A comparative study of turbulence models for predicting the aerodynamic drag of a spin-stabilized projectile

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Abstract:

Introduction/purpose: In this research, the influence of different turbulence models on the aerodynamic drag prediction of a generic spin-stabilized projectile was analyzed. The turbulence models chosen for investigation were one-equation Spalart-Allmaras, two-equation models Standard k-ε, Realizable k-ε, Standard k-ω and SST k-ω. The special sniper projectile M118 was selected for the study.

Methods: The flows around the projectile were numerically simulated using RANS equations intergrated into ANSYS Fluent software with different turbulence models. The numerical simulation was carried out at various Mach numbers to study the effect of turbulence models on the projectile aerodynamic drag prediction. The computational results were compared to the available experimental data to evaluate the ability of the turbulence models.

Results: The research results have shown that the turbulence models significantly affect the numerical simulation results. The Spalart-Allmaras turbulence model performs better than other models in the subsonic flow regime. The Standard k-ε, Realizable k-ε and SST k-ω models perform better than other models in the supersonic flow regime.

Conclusion: Computational Fluid Dynamics is a powerful tool to analyze the aerodynamics of flying bodies. By appropriately selecting turbulence models, the flow around flying bodies can be accurately investigated. In the case of generic ogive-cylinder-boattail projectiles, on the one hand, the Spalart-Allmaras model is suitable for subsonic flow, and the Standard k-ε, Realizable k-ε and SST k-ω models are recommended for the supersonic flight regime, on the other hand.

Key words: turbulence models, Ansys Fluent, spin-stabilized projectiles, subsonic flow, supersonic flight regime.

Introduction

RANS equations have been widely used in aerospace and defense industry for years. They are solved together with a turbulence model describing the turbulence behavior of the flow. Selecting an appropriate turbulence model is crucial in aerodynamic analysis of flying bodies.

Generally speaking, aerodynamics has provided various models to describe the turbulent behavior of the flow around a body. Each model has its own strengths and shortcomings and has been proven to be effective in different applications. No turbulence model is universally suitable for all turbulent flows. Researchers have selected turbulence models based on their own knowledge and experience.

In the field of weapon design, various turbulence models have been successfully used so far to analyze flows around projectiles. Xu et al. (2022) adopted the Spalart-Allmaras turbulence model to investigate the aerodynamic characteristics of a 57mm projectile with a drag controlling device. Demir et al. (2024) analyzed the drag reduction of modified bullets using the Spalart-Allmaras turbulence model. The Standard k-ε turbulence model was applied by Silton at the Army Research Laboratory to conduct Navier-Stokes computations for a 0.50 cal. projectile (Silton, 2002). Many other authors have also implemented the Standard k-ε turbulence model to study flows around various flying bodies (Muthukumaran et al, 2013; Gholap et al, 2022; Bui et al, 2024; Nguyen et al, 2024). Hao et al. (2024) used the Realizable k-ε turbulence model to carry out the aerodynamic characterization of bullet heads with different arcuate curves. Ferfouri et al. (2023) adopted the Realizable k-ε turbulence model for predicting the aerodynamic drag coefficient of the M107 155mm projectile. The Realizable k-ε turbulence model was also applied by Silton to perform numerical computation for spinning projectiles from subsonic to supersonic speeds (Silton, 2005, 2011). Meanwhile, Hamel & Gagnon (2011) implemented the Standard k-ω turbulence model for a parametric study on a 155mm artillery shell equipped with a roll-decoupled course correction fuze. The SST k-ω model has also been used in multiple research studies. Luo et al. (2024) adopted the SST k-ω model to study the aerodynamic characteristics of a tail-stabilized projectile with the asymmetrical diversion groove. The SST k-ω turbulence model was applied by Jiajan et al. (2015) to investigate the effect of boattail junction shaping on the aerodynamic drag and stability of supersonic spin-stabilized rounds. Sertkaya et al. (2022) used the SST k-ω turbulence model for computing the aerodynamic coefficients of 155 mm ammunition.

In order to select an appropriate turbulence model for a specific flow, one has to know the performance characteristics of each model. A comparative study on the prediction of the aerodynamic characteristics of four aircraft with different turbulence models performed by Jang et al. (2018) has shown that the skin friction drag predicted with the SST k-ε is the smallest, while the k- ε model predicts the largest skin friction drag for all configurations. Somashekar & Immanuel Selwyn Raj investigated the effect of six turbulence models, namely, the Spalart-Allmaras, the Standard k-ε, the k-ε RNG, the Realizable k-ε, the Standard k-ω, and the SST k-ω, on the prediction of the aerodynamic characteristics of a mini-unmanned aerial vehicle. They have drawn a conclusion that these six turbulence models have the same general behavior with some differences in the coefficients of lift and drag, and the Spalart-Allmaras model is the most efficient model to describe the turbulence of the subsonic flow around a mini-UAV in terms of the deviation of the coefficients of lift and drag values and the calculation time (Somashekar & Immanuel Selwyn Raj, 2021). Julian et al. (2023) carried out a study on the effect of the Spalart - Allmaras, the Standard k-ε and the Standard k-ω turbulence models on the aerodynamic performance of the NACA 4415 airfoil. However, in the field of projectile design, to the best of the author's knowledge, there is still no published work dedicated to the comparative analysis of the performance of different turbulence models in studying flows around a spin-stabilized projectile.

Therefore, inspired by the above literature review conclusion, the main objective of this research is to study the comparative performance of five widely used turbulence models, namely, the Spalart-Allmaras, the Standard k-ε, the Realizable k-ε, the Standard k-ω and Menter's SST k-ω turbulence models, in prediction of the aerodynamic drag coefficient of a spin-stabilized projectile for better understanding the turbulence models' ability to predict the drag acting on a generic projectile stabilized by spinning. The M118 projectile is chosen for the present study because its aerodynamic data obtained experimentally has been published in the open literature and can be used for validating the simulation results.

Mathematical model

Governing equations

The continuous flow around a projectile is described by the 3D Navier-Stokes conservation equations as follows:

The conservation of the mass:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \tag{1}$$

The conservation of the momentum:

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial\tau_{ij}}{\partial x_j}+\rho f_i \tag{2}$$

The conservation of the energy:

$$\frac{\partial}{\partial t}\rho\left(e+\frac{1}{2}u_i u_i\right)+\frac{\partial}{\partial x_j}\left[\rho u_j\left(h+\frac{1}{2}u_i u_i\right)\right]=\frac{\partial}{\partial x_j}\left(\sigma_{ij}u_i\right)-\frac{\partial q_j}{\partial x_j} \tag{3}$$

where *ρ* is the air density, u_i is the i-th component of the velocity vector, x_i is the i-th component of the position vector, *p* is the air pressure, *e* is the specific internal energy, and *h* is the specific enthalpy, q_j is the j-th component of the heat flux vector, and σ_{ij} is the stress tensor.

The Navier-Stokes equations are resolved using the RANS method coupled with one of the following turbulence models.

Spalart–Allmaras model

The one-equation Spalart-Allmaras turbulence model was originally presented in 1992 and has been widely used in aerospace and defence industry (Spalart & Allmaras, 1992). Its transport equation is as follows:

$$\frac{\partial}{\partial t}(\rho\tilde{v})+\frac{\partial}{\partial x_i}(\rho\tilde{v}u_i)=$$
$$=G_v+\frac{1}{\sigma_{\tilde{v}}}\left\{\frac{\partial}{\partial x_j}\left[(\mu_t+\rho\tilde{v})\frac{\partial\tilde{v}}{\partial x_j}\right]+C_{b2}\rho\left(\frac{\partial\tilde{v}}{\partial x_j}\right)^2\right\}-Y_v+S_{\tilde{v}} \tag{4}$$

where $\tilde{v}$ is the eddy viscosity, μ_t is the turbulent viscosity coefficient, C_{b2} is a constant, G_v is the production term, Y_v is the destruction term, and $S_{\tilde{v}}$ is the user-defined source term.

The turbulent viscosity coefficient μ_t is determined as follows:

$$\mu_t=\rho\tilde{v}f_{v1}\,,\ f_{v1}=\frac{\chi^3}{\chi^3+c_{v1}^3}\,,\ \chi=\frac{\tilde{v}}{v}\ , \tag{5}$$

The production term G_v is given by:

$$G_v = C_{b1}\rho\tilde{S}\tilde{v}\ ,\ \tilde{S} = S + \frac{\tilde{v}}{\kappa^2 d^2} f_{v2}\ ,\ f_{v2} = 1 - \frac{\chi}{1+\chi f_{v1}} \tag{6}$$

where C_{b1} and κ are constants, *d* is the distance from the wall, f_{v1} and f_{v2} are damping functions, and *S* is a scalar measure of the deformation tensor and is determined as follows:

$$S = \sqrt{2\Omega_{ij}\Omega_{ij}}\ ,\ \Omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_i} - \frac{\partial u_j}{\partial x_j}\right) \tag{7}$$

The destruction term is calculated as follows:

$$Y_v = C_{\omega 1}\rho f_\omega \left(\frac{\tilde{v}}{d}\right)^2\ ,\ f_\omega = g\left(\frac{1+C_{\omega 3}^6}{g+C_{\omega 3}^6}\right)^{1/6} \tag{8}$$

where $g = r + C_{\omega 2}\left(r^6 - r\right),\ \ r = \frac{\tilde{v}}{\tilde{S}\kappa^2 d^2}$, and (9)

$C_{\omega 1}$, $C_{\omega 2}$ and $C_{\omega 3}$ are constants. The values of the model constants were provided by Spalart and Allmaras (Spalart & Allmaras, 1992).

Standard k-ε model

The *k-ε* turbulence model was proposed by Launder & Spalding (1974). It enables to take into account turbulent eddy viscosity using kinetic energy *k* and dissipation rate *ε.* These parameters are defined by:

$$\frac{\partial(\rho k)}{\partial t} + u\frac{\partial(\rho k)}{\partial x} + v\frac{\partial(\rho k)}{\partial y} + w\frac{\partial(\rho k)}{\partial z} = \frac{\partial}{\partial x}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right] + $$
$$= \frac{\partial}{\partial y}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right] + \frac{\partial}{\partial z}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right] + P_k - \rho\varepsilon, \tag{10}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + u\frac{\partial(\rho \varepsilon)}{\partial x} + v\frac{\partial(\rho \varepsilon)}{\partial y} + w\frac{\partial(\rho \varepsilon)}{\partial z} = \frac{\partial}{\partial x}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x}\right] + $$
$$= \frac{\partial}{\partial y}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial y}\right] + \frac{\partial}{\partial z}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial z}\right] + P_k C_{1\varepsilon}\frac{\varepsilon}{k} - \rho C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{11}$$

where the function P_k is defined as:

$$P_k = \tau_{xx}\frac{\partial u}{\partial x} + \tau_{xy}\frac{\partial u}{\partial y} + \tau_{xz}\frac{\partial u}{\partial z} + \tau_{yx}\frac{\partial v}{\partial x} + \tau_{yy}\frac{\partial v}{\partial y} + \tau_{yz}\frac{\partial v}{\partial z} + \\ + \tau_{zx}\frac{\partial w}{\partial x} + \tau_{zy}\frac{\partial w}{\partial y} + \tau_{zz}\frac{\partial w}{\partial z}, \tag{12}$$

where k is the kinetic energy, ε is the dissipation rate, E_{ij} represents the component of the rate of deformation, and μ_t represents the eddy viscosity. $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k and σ_ε are constant numbers: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1.00$ and $\sigma_\varepsilon = 1.30$.

The turbulent viscosity coefficient μ_t is calculated using the equation below:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \tag{13}$$

where the parameter C_μ is a constant number, $C_\mu = 0.0845$.

Realizable k-ε model

The Realizable k-ε is a modification to the Standard k-ε turbulence model to enhance its performance. It was first presented by Shih et al. (1994). The transport equations for k and ε of this model are given as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \\ = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{14}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \\ = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{15}$$

where $C_1 = max\left[0.43, \frac{n}{n+5}\right]$, $n = S\frac{k}{\varepsilon}$, $S = \sqrt{2S_{ij}S_{ij}}$; G_k is the turbulence kinetic energy due to the mean velocity gradients; G_b is the turbulence kinetic energy due to the buoyancy; Y_M is the contribution of the fluctuating dilatation on compressible turbulence to the overall dissipation rate; S_k and S_ε are the user-defined source terms; and C_2, $C_{1\varepsilon}$, and $C_{3\varepsilon}$ are constants of the model (Shih et al, 1994).

Standard k-ω model

The Standard k-ω model is a two-equation turbulence model developed by Wilcox and first introduced in 1998 (Wilcox, 1998). It is based on the turbulent kinetic energy *k* and the specific dissipation rate *ω*. The transport equations for *k* and *ω* are as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right)+G_k-Y_k+S_k \tag{16}$$

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right)+G_\omega-Y_\omega+S_\omega \tag{17}$$

where G_k is the turbulence kinetic energy due to the mean velocity gradients; G_ω is the generation of *ω*; Γ_k and Γ_ω are respectively the effective diffusivity of *k* and *ω*; Y_k and Y_ω are respectively the dissipations of *k* and *ω* due to the turbulence; and S_k and S_ω are the user-defined source terms.

Γ_k and Γ_ω are defined as follows:

$$\Gamma_k=\mu+\frac{\mu_t}{\sigma_k},\ \Gamma_\omega=\mu+\frac{\mu_t}{\sigma_\omega} \tag{18}$$

where σ_k and σ_ω are respectively the turbulent Prandtl numbers for *k* and *ω*, and the turbulent viscosity is determined through the following expression:

$$\mu_t=\alpha^*\frac{\rho k}{\omega} \tag{19}$$

The turbulence kinetic energy G_k is calculated as:

$$G_k=-\rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i} \tag{20}$$

The quantity G_ω is defined as:

$$G_\omega = \alpha \frac{\omega}{k} G_k \quad (21)$$

where *α* and *α** are the closure coefficients of the model (Wilcox, 1998).

The dissipations Y_k and Y_ω are determined as follows:

$$Y_k = \rho\beta^* f_{\beta^*} k\omega,\ Y_\omega = \rho\beta^* f_{\beta^*} \omega^2 \quad (22)$$

The values of the model constants are: $\sigma_{k,1}$ = 1.176, $\sigma_{\omega,1}$ = 2.0, $\sigma_{k,2}$ = 1.0, $\sigma_{\omega,2}$ = 1.168, $\beta_{i,1}$ = 0.075, $\beta_{i,2}$ = 0.0828, β^* = 0.09, k = 0.41.

Shear Stress Transport (SST) k-ω model

The SST k-ω turbulence model was introduced by Menter (1994). It is a two-equation eddy-viscosity model which has been used for a wide variety of aerodynamic applications. This turbulence model blends the k-ε and the k-ω models to combine their advantages. The two transport equations are defined as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \quad (23)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \quad (24)$$

Here D_ω is the the cross-diffusion term.

The turbulent viscosity coefficient μ_t is computed as follows:

$$\mu_t = \frac{\rho k \alpha_1}{\max\left[\alpha_1 \omega,\ S F_2\right]}, \quad (25)$$

where α_1 is a constant of the turbulence model, *S* is the strain rate magnitude, and F_2 is a blending function.

In the SST k-ω model, the turbulent Prandtl numbers σ_k and σ_ω are defined as:

$$\sigma_k = \frac{1}{\dfrac{F_1}{\sigma_{k,1}} + \dfrac{1-F_1}{\sigma_{k,2}}},\ \sigma_\omega = \frac{1}{\dfrac{F_1}{\sigma_{\omega,1}} + \dfrac{1-F_1}{\sigma_{\omega,2}}} \quad (26)$$

where F_1 is a blending function and $\sigma_{k,1}$, $\sigma_{k,2}$, $\sigma_{\omega,1}$, and $\sigma_{\omega,2}$ are constants.

The parameters G_k and G_ω are defined as:

$$G_k = min\left(G_k, 10\rho\beta^* k\omega\right),\ G_\omega = \frac{\alpha}{\upsilon_t} G_k, \tag{27}$$

where β^* is a constant the value of which is 0.09, $\upsilon_t = k / \omega$.

The cross-diffusion term D_ω is determined as follows:

$$D_\omega = 2\left(1 - F_1\right)\rho\sigma_{\omega,2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{28}$$

The values of the constants in the SST k-ω model are as the same as of the constants in the Standard k-ω model.

Projectile geometry

The 7.62mm M118 sniper projectile has been widely used and its aerodynamics has been studied experimentally (McCoy, 1988). Therefore, this projectile will be used for the evaluation of the turbulence models. The M118 projectile configuration reproduced from published work (McCoy, 1988) is presented in Figure 1 (all measurements are in mm). The total length of the bullet is 32.76mm. The bullet bearing cylinder diameter is 7.82mm. The bullet secant ogive nose is 16.89mm in length with a 55mm radius. Additionally, the 9.30-degree filleted boattail is 5.78mm of length and the meplat diameter is 1.40mm. The projectile 3D model created using Inventor 2021 software (Figure 2) is imported into Ansys Fluent for the subsequent numerical simulation.

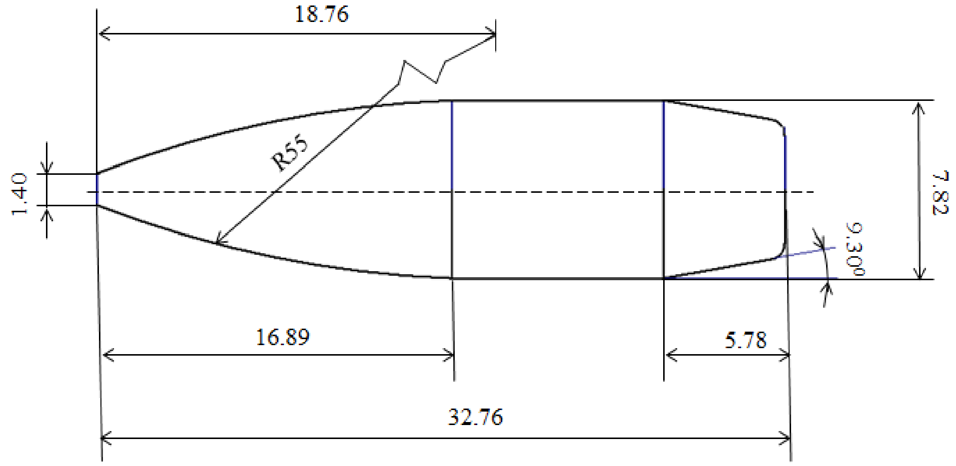

Figure 1 – M118 projectile dimensions (in mm)

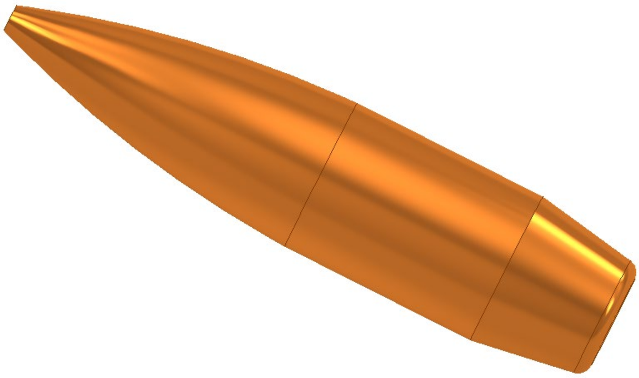

Figure 2 – 3D geometry model of the M118 projectile

Computational approach

Computational domain

The numerical simulation of the flow around the projectile was performed using the Ansys Fluent package (Matsson, 2023). A rectangular computational domain is adopted in this research as illustrated in Figure 3. The computational domain has to be large enough to capture the complex features of the flow around the projectile. Hence, in this study, the dimensions of the computational domain are set to a length of 50L, a height of 10L, and a width of 10L. Here L is the total length of the projectile (L = 32.76mm).

Solver setup and boundary conditions

The simulation employed the pressure-based solver and the finite volume method with the second order of accuracy for pressure, density, momentum, and turbulent kinetic energy. The Coupled algorithm was adopted in this study. The air is considered the ideal gas. The air viscosity model is the three component Sutherland model. The computational domain was set with the following boundary conditions: inlet, outlet, and wall. For the inlet flow, static pressure, static temperature and velocity were defined. The static pressure was set for the outlet flow. The wall was established as non-slip. The atmosphere parameters were set as follows: $p_0 = 101325Pa$ and $T_0 = 288{,}16K$. The convergence criterion was set to 10^{-3} to the residuals of the solution.

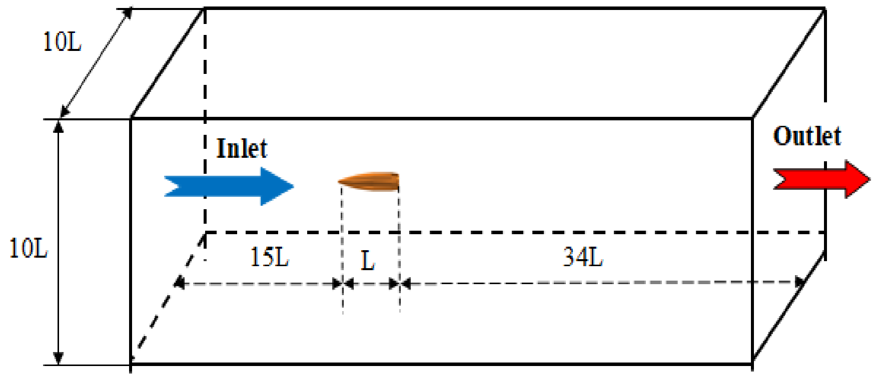

Figure 3 – Computational domain

Results and discussion

The numerical determination of the aerodynamic drag coefficient of the M118 projectile was performed at subsonic and supersonic speeds using five different turbulence models, namely, the Spalart-Allmaras, the Standard k-ε, the Realizable k-ε, the Standard k-ω and the SST k-ω turbulence models to investigate their ability to describe the flows around a generic spin-stabilized projectile.

Comparative performance of the turbulence models at subsonic flow

To evaluate the performance of different turbulence models at the subsonic flow, the aerodynamic zero-yaw drag coefficient was computed at the Mach number of 0.8 using the five abovementioned turbulence models. First, a mesh independence study was conducted to ensure that the simulation result is not affected by the mesh size. In the process of mesh generation, the dimensionless distance y+ was set below 1 for the Spalart-Allmaras, the Standard k-ω, and the SST k-ω turbulence models to better resolve the turbulent boudary layer. In the case of the Standard k-ε and the Realizable k-ε models, the y+ value was maintained at around 30 for better wall treatment with wall functions. The mesh size was then gradually increased by adjusting the size of elements on the projectile surface and in the computation domain to get better resolution. The computation results of the zero-yaw aerodynamic drag coefficient (C_d) of the M118 projectile for different turbulence models and mesh sizes are presented in Table 1.

Table 1 – Computational drag coefficients obtained with different turbulence models and mesh sizes at Mach 0.8

Turbulence models	**Mesh size (Million elements)**	**C_d**
Spalart-Allmaras	0.326	0.168
	2.514	0.131
	3.653	**0.128**
	5.273	0.128
Standard k-ω	0.326	0.175
	2.514	0.127
	3.653	**0.113**
	5.273	0.113
SST k-ω	0.326	0.158
	2.514	0.119
	3.653	**0.114**
	5.273	0.114
Standard k-ε	0.309	0.167
	2.392	0.125
	3.266	**0.118**
	4.886	0.118
Realizable k-ε	0.309	0.163
	2.392	0.116
	3.266	**0.110**
	4.886	0.110

It can be seen from Table 1 that for the Spalart-Allmaras, the Standard k-ω and the SST k-ω turbulence models, from the mesh size of 3.653 million elements, the drag coefficients remain unchanged with the subsequent increase of the mesh size. Meanwhile, for the Standard k-ε and the Realizable k-ε models, from the mesh size of 3.266 million elements, the drag coefficients also remain unchanged with the subsequent increase of the mesh size. Consequently, the drag coefficients with the mesh sizes of 3.653 and 3.266 million elements can be taken as computational drag coefficients for the respective investigated turbulence models. The drag coefficient of the M118 projectile obtained experimentally is 0.132 (McCoy, 1988). The comparison of the drag coefficients obtained computationally against the experimental data is presented in Table 2.

Table 2 – Comparison of the computational drag coefficients with different turbulence models against the experimental data at Mach 0.8

Turbulence models	Computational C_d	Experimental C_d	Difference
Spalart-Allmaras	0.128	0.132	3.0%
Standard k-ω	0.113		14.4%
SST k-ω	0.114		13.6%
Standard k-ε	0.118		10.6%
Realizable k-ε	0.110		16.6%

Obviously, the drag coefficient obtained with the Spalart-Allmaras model is the closest to the experimental value (the discrepancy is only 3.0%), while the differences between the drag coefficients obtained with four remaining turbulence models and the experimental value are greater than 10%. Additionally, the Realizable k-ε has shown the lowest prediction of the drag coefficient. The Standard k-ω and the SST k-ω turbulence models have given similar values of aerodynamic drag coefficients. Except the Spalart-Allmaras model, the remaining models have a significantly underpredicted aerodynamic drag coefficient. Overall, it can be concluded that the Spalart-Allmaras is the most adequate turbulence model to predict the aerodynamic drag of a spin-stabilized projectile at subsonic speed.

Comparative performance of the turbulence models at supersonic flow

In this section, the aerodynamic zero-yaw drag coefficient of the M118 projectile was obtained using CFD simulation at the Mach number of 1.8 with five turbulence models of interest and compared against experimental data to assess the capability of each turbulence model at the supersonic flow regime. The research strategy used previously for the subsonic flow is also adopted for the supersonic flow here. In the end, the simulation results of the aerodynamic drag coefficients with different turbulence models and mesh sizes are presented in Table 3.

Clearly, the mesh independence study has indicated that from the mesh sizes of 3.653 million elements for the Spalart-Allmaras, the Standard k-ω and the SST k-ω models and of 3.344 million elements for the Standard k-ε and the Realizable k-ε models, the subsequent additional mesh refinements will not change the simulation results. Therefore, the aerodynamic drag coefficients obtained with these mesh sizes can be accepted as the computational drag coefficients for the respective turbulence models.

Table 3 – Computational drag coefficients obtained with different turbulence models and mesh sizes at Mach 1.8

Turbulence models	**Mesh size (Million elements)**	C_d
Spalart-Allmaras	0.326	0.389
	2.522	0.377
	3.653	**0.374**
	5.273	0.374
Standard k-ω	0.326	0.370
	2.522	0.345
	3.653	**0.328**
	5.273	0.328
SST k-ω	0.326	0.369
	2.522	0.351
	3.653	**0.348**
	5.273	0.348
Standard k-ε	0.311	0.382
	2.436	0.352
	3.344	**0.348**
	4.963	0.348
Realizable k-ε	0.311	0.380
	2.436	0.338
	3.344	**0.335**
	4.963	0.335

To assess the performance of the turbulence models, the computational aerodynamic drag coefficients are compared to the experimental data (McCoy, 1988) as presented in Table 4.

It is evident that the drag coefficients obtained using the SST k-ω, the Standard k-ε and the Realizable k-ε models are the closest to the experimental value with the discrepancies of 2.0%, 2.0% and 1.8%, respectively. The Spalart-Allmaras model has significantly overpredicted the aerodynamic drag with the discrepancy of nearly 10%, meanwhile the Standard k-ω has slightly underpredicted the aerodynamic drag with the discrepancy of 3.8%. Therefore, these observations lead to the conclusion that it is appropriate to apply the SST k-ω, the Standard k-ε or the Realizable k-ε turbulence model in predicting the aerodynamic drag of a spin-stabilized projectile flying at supersonic speed.

Table 4 – Comparison of the computational drag coefficients with different turbulence models against the experimental data at Mach 1.8

Turbulence models	Computational C_d	Experimental C_d	Difference
Spalart-Allmaras	0.374	0.341	9.7%
Standard k-ω	0.328		3.8%
SST k-ω	0.348		2.0%
Standard k-ε	0.348		2.0%
Realizable k-ε	0.335		1.8%

Conclusion

In this study, the comparative performance of five distinct turbulence models in predicting the aerodynamic drag coefficient of the M118 projectile at subsonic and supersonic flows was numerically investigated. In summary, the following conclusions can be drawn from the study:

Firstly, CFD is a powerful numerical tool to study the flow around projectiles as well as to predict their aerodynamic characteristics. The obtained simulation results have shown a good agreement with the experimental data measured from spark range firings.

Secondly, the turbulence models perform differently at different flow regimes. In general, the Spalart-Allmaras is the most suitable turbulence model for the subsonic flow, meanwhile the Standard k-ε, the Realizable k-ε and the SST k-ω turbulence models are recommended for the supersonic flow regime.

The findings in this study provide necessary guidance for the selection of an appropriate turbulence model to predict and analyze the aerodynamic characteristics of a spin-stabilized projectile. The comparative result obtained in the present research is a significant contribution to the field of computational aerodynamics for better understanding the capability of the available turbulence models in the RANS approach.

Future work

Although the presented study has shed light on some questions regarding the performance of five most widely used turbulence models on the aerodynamic drag coefficient prediction, further work needs to be done to establish whether each of the turbulence models is suitable for predicting dynamic aerodynamic coefficients, such as roll-damping moment coefficient, pitch-damping moment coefficient, Magnus force and moment coefficients of a spin-stabilized projectile. Therefore, further analysis of dynamic aerodynamic coefficients would be recommended for a deeper understanding of the ability of the existing turbulence models.

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Un estudio comparativo de modelos de turbulencia para predecir la resistencia aerodinámica de un proyectil estabilizado por giro

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CAMPO: ingeniería mecánica, dinámica de fluidos, balística exterior
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: En esta investigación, se analizó la influencia de diferentes modelos de turbulencia en la predicción de la resistencia aerodinámica de un proyectil genérico estabilizado por giro. Los modelos de turbulencia elegidos para la investigación fueron Spalart-Allmaras de una ecuación, los modelos de dos ecuaciones Standard k-ε, Realizable k-ε, Standard k-ω y SST k-ω. El proyectil especial de francotirador M118 se seleccionó para el estudio.

Métodos: Los flujos alrededor del proyectil se simularon numéricamente utilizando ecuaciones RANS integradas en el software ANSYS Fluent con diferentes modelos de turbulencia. La simulación numérica se llevó a cabo a varios números de Mach para estudiar el efecto de los modelos de turbulencia en la predicción de la resistencia aerodinámica del proyectil. Los resultados computacionales se compararon con los datos *experimentales disponibles para evaluar la capacidad de los modelos de turbulencia.*

Resultados: Los resultados de la investigación han demostrado que los modelos de turbulencia afectan significativamente los resultados de la simulación numérica. El modelo de turbulencia de Spalart-Allmaras funciona mejor que otros modelos en el régimen de flujo subsónico. Los modelos Standard k-ε, Realizable k-ε y SST k-ω funcionan mejor que otros modelos en el régimen de flujo supersónico.

Conclusión: La dinámica computacional de fluidos es una herramienta poderosa para analizar la aerodinámica de cuerpos voladores. Al seleccionar adecuadamente los modelos de turbulencia, se puede investigar con precisión el flujo alrededor de los cuerpos voladores. En el caso de proyectiles genéricos de ojiva-cilindro-cola de barco, por un lado, el modelo de Spalart-Allmaras es adecuado para el flujo subsónico, y por otro lado, se recomiendan los modelos Standard k-ε, Realizable k-ε y SST k-ω para el régimen de vuelo supersónico.

Palabras claves: modelos de turbulencia, Ansys Fluent, proyectiles estabilizados por giro, flujo subsónico, régimen de vuelo supersónico.

Сравнительное исследование моделей турбулентности для прогнозирования аэродинамического сопротивления снаряда стабилизируемого вращением

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РУБРИКА ГРНТИ: 30.17.33 Газовая динамика,
30.17.53 Прикладная аэродинамика
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье исследовано влияние различных моделей турбулентности на прогнозирование аэродинамического сопротивления снаряда, стабилизируемого вращением вокруг продольной оси. Для проведения исследования были выбраны следующие модели турбулентности: модель Спаларта-Аллмараса с одним уравнением, модель Standard k-ε с двумя уравнениями, Realizable k-ε, Standard k-ω и SST k-ω. В качестве снаряда был выбран специальный снайперский патрон M118.

Методы: Потоки вокруг снарядов были численно проанализированы с использованием уравнений RANS, интегрированных в программное обеспечение ANSYS Fluent с *различными моделями турбулентности. Численное моделирование было проведено при различных числах Маха с целью изучения влияния моделей турбулентности на прогнозирование аэродинамического сопротивления снарядов. Для проверки моделирования результаты вычислений были сравнены с имеющимися экспериментальными данными.*

Результаты: Результаты исследований показали, что модели турбулентности оказывают существенное влияние на результаты численного моделирования. Модель турбулентности Спаларта-Аллмараса работает лучше других моделей при дозвуковом режиме течения. Модели Realizable k-ε и SST k-ω показали лучшие результаты при сверхзвуковом режиме течения.

Выводы: Вычислительная гидродинамика является эффективным инструментом для анализа аэродинамики летящих тел. Путем соответствующего выбора моделей турбулентности на разных скоростях можно с точностью испытать поток вокруг летящих тел. С одной стороны, для случаев типовых снарядов, таких как оживально-цилиндрическо-конический (boat tail), модель Спаларта-Аллмараса подходит для дозвукового режима течения. С другой стороны, модели Standard k-ω, Realizable k-ε и SST k-ω рекомендуются для сверхзвукового режима течения.

Ключевые слова: модели турбулентности, Ansys Fluent, стабилизируемые вращением снаряды, дозвуковой поток, сверхзвуковой режим полета.

Компаративна студија модела турбуленције за предвиђање аеродинамичког отпора код пројектила стабилизованог ротацијом око уздужне осе

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ОБЛАСТ: машинство, динамика флуида, спољна балистика
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У овом истраживању анализиран је утицај различитих модела турбуленције на предвиђање аеродинамичког отпора генеричког пројектила стабилизованог ротацијом око уздужне осе. Модели турбуленције који су одабрани за истраживање били су Spalart-Allmaras-ов модел са једном једначином, као и модели са две једначине: Standard κ-ε, Realizable κ-ε, Standard κ-ω и SST κ-ω. За студију је одабран специјални снајперски метак М118.

Методе: Урађена је нумеричка симулација струјања око пројектила помоћу RANS једначина интегрисаних у софтверу ANSYS Fluent са различитим моделима турбуленције. Нумеричка симулација је изведена за различите бројеве Маха ради проучавања утицаја модела турбуленције на предвиђање аеродинамичког отпора пројектила. Резултати прорачуна упоређени су са доступним експерименталним подацима ради процене модела турбуленције.

Резултати: Показано је да модели турбуленције имају значајан утицај на резултате нумеричке симулације. Spalart-Allmaras-ов модел турбуленције показао се бољи од других модела у режиму подзвучног струјања, док су модели Realizable κ-ε и SST κ-ω ефикаснијиод других модела у режиму суперсоничног струјања.

Закључак: Рачунарска динамика флуида је моћан алат за анализу аеродинамике тела у лету. Струјање око тела у лету може се прецизно испитати помоћу одговарајућег избора модела турбуленције. Код типова генеричких пројектила, са оживално-цилиндричним и делимично конусним задњим делом (boat tail), модел Spalart-Allmaras је погодан за подзвучни режим струјања, док су, с друге стране, модели Standard k-ω, Realizable κ-ε и SST κ-ω погоднији за режим надзвучног струјања.

Кључне речи: модели турбуленције, Ansys Fluent, пројектили стабилизовани ротацијом око уздужне осе, подзвучно струјање, режим надзвучног лета.

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