COMPUTATIONAL ANALYSIS OF AERODYNAMIC PARAMETERS FOR SUPERSONIC ARTILLERY PROJECTILES

MD RAFIQUR RAHMAN

DEPARTMENT OF MECHANICAL ENGINEERING , MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY, MIRPUR CANTONMENT, DHAKA, BANGLADESH

ABSTRACT

Aerodynamic parameters have a huge impact on the trajectory of a projectile which in turn results in its range and accuracy. The influence aerodynamic parameters for the estimation of trajectory elements are drag Coefficients, lift Coefficients, angles of attack, muzzle velocity, atmospheric conditions, and the projectile shape and size. Thus proper methods for determining the drag and lift forces of the projectile is very important. The trajectory of a projectile through the air is affected both by gravity and by aerodynamic forces. In this paper 57 mm and 37 mm anti aircraft projectile was considered for the analysis. Here main emphasis was given to determine pressure coefficient, Drag coefficients, lift coefficient of the projectiles at different angle of attack. To study the aerodynamic parameters the experiment was conducted in an open circuit subsonic wind tunnel where uniform flow velocity is maintained across the flow direction. For the experiment varied angles of the attack was considered. Here inclined manometer was used to find out the surface static pressure and the pressure coefficient was determined from that. Then the drag & lift forces and their coefficients was determined. Finally, for the computational analysis, the ANSYS Software was used to simulate the experimental data.

KEYWORDS

Aerodynamic Parameters, Projectile, Drag Force, Lift Force, Pressure Coefficient, Drag Coefficient, Lift Coefficient, Angle of Attack, Computational analysis, Ansys software,

1. INTRODUCTION

Accurate experimental methods for determining the aerodynamic parameters of the projectile is very important. In modern warfare, the design of the projectiles is largely focused on its range and accuracy. Aerodynamics forces have a huge impact on the trajectory of a projectile. The influence Parameters for the estimation of trajectory elements are drag Coefficients, lift Coefficients, angles of attack, muzzle velocity, atmospheric conditions, and the projectile shape and size. When a projectile is launched it experiences some aerodynamic parameters which is more than the gravitational force. These parameters depend on the angles of attack, the nose shape, velocity, and surface smoothness of the projectile. However, the drag experienced by a single projectile will be different from the drag force experienced by two projectiles flying side by side since the disturbance created in the flow field by one projectile will affect the other one. These parameters are the prime reason for reducing projectile velocity and accuracy. Therefore, it is very important to determine and minimize the effect of drag and lift .

In this paper both experimental and computational analysis are done on projectiles. Here good agreements between computational analysis and experimental observations are obtained where the coefficient of drag and lift are obtained at different speed and different angle of attack. We have considered two different types of Projectiles i.e 57 mm and 37 mm anti-aircraft projectiles in the present study to emphasis on determining the pressure Coefficient from the surface static pressure. Then other parameters i.e drag & lift forces and its Coefficient at various angles of attack was determined. Here the experiment was done in subsonic wind tunnel and computational analysis was done through Ansys software.

2. REVIEW OF LITERATURE

Many studies and researches are performed at the past to study the aerodynamic parameters for various types of projectiles. All those researches are essential as any findings will help in the overall projectiles aerodynamic characteristics and its performances.

Mohammad Amin et al. [1] prepared an article that focused on the study of various methods for reducing the base drag of artillery projectiles caliber 122mm. The computational fluid dynamics (CFD) numerical simulations (RANS, 2-D axisymmetric configuration) were performed, to investigate the base drag characteristics of the projectiles. Chand et al. [2] discussed in their paper the feasibility of the application of the system dynamics approach in the artillery projectile motion analysis under the test and evaluation curriculum activities using a point-mass mathematical model. Goran et al. [3] present the modification of the existing guided missile in their study. The modification was performed based on required aerodynamic coefficients for the existing guided missile. The preliminary aerodynamic configurations of the improved missile front parts were designed based on theoretical and computational fluid dynamics simulations. Sahoo et al. [4] in their study, made a numerical estimation of the drag variation and trajectory elements of a supersonic projectile having two different nose shapes. The coefficient of drag (CD) obtained from the simulation is used as an input parameter for the estimation of trajectory elements. The numerical results, i.e, the coefficient of drag at different Mach numbers and trajectory elements are validated with the data recorded by tracking radar from an experimental firing.

There are many more other study on this like Jian et al. [5] in their analysis shows a hypersonic aerodynamics analysis of an electromagnetic gun launched projectile configuration is undertaken to ameliorate the basic aerodynamic characteristics in comparison with the regular projectile layout. With a steady-state computational fluid dynamics (CFD) simulation, the basic density, pressure, and velocity contours of the EM gun projectile flow field at Mach number 5.0, 6.0, and 7.0 (angle of attack= 0o) have been analyzed. Mahfouz et al. [6] in their study applied computational fluid dynamics (CFD) to simulate a 2-D hollow projectile with optimal geometry at different Mach numbers at $1 < Ma < 1.8$ and different angles of attack to investigate the shock wave structures and drag characteristics. Shubham et al. [7] presented in their paper steady-state, two-dimensional computational investigations performed on NACA 0012 airfoil to analyze the effect of variation in Reynolds number on the aerodynamics of the airfoil without and with a Gurney flap. Both lift and drag coefficients increase with Gurney flap compared to those without Gurney flap at all Reynolds numbers at all angles of attack. Damir et al. [8] shows in this paper the research of aerodynamic characteristics of classic symmetric projectile. On the basis of constructed parameters and dynamic characteristics of 40 mm projectile model it calculates aerodynamic coefficients and their derivatives. Kiran et al. [9] Investigated in their research the aerodynamic properties of a standard M549, 155mm projectile. The detailed study was done and validated to reduce drag and to see its effect on the projectile design for both transonic and supersonic speeds.

3. EXPERIMENT

The experiment will be conducted in an open circuit subsonic wind tunnel. The experiment comprises the measurement of aerodynamic parameters of the model in the wind tunnel. The wind tunnel has a bell mouth entry, a flow Straightener, diverging section, and two axial flow fans. The projectile will be placed at the exit end of the wind tunnel. A set of dummy 37 mm and 57 mm projectiles will be considered for the experiment. The dimensions are collected from the commonly used shell . At different angles of attack (30^o to 50^o) the static pressure measurement will be made. The speed of the tunnel (4.7 m/s) will be maintained at maximum to simulate the actual flow experienced by projectile. From the static pressure distributions, using numerical computations, the drag and lift coefficients will be measured and compared for different size and flow configuration. For numerical scheme the ANSYS software will be used to simulate the experiment .

3.1. Requirement of Model study

There are roughly four classes of techniques to predict aerodynamic parameters on a projectile in atmospheric flight. These are empirical methods, wind tunnel testing, computational fluid dynamics simulation, and spark range testing. In computational fluid dynamic (CFD) simulations, the fundamental fluid dynamic equations are numerically solved for a specific configuration. Wind tunnels testing and full-scale results are always different due to Reynold's number inequality. In most of the wind tunnel test, the full-scale Reynolds number is difficult to achieve.

For determining aerodynamic Coefficient data including the total aerodynamic drag and lift, studies with the model and full-scale projectile are performed to validate the model. But full-scale experiments are both costly and difficult to perform. For the present study with anti-aircraft artillery projectiles, full-scale experiments will be a complex and costly. At the same time it will be difficult to record reliable pressure distribution simultaneously on the single as well as a group of the projectile as there will be a variation of speeds and direction of the wind with time. The flow around projectile in the actual environment is very complex and formulation of a mathematical model to predict the flow is almost impossible. Thus for solution accuracy model study of anti-aircraft artillery & tank projectile and various data obtained from the simulation will become very handy for practical analysis.

3.2. Preparation of the Model (Dummy Projectile)

Projectiles of existing anti-aircraft Artillery which are used in worldwide were selected for the preparation of the model. For this study projectiles of existing 37 mm and 57 mm was used for the preparation of the model. We have prepared the dummy model by wood instead of metal because with the metal the dummy model will be heavier and will be difficult to use during the experiment. So each of the models was made of seasoned teak wood to avoid bucking and expansion due to the change in weather. Wooden dummy model is shown in Figure 1 . The dimensions of the 37 mm and 57 mm projectiles are shown in Figure 2. Dummy projectile contained 10 tapping point for 37 mm projectile and 17 tapping points for 57 mm projectiles. The distance between the consecutive tapping points was equal as shown in the figure . Inner Diameter of each tapping point is 1 mm.

Figure 1 : Dummy Model of existing 37 mm & 57 mm Projectile

The tapings were made along the circular-section of the projectiles. Since the velocity was two-dimensional flow, this would not make any effect on the experimental result. Keeping the outside of the projectiles intact the inside of the projectiles was made hollow through which the plastic tubes were allowed to pass.

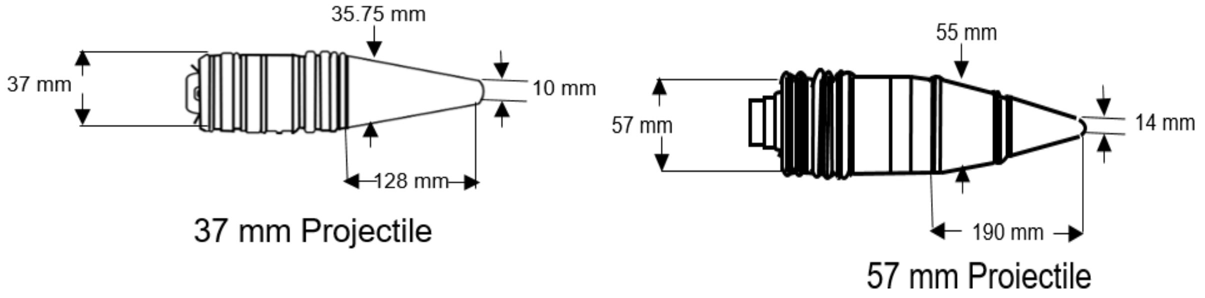


Figure 2 : Dimensions shown in Dummy Projectiles

The plastic tubes were connected with the copper capillary tubes at one side and the other side with the inclined multi-manometer. The tapings were made of copper tubes of 2 mm outside diameter. Each tapping was of 50 mm length approximately. From the end of the copper tube flexible plastic tube of 1.5 mm, inner diameter was press-fitted. The tapping positions on the cross-section of the projectiles are shown in Figure 3.

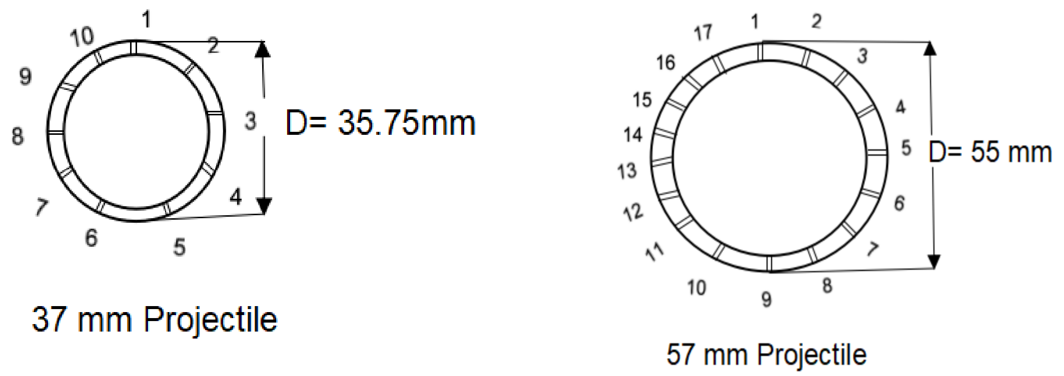


Figure 3 : Tapping position shown on Projectiles

In the experimental investigation, initial reading was taken placing the single projectile in front of the wind tunnel shown in Figure 4. The wind velocity across the test section of the wind tunnel was measured with the help of a digital anemometer. A pitot tube was also used to measure the velocity to cross-check. The pitot tube was connected to an inclined manometer and the limb of which contained manometer fluid. The surface static pressures were measured with the help of an inclined manometer.

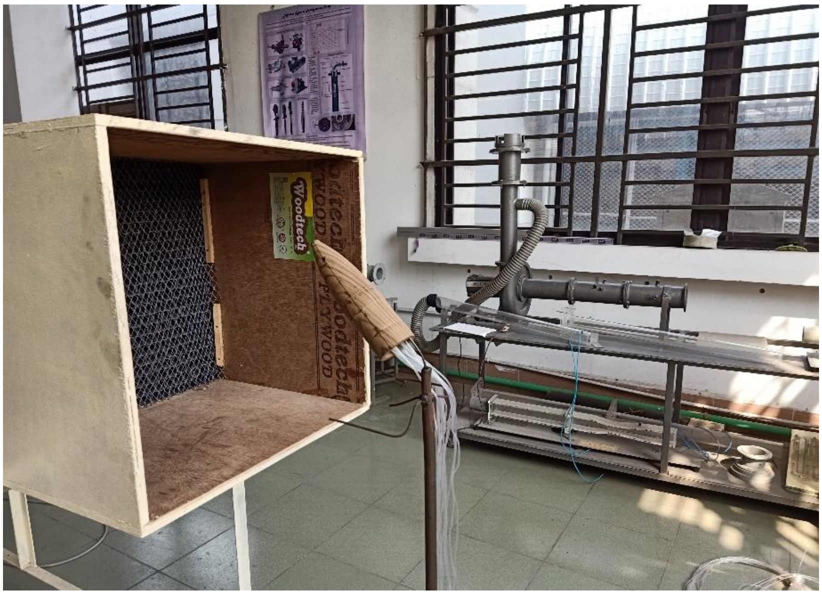


Figure 4: Experimental setup of projectile for measuring static pressure.

3.3. Experimental Conditions:

The static pressure was measured with a manometer and it had a minimum deflection of 1 mm. The experimental conditions are shown in Table 1. A Computational Fluid Dynamics (CFD) simulation was done with ANSYS Multiphysics software on similar conditions to compare the experimental and simulation results.

Table 1. Experimental Conditions for Different Projectiles.

Projectile Size (mm)	The angle of Attack, AOA, (°)	Air Velocity (m/s)	Number of Tapping Points
37	30, 35, 40, 45, 50	4.7	10
57	30, 35, 40, 45, 50	4.7	17

4. Mathematical Model

For the study, from the wind tunnel pressure tap, static pressure at the upstream of the test section was measured for calculating the lift and drag force. The inclined manometer was used to measure the static pressure on the projectile surface. A constant Wind Velocity of the Wind tunnel was chosen which was 4.7 m /s, measured directly with an anemometer which is later used to calculate the drag, lift, and pressure coefficient.

The pressure coefficient is a dimensionless number which describes the relative pressures throughout a flow field in fluid dynamics. The pressure is measured at the tapping by using Equation 1.

$$P = \Delta l_k \rho_k g \text{ ....(1)}$$

Where

P = Static Pressure

Δl_k = Manometer reading

ρ_k = Density of Kerosene

g= Gravitational Acceleration

The acting force on a single segment is calculated from Equation 2.

$$F_1 = P * S_{Projected\ 1} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . (2)$$

Then the Total Force acting on the Projectile will be

$$F = F_1 + F_2 + F_{3+} \dots \dots \dots \dots \dots \dots \dots .. + F_n \dots \dots \dots \dots \dots (3)$$

As the air is coming at an angle, therefore, the Total forces will be divided into Horizontal and Vertical direction. If the Angle of Attack is 'α' then the drag and lift force is calculated from Equation 4 and 5.

$$L_D = F \cos \alpha \dots \dots \dots \dots \dots \dots \dots . (4)$$

$$L_L = F \sin \alpha \dots \dots \dots \dots \dots \dots \dots . (5)$$

The Drag Coefficient (C_D), Lift Coefficient (C_L), and Pressure Coefficient (C_P) are calculated from Equation 6, 7, and 8.

Drag coefficient is a dimensionless quantity that is used to quantify the drag or resistance of an object. The drag coefficient is defined as

$$C_D = \frac{2 * L_D}{S_{Total} * \rho_k * U_\infty^2} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots .. (6)$$

Lift coefficient is a dimensionless coefficient that relates the lift generated by a lifting body. The lift coefficient is defined by

$$C_L = \frac{2 * L_L}{S_{Total} * \rho_k * U_\infty^2} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (7)$$

$$C_p = \frac{\Delta P}{0.5 * \rho_{air} U_\infty^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (8)$$

Where, $\Delta P = P - P_\propto$

P = Static pressure on the surface of the projectile

$P_\propto$ = The ambient pressure

ρ_{air} = the density of the air

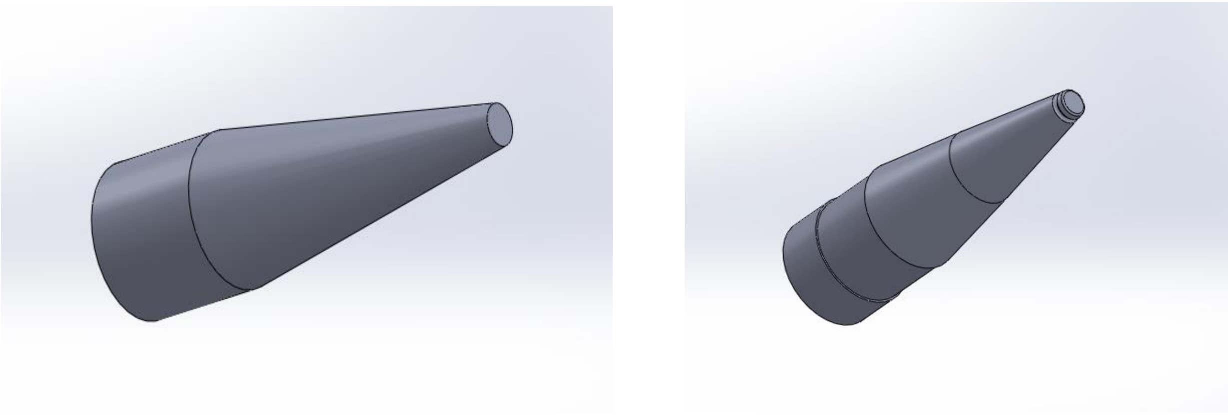
u=the free stream velocity

S_{Total}= Total Active Projected Area (S_1+S_2+S_3+………+S_n)

5. COMPUTATIONAL SIMULATIONS

5.1. Geometrical setup

Geometry of the projectile was prepared for the computational simulation . Here we have considered the dimensions of 37 mm and 57 mm projectiles. With the help of solid works, we have developed the geometry of the projectile. The Solid Works model was made for measuring the projected area which is used for simulation. Ansys software is used to analyse the CFD model. Numerical results are highly influenced by the dimensions of the geometrical domain. The projectile is considered as a solid domain and outside of it is considered as air domain. The k-ε turbulence model is used for solving the problem. The inlet condition was 4.7 m/s air and outlet condition was atmospheric condition similar to experiment. The rest of the surface is considered a wall. Figure 5 shows the geometry of the 37 mm and 57 mm projectiles.

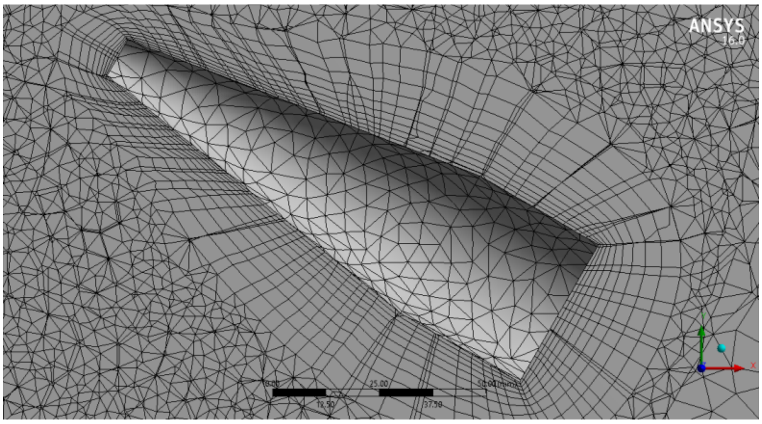


(a) (b)

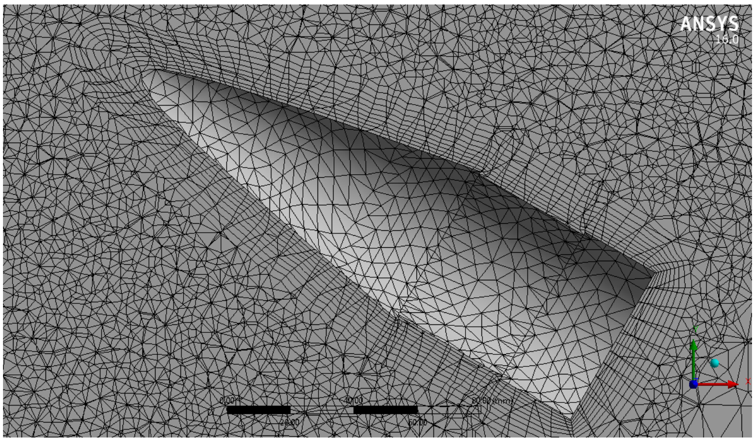
Figure 5. Geometry files for CFD simulation of (a) 37 mm and (b) 57 mm Projectiles

5.2. Meshing and other Simulation of Projectile

Meshing of the projectile was done for rendering a computer screen and for physical simulation i.e for finite element analysis or CFD. Here resolution of the meshing was greater in the regions where greater computational accuracy was needed. It is done at 45° having the boundary condition greater than the projectile. The mesh file for simulation is shown in Figure 6 and the simulation settings for the projectiles are shown in Figure 7.



(a)

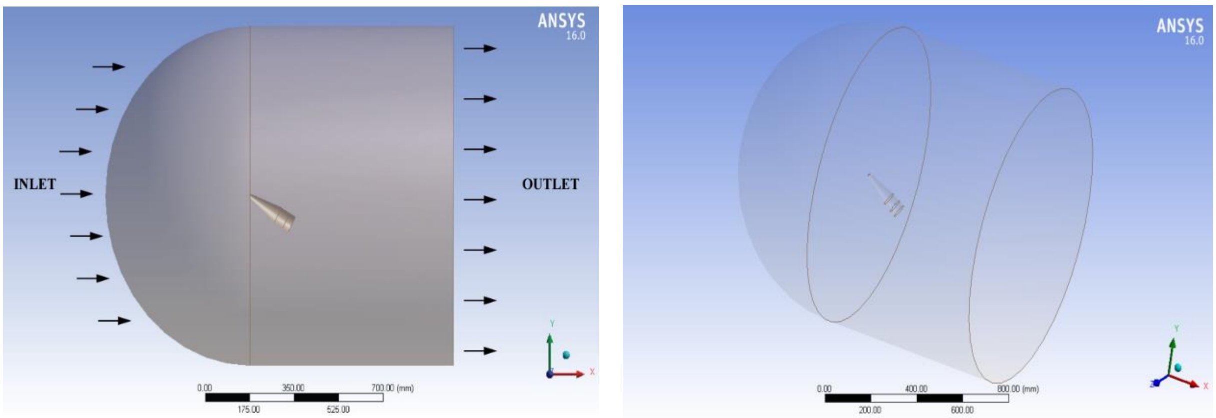


(b)

Figure 6 : Mesh of the CFD Simulation for (a) 37 mm,

(b) 57 mm (zoomed) Projectiles

The geometry of the projectiles with the same dimension of was put forward to simulation with scale 1:1. The geometric model of the projectile is shown in Fig. No 5. The projectile model was sketched on Solid Works 2017 then imported to ANSYS Geometry. The boundary is C-type pattern with 10D at the upstream side and 15D at the downstream side from the surface of the model where D is the diameter of the projectile.



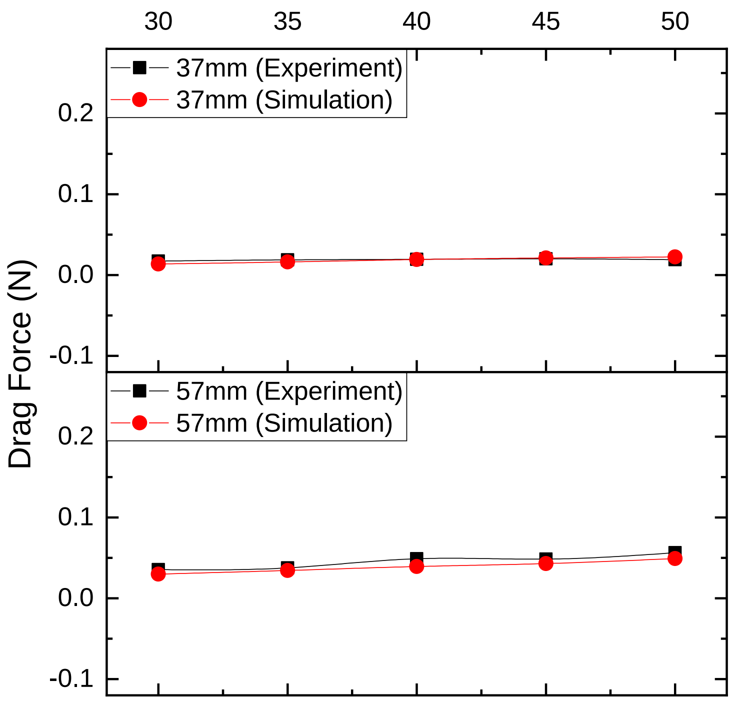
(a) (b)

Figure 7 : Ansys CFD Simulation setting for (a) 37 mm and (b) 57 mm Projectiles.

The air enters into the domain with a velocity of 4.7 m/s. The density of air was 1.225 kg/m3 and viscosity about 1.7894e-05 kg/m-s. At the outlet, the pressure outlet condition is applied in the domain. The steady and incompressible flow of air is considered in this Analysis. In these calculations, the second-order upwind scheme based on a multidimensional linear reconstruction approach is used. These computations are carried out using FVM solver (ANSYS FLUENT 2016), a commercial CFD package with a 3D double-precision Configuration. The default convergence criterion in FLUENT is maintained. This criterion requires that the scaled residuals decrease to 10^{-5}.

6. Results and Discussion

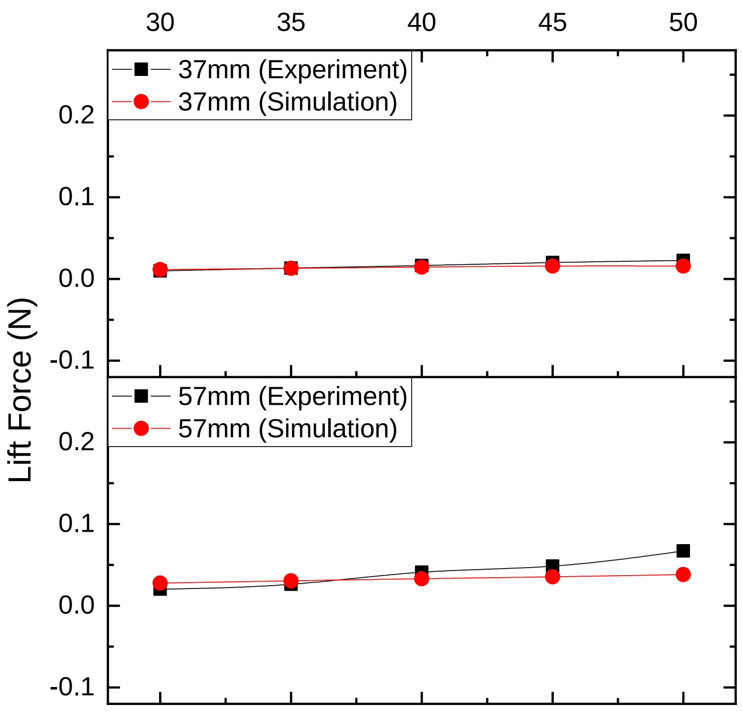
Experimental test for two types of dummy projectile model was done for the determination of aerodynamic parameters and for the determination of its characteristics at various angle of attack. Here computational analysis was done to validate the experimental results. From the wind tunnel primarily with the help of inclined manometer, the static pressure on the surface of the projectiles at various angles of attack was taken, then the distribution of the static pressure coefficients on the surface of the projectile is compared numerically. Finally, the other aerodynamic parameters are also compared. Results for the CFD analysis of the dummy projectile models are obtained during validation. The static pressure acting on the projectiles are calculated from the inclined manometer, here friction of the projectile is not considered in the experimental and simulated evaluation. But the surface friction has a contribution to the drag force and lift forces. Combining the drag and lift forces acting on each segment of the projectiles can determine the total force acting on the projectile.



Angle of Attack (Degree)

Figure 8 : Angle of Attack Vs Drag Force

The drag forces found for 37 mm & 57 mm projectile are 0.0224 N and 0.0492 N. The lift forces also increase from 0.0159 N to 0.0382 N for 37 mm & 57mm projectiles. Drag force and lift force Vs angle of attack is shown in Figure 8 & 9 respectively.



Angle of Attack (Degree)

Figure 9 : Angle of Attack vs Lift Force.

The drag and lift forces of hollow projectile found to be the function of the angle of attack as well. As the angle of attack increases the drag and lift forces also increases slightly as well. The drag forces are almost constant if the angle of attack is low. In this investigation, the rate of increasing the lift forces is more than the drag forces. There was some deviation between the experimental and simulated findings which can be coming from the lack of precision measurement, the ignored friction coefficient of the projectile surface, and the geometrical inaccuracy due to manual fabrication. The increase in the drag and lift forces are common for all the projectiles. The corresponding data sets are shown in Tables 2 and 3.

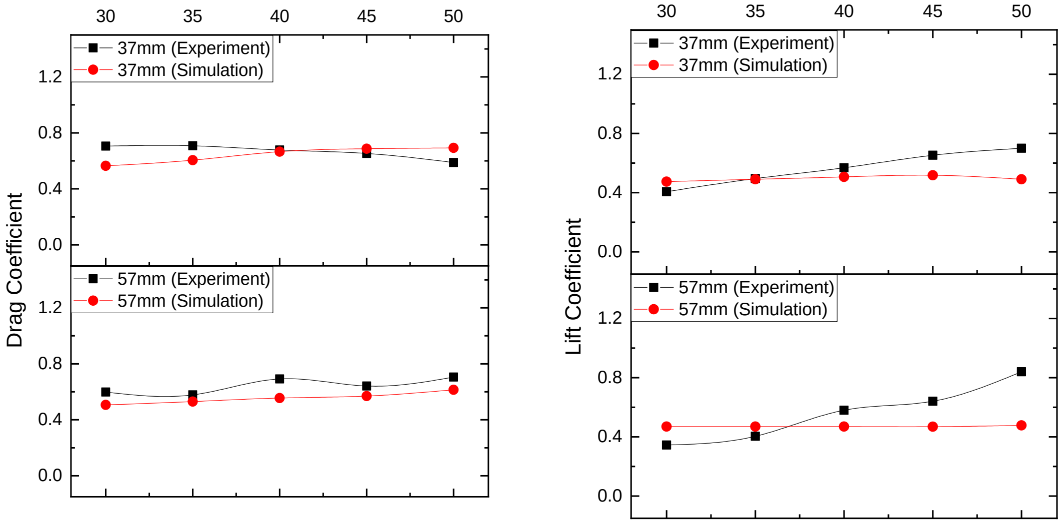
Table 2: Simulation and Experimental Drag Forces for 37 and 57 mm Projectiles at different AOA.

Angle of Attack (°)	37S (N)	57S (N)	37E (N)	57E (N)
30	0.0138	0.0300	0.0040	0.0204
35	0.0162	0.0345	0.0051	0.0308
40	0.0192	0.0393	0.0164	0.0551
45	0.0211	0.0431	0.0201	0.0643
50	0.0224	0.0492	0.0227	0.0806

Table 3: Simulation and Experimental Lift Forces on 37 and 57 mm Projectiles at different AOA .

Angle of Attack (°)	37S (N)	57S (N)	37E (N)	57E (N)
30	0.0116	0.0278	0.00696	0.0355
35	0.0132	0.0306	0.00741	0.0441
40	0.0146	0.0332	0.01959	0.0657
45	0.0159	0.0355	0.0201	0.0644
50	0.0159	0.0382	0.0190	0.0677

The overall experimental drag coefficients is higher than simulated drag coefficients except for 37 mm projectile where the experimental drag coefficients slightly lower than the simulation. For the lift coefficient it is slightly higher than the simulation. The deviation between the experimental and simulated results may be the result of measurement inaccuracies, geometrical inaccuracies, and ignored surface roughness. The projectiles are made with a manual lathe and therefore, the manufacturing deviation could play a vital role is the deviation of the results. The simulated and experimental drag and lift coefficients are plotted in Figures 10. Table 4 and Table 5 shows the corresponding data for drag and lift coefficients.



Angle of Attack (Degree) Angle of Attack (Degree)

Figure 10 : Angle of Attack vs Drag and Lift Coefficients.

Table 4: Simulation and Experimental Drag Coefficients on 37 and 57 mm Projectiles at Different AOA

Angle of Attack (°)	37S	57S	37E	57E	37 S-E Error(%)	57 S-E Error(%)
30	0.0158	0.033	0.0173	0.036	8.4	6.8
35	0.0162	0.035	0.0190	0.038	14.5	8.3
40	0.0193	0.044	0.0196	0.049	1.76	9.5
45	0.0211	0.043	0.0201	0.049	5.08	11.1
50	0.0225	0.049	0.0191	0.056	17.7	12.8

Table 5: Simulation and Experimental Lift Coefficients on 37 and 57 mm Projectiles at Different AOA

Angle of Attack (°)	37S	57S	37E	57E	37 S-E Error(%)	57 S-E Error(%)
30	0.012	0.023	0.009	0.020	16.6	11.6
35	0.013	0.031	0.013	0.026	1.0	16.2
40	0.015	0.035	0.016	0.041	10.8	14.1
45	0.019	0.046	0.020	0.048	5.7	6.1
50	0.02	0.058	0.023	0.067	12.3	13.3

6.1 Simulation at Supersonic Speed

A supersonic simulation was done to investigate the drag and lift forces. The simulation in supersonic speed is not the same as the subsonic speed therefore the comparison of the simulation result was different. However, the trend was familiar as the lift and drag coefficient changes near our Experimental speed is almost negligible.

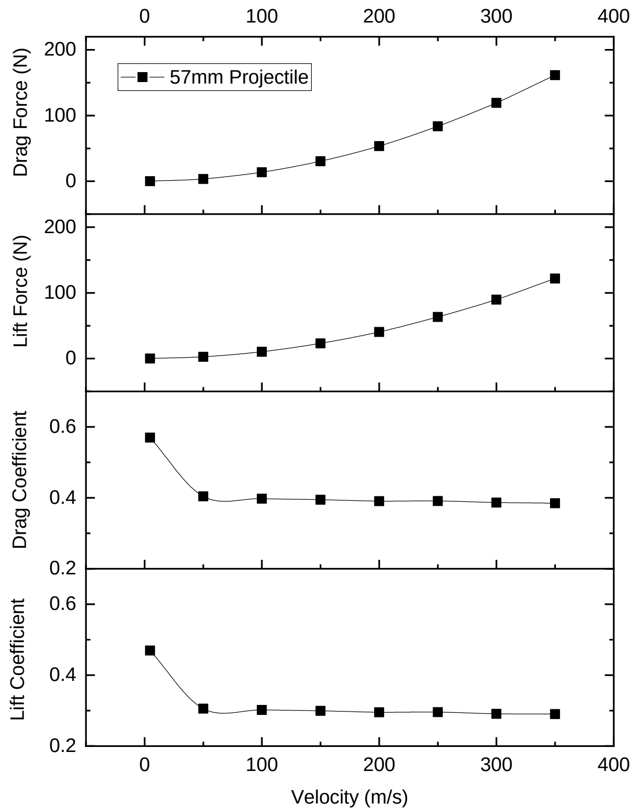


Figure 11 : The lift and drag coefficient of 57 mm projectile at 45° AOA for supersonic speed.

6.2 Pressure and Velocity Simulation

The pressure was mostly felt at the front of the projectile at 45° angle regardless of their sizes and shapes. The velocity plot shows the turbulence due to the shape of the projectiles. As the projectile size increases, the visual streamline from the simulation shows that the smaller size projectile gets more turbulence compared to the large size projectile. The simulation pressure and velocity plots are shown for 37 mm and 57 mm projectiles in Figures 12 and 13.

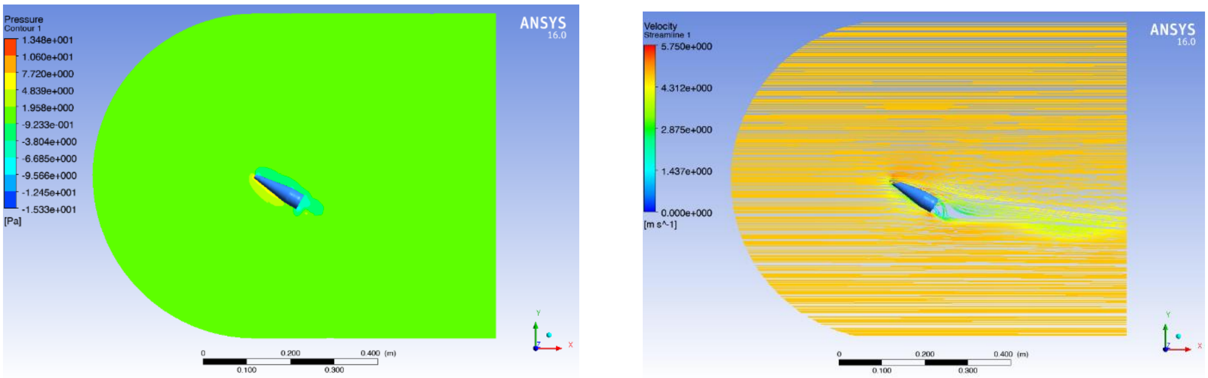


Figure 12 : The pressure and velocity contour for 37 mm projectile at 45°AOA

The velocity of the air increases as the streamline passes over the projectile. The reason could be the shape of the projectiles. However, the velocity streamline plots show that the streamline is flowing over the 37 mm projectile.

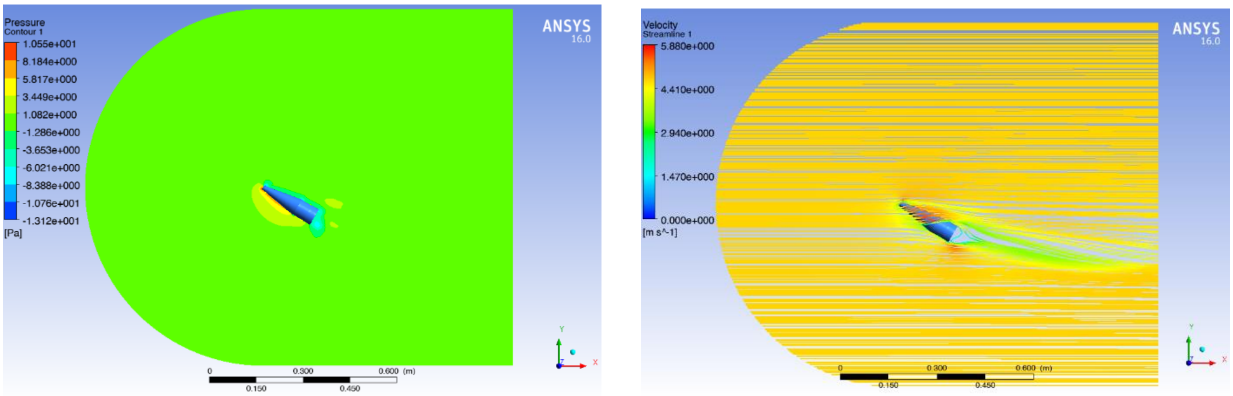


Figure 13 : The pressure and velocity contour for 57 mm projectile at 45°AOA

7. Conclusion

Aerodynamic parameters has a big impact on the range and accuracy of the projectile. The drag force will reduce the projectile range and lift force will increase the range of the projectile. For that, main focus was given on the drag and lift forces of the projectiles both in experimental and Computational analysis. In this study, the experiment was done on the projectiles model in a subsonic wind tunnel and similar experimental conditions were applied for computational analysis to investigate further parameters that are not possible to measure or visualize in real-time through Ansys software. The projectile travel in the air at supersonic speed and not in subsonic speed. We have done the experiment at a subsonic wind tunnel. Here the experiment is conducted at 4.7 m/s which provides the initial flight scenario and its related aerodynamic parameters.

In our study we have done one simulation at supersonic speed for 57 mm projectile though experimentally it couldn't be done. The trend was familiar as the lift and drag coefficient changes near our experimental speed is almost negligible. The trend of the increase is found to be linear for subsonic airspeed. The lift and drag forces increase as the angle of attack increases. Lift forces increasing rate is little higher and it is similar for drag and lift coefficients. For smooth conduct of the computational analysis on the topic, experiment in supersonic wind tunnel could have given more realistic results.

References

1. Mohammad A. D. and Slobodan J. , " Various Methods of Artillery Projectiles Base Drag Reduction", 8th International Scientific Conference on defence Technology Belgrade, Serbia, October 2018.

2. Chand K. K. and Pattnaik S., "Modeling Projectile Motion: A System Dynamics Approach", International Journal on Information Science and Computing Orissa, India, Vol.2, No.1, July 2008.

3. Goran. J. O., Bosko P. R. and Aleksandar C. B., "Aerodynamic Shape Optimization of Guided Missile Based on Wind Tunnel Testing and Computational Fluid Dynamics Simulation", Serbia, Scientific Paper, Vol. 21, No. 3, pp. (1543-1554), 2017.

4. Sahoo S. and Laha M.K., "Coefficient of Drag and Trajectory Simulation of 130 mm Supersonic Artillery Shell with Recovery Plug of Fuze", Defence Science Journal, India, Vol. 64. No. 6. pp. (502-508), November 2014.

5. Jian S., Shaobo F., Yaxin J., Zhu Q. and Duan J., "Aerodynamics Analysis of a Hypersonic Electromagnetic Gun Launched Projectile", Journal Pre-Proof, China, Ref. DT 592, January 2020.

6. Mahfouz E. W., Zhengui H. and Zhihua C. "Aerodynamic Characteristics and Flow Field Investigations of an Optimal Hollow Projectile". 5th International Conference on Mechanical Engineering and Mechanics, China, August 2014.

7. Shubnam J., Nekkanti S. and Sriram K., "Effect of Reynolds Number on Aerodynamics of Airfoil with Gurney Flap", International Journal of Rotating Machinery, India, Vol.2015, August 2015.

8. Damir D.J. and Marija S., "The Aerodynamic Characteristics Determination of Classic Symmetric Projectile", 5th International Symposium about forming and design in Mechanical Engineering, Serbia, September 2008.

9. Kiran. and Basawaraj, "Drag Prediction and validation of Standard M549, 155mm Projectile", International journal of Engineering Research and Reviews, India, Vol-2, Issue 3, pp. (26-32), 2014.

10. Suliman M. A., Mahmoud O. K., Al Sanabawy M. A. and Abdel Hamid O.E., "Computational Investigation of Base Drag Reduction for a Projectile at Different Flight Regimes", 13th International Conference on Aerospace Science and Aviation technology Coiro, Egypt, May 2009.

11. Elsaadany A. and Wenjun YI., "Investigation on Trajectory Correction for Typical Artillery Projectiles", 5th International conference on Mechanical Engineering and Mechanics, China, August 2014.

12. Alexey. M.L, Stanishlav, A.K, Ivan. G.R, (2017), “Optimization of Aerodynamic Form of Projectiles for Solving the Problem of Shooting Range Increasing”, AIP Conference Proceeding 1893, 030085.