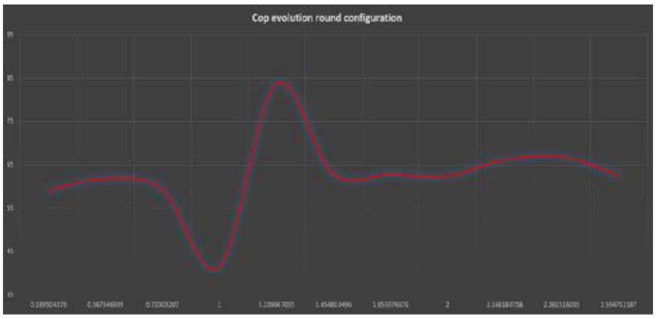

Figure 14. Center of Pressure position evolution on variation of Mach number for the projectile equipped with round nose ballistic cap

VII. CONCLUSION

After analyzing the data obtained from the CFD simulations, it is pointed out that the drag coefficient and the location of center of pressure are influenced by the geometrical configuration of the projectile.

The obtained results are presented in Table X.

TABLE X. OBTAINED RESULTS OF THE CFD SIMULATIONS

Characteristic	**Square nose geometry**	**Round nose geometry**
C_D min	0.220	0.205
C_D max	0.437	0.391
Average C_D	0.313	0.307
CoP min	40,899 mm	41,508 mm
Cop max	68,331 mm	66,879 mm
Average CoP	64.721 mm	62.646 mm
Coefficient of static stability min	9.3594%	6.277%
Coefficient of static stability max	54.153%	53,570%

Fig. 15 presents the variations of the drag coefficient over the Mach number for the studied projectiles configurations.

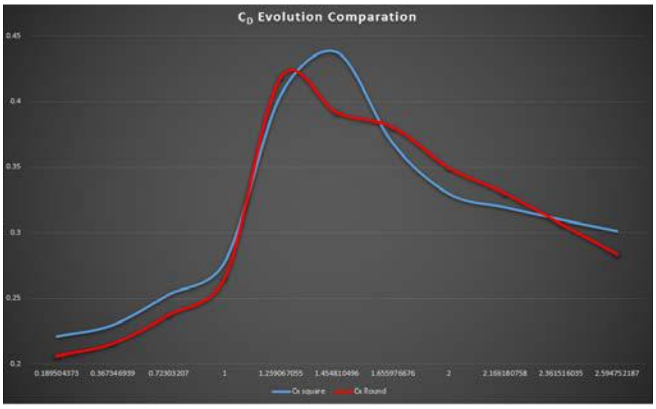

Figure 15. Variation of the drag coefficient for the studied projectile configurations

Fig. 16 presents the variations of the Center of Pressure over the Mach Number for the studied projectiles configurations.

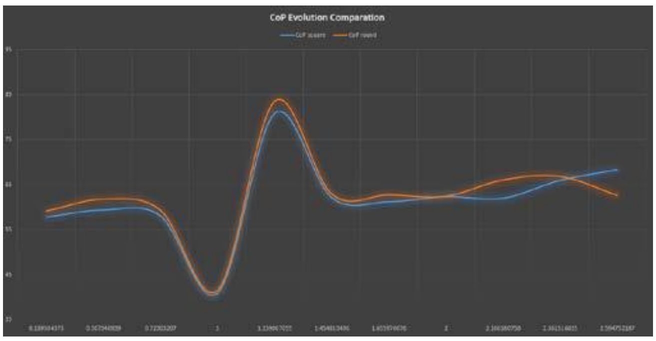

Figure 16. Variation of the Center of Pressure for the studied projectile configurations

Based on detailed investigations, the following conclusions can be drawn:

- The evolution of drag coefficient was analyzed for two different configurations of ballistic cap (square nose and round nose) at Mach values varying from 0.189 to 2.594.
- As it was presented in Table X and Fig. 15, the projectile with the round nose ballistic cap configuration performed slightly better. A projectile with a round nose ballistic cap will have to overcome a lower drag during its flight on the trajectory.
- For the studied configurations of projectiles, the position of Center of Pressure was analyzed at Mach values varying from 0.189 to 2.594.
- As it was presented in Table X and Fig. 16, the values of the Coefficient of static stability varies in a large scale (9% - 54% and 6% - 53%) while the recommended values are between 10% and 20%. Although, the values for CoP are placed in front of the position of Center of Mass on the longitudinal axes of the projectile.
- The results obtained in these CFD analyses represent a good start and they should be continued with real experiments in the wind tunnel.

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