Авиационная и ракетно-космическая техника

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Корректировка модели турбулентности для определения коэффициента сопротивления осесимметричной модели с лодочной хвостовой частью на транс- и сверхзвуковых скоростях

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Adjustment of the turbulence model for determining drag coefficient of an axisymmetric boattail model at transonic and supersonic conditions*

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Для повышения точности численных результатов по определению коэффициента сопротивления осесимметричной модели с лодочной хвостовой частью на сверхзвуковых скоростях выполнена корректировка модели турбулентности k–ω SST. Численный метод модифицирован путем уточнения параметров модели турбулентности: a_1 и β^* для различных значений числа Маха. Скорректированная модель турбулентности k–ω SST позволяет снизить погрешность численных результатов на 0,06…0,18 % по сравнению с экспериментальными данными при числе Маха 1,2…2,5. Результаты подтверждены для 130-миллиметровой модели снаряда.

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Ключевые слова: вычислительная гидродинамика, модель турбулентности, численный анализ, трансзвуковая скорость, коэффициент сопротивления

To improve accuracy in numerical results of determining the drag coefficient for an axisymmetric boat tail model at the supersonic speeds, the paper adjusts the k–ω SST turbulence model. The numerical method is modified by refining the a_1 and β^* turbulence model parameters for the different Mach numbers. The adjusted k–ω SST turbulence model allows reducing the error in numerical results by 0.06…0.22 % compared to the experimental data obtained at the Mach number of 1.2…2.5. The results were confirmed using the 130-mm projectile model.

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Keywords: computational fluid dynamics, turbulence model, numerical analysis, drag coefficient

In engineering applications, most fluid flows are turbulent. In computational fluid dynamics (CFD) the turbulent characteristics of the flow are modeled through turbulence models. The complexity of a turbulence model is evaluated based on the number of differential equations and the number of additional empirical constants required to describe the turbulent flow. Currently, basic turbulence models include: Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), Detached Eddy Simulation (DES) and Reynolds-Averaged Navier-Stokes (RANS). DNS [1] provides the most accurate results because it solves directly the Navier-Stokes equations without any additional equations. However, the computational resources are extremely large, especially at high Reynolds numbers. As a result, its application is limited to problems with low Reynolds numbers and small computational domains. The main goal of LES [2] is to reduce the computational cost of numerical simulations by ignoring smaller turbulent eddies in a turbulent flow. However, its computational demands are still high for most practical applications. Due to its lower computational requirements and relative accuracy in many aerodynamic applications, RANS mainly is used for CFD applications and it is considered the most practical choice for turbulence modeling [3]. Among RANS turbulence models, the k–ω SST model (where k is turbulent kinetic energy; ω is specific dissipation rate; SST is Shear Stress Transport) has many advantages in accurately reflecting the characteristics of boundary layer flows and far-field flows. This turbulence model is widely used to describe flows around flying objects.

For the flow around the blunt axisymmetric body using boattail, particularly the research by Tran et al. [4] and Marioti et al. [5], the turbulent flow structure around the boattail is highly complex. There are regions of flow separation behind the model and reattachment positions on the surface of the boattail. Flow separation is a complex issue in fluid dynamics. For flying objects, flow separation leads to a reduction in lift and an increase in drag. In many cases, it can cause stall or vibrations; therefore, accurately predicting flow separation is crucial in designing flying objects. However, using RANS in numerical simulations faces many challenges. The difficulty arises due to the presence of large adverse pressure gradients in the separation region. The study by Forsythe et al. [6], using DES and RANS models to simulate the flow around the tail, show that RANS inaccurately predicted the flow at the tail comparing to experimental results, especially in terms of pressure distribution. In contrast, DES provided more accurate prediction of the boundary layer comparing to experimental results. To overcome the discrepancies between numerical simulation results using RANS and experimental results, a proposed solution is recommended by adjusting the parameters of the turbulence model. Although adjusting these turbulence model parameters has not been applied to axisymmetric flying object models, it has been utilized in several simulations of wing models. For instance, the study by Rocha et al. [7] involved adjusting the k–ω SST turbulence model by experimenting with different values of the turbulent diffusion coefficient β^* when simulating the flow around a NACA 0012 wing. The results showed that changes in β^* significantly affected the viscous friction on the wing surface. Another adjustment method was used by Matyushenko and Garbaruk [8] to predict the flow characteristics around a wing under stall conditions by adjusting structural coefficient a_1. The results show that reducing a_1 increased the size of the recirculation region. In the Menter's report [9], the authors also affirmed that adjusting a_1 is necessary for different research models. Additionally, Hellsten [10] suggested that the limitations of the k–ω SST turbulence model are only suitable for fully wall-bounded flows. Younoussi and Ettaouil [11] also adjusted a_1 and β^* to improve the k–ω SST turbulence model for simulating the flow over the wind turbine in stall condition.

Thus, it can be seen that the adjustment method for turbulence models is a potential solution for accurately simulating the flow separation around the boattail of the axisymmetric body. This type of adjustment has not been previously applied to similar models, which requires further research. This paper proposed adjusting the k–ω SST turbulence model through the structural parameter a_1 and the turbulent diffusion parameter β^*. This solution can fill the gap between simulation results and experimental results of the drag coefficient of the boattail axisymmetric model.

Numerical methods. ***RANS k–ω SST turbulence model.*** To solve the system of Navier—Strokes equations, a turbulence model must be developed to describe the Reynolds shear stress. The complexity of a turbulence model is assessed by the number of transport equations. The well-known two-equation models are the k–ε and k–ω models. In that, one equation describes the quantity eddy-viscosity μ_t through the turbulent dissipation rate ε or ω, while another equation describes the turbulent kinetic energy k. Based on the k–ε and k–ω turbulence models, Menter [12] proposed k–ω SST models, which use two transport equations (1) and (2) to achieve the advantages from both k–ε and k–ω models:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_j k)}{\partial x_j}=$$

$$=\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right]+\tau_{ij}\frac{\partial u_i}{\partial x_j}-\beta^*\rho\omega k; \quad (1)$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho u_j\omega)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial \omega}{\partial x_j}\right]+\alpha S^2-$$

$$-\beta\rho\omega^2+2(1-F_1)\sigma_{\omega 2}\frac{\rho}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, \quad (2)$$

where ρ is density; t is time; u_j is velocity vector; x_j is position vector; μ is molecular viscosity; σ_k is turbulent Prandtl number for k; μ_t is eddy-viscosity; σ_ω is turbulent Prandtl number for ω; α is blending function coefficient for eddy viscosity; S is strain rate magnitude; β is turbulent destruction coefficient; F_1 is the first blending function; $\sigma_{\omega 2}$ is turbulent Prandtl number in the far field.

In the above equations, the two default coefficients a_1 and β^* are set as 0.31 and 0.09 respectively. Other coefficients were presented in Menter's study [12] .

The eddy-viscosity is

$$\mu_t=\rho\nu_t=\frac{\rho a_1 k}{\max(a_1\omega,\, SF_2)},$$

where ν_t is turbulent eddy viscosity; F_2 is the second blending function.

Due to the advantages of the k–ω SST turbulence model in accurately describing flow around objects, especially in characterizing the boundary layer on the surface of objects, this study selected this turbulence model for calculating and simulating the flow around axisymmetric flying bodies. However, it is noted that turbulence models are typically developed from certain experimental data. Most of Menter' research was based on data of the flow over flat plates under specific flow conditions. The selection of these coefficients in the transport equations generally applies for several cases. Therefore, it is crucial to calibrate the turbulence model for specific calculation models. Additionally, it can be observed that flow separation and reattachment depend on the estimation of eddy viscosity in the turbulence model, specifically on the coefficient a_1. The flow around the boattail plays a crucial role in the formation of drag so accurately determining turbulent viscosity is essential. According to Menter's research [9], adjusting a_1 is necessary to improve the efficiency of the k–ω SST turbulence model. Besides a_1, due to the Production P_k and Dissipation D_k quantities of turbulent kinetic energy, adjusting the turbulent diffusion coefficient β^* is also needed. P_k and D_k are defined as:

$$D_k=\beta^*\rho k\omega.$$

The values of these two coefficients are not fixed and depend on different specific model. Menter [12] also proposed that in adverse pressure gradient flow, $P_k >> D_k$ so the relation between a_1 and β^* can be found that

$$a_1 S>\beta^*\omega.$$

Moreover, in order to effectively use the blending function F_1 and F_2 in the k–ω SST turbulence model for describing the boundary layer, a_1 is also satisfied as

$$a_1\omega\geq S.$$

Thus, in order to describe large negative pressure gradient flow and boundary layer, when a_1 and β^* must be satisfied:

$$a_1^2>\beta^*. \quad (3)$$

This condition also is appropriate with the default coefficients $a_1=0.31$ and $\beta^*=0.09$ in the k–ω SST model [9]. The values of a_1 and β^* were modified following the equation (3) in different Mach numbers in order to find the most appropriate values closed to experimental data. The research used the Ansys Fluent software.

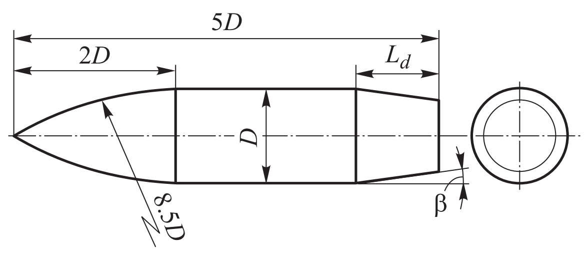

Figure 1. Model geometry

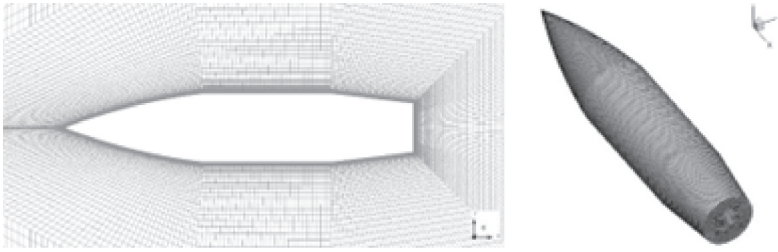

Figure 2. Mesh around and on the model

Numerical model. The axisymmetric model has the dimensions (Figure 1): D = 57 mm; $L = 5D$ = = 285 mm and $\beta = 7°$. This model is the same one used in experiments conducted by Platou [13]. This study uses experimental results from Platou's research to adjust the k–ω SST turbulence model. The numerical domain has a dimension of $36.5D \times 22D \times 22D$ in x, y, and z directions, which was used in the previous studies of the axisymmetric models [14].

To verify grid independence, the number of grid cells was increased from 1.44 million to 4.40 million. The convergence criterion was set with a residual of 10^{-5}. The results showed that the drag coefficient C_{D0} remained nearly unchanged when the number of grid cells reached 3.16 million (Figure 3). Therefore, the grid with 3.16 million cells was selected for the numerical simulation to ensure both accuracy and optimal computation time. In addition, Figure 4 illustrates the y^+ values on the surface of the model. The results show that $y^+ < 1$ across the entire surface of the model, which are appropriate to the k–ω SST model. The accuracy of the numerical results are presented in the Figure 5. Based on the small difference between numerical and experimental results of the drag coefficient, the numerical model is good enough for simulating the flow over the research model.

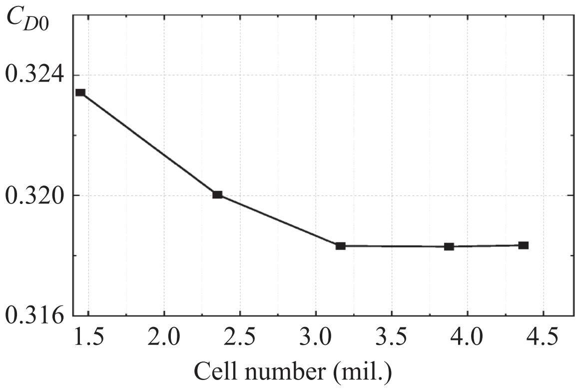

Figure 3. Effect of mesh on the model drag coefficient

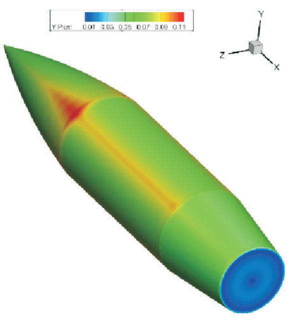

Figure 4. Values of y^+ in the model surface

Results and discussions. *Comparison between k–ε, k–ω, k–ω SST turbulence models.* In this study, RANS equations with k–ω SST turbulence model were used for the simulation. The k–ω SST turbulence model combine both advantages of the k–ε and k–ω. The k–ε turbulence model is considered one of the most popular turbulence models. The k–ε can obtain accurate results for flow far form wall, but it has limitations in describing cases with large pressure gradients. In contrast, for boundary layer flows, the k–ω model proposed is more advantageous in handling the near-wall viscous region and in its calculations for the effects of flow pressure gradients. Thus, the research on three turbulence models at M = 2.0 was conducted to clarify the advantage of the k–ω SST turbulence model. The results are presented in Table 1.

The results show that the k–ω SST turbulence model provided results that are closest to the experimental data. This clearly confirms the ad-

Table 1

Comparison of numerical results from different turbulence models at M = 2.0

Turbulent model	Drag coefficient	Error (%)
k–ε	0.37778	–13.92
k–ω	0.29689	10.47
k–ω SST	0.31874	3.88
Experimental Results [13]	0.33162	–

vantages of using this turbulence model, as it can accurately describe both the boundary layer and the flow away from the model surface. The k–ω SST model reduces the error from over 10 % to 3.88 % in comparison to the experimental results. Therefore, the study used the k–ω SST model for adjustment is reasonable.

Adjusted SST turbulence models. In order to adjust the k–ω SST turbulence model, the research was conducted with wide ranges of a_1 and β^*. The results of the effects of a_1 and β on the drag coefficient of the axisymmetric model are presented in Figure 4 and 6.

Figure 6 illustrates the impact of the a_1 on the drag coefficient of the axisymmetric model at $\beta^* = 0.09$. The results indicate that as a_1 increases, the drag coefficient value also rises. However, when $a_1 \geq 0.4$, the increase in drag becomes insignificant. The results show that the drag coefficient reaches its critical value at $a_1 = 0.4$ at $\beta^* = 0.09$.

Figure 7 presents the drag coefficient results at M = 2.0 at different value of β^*. It can be seen that as the value of β^* increases, drag coefficient according to all a_1 increases rapidly. At high value of a_1, the drag coefficient reaches peaks, then decreases following the increasing value of β^*. The maximum peak is nearly 0.355 at $a_1 = 0.9$ at $\beta^* = 0.5$. Notably, at lower β^* values, increasing a_1 does not significantly affect the drag coefficient. This outcome aligns with the previous observation that when a_1 reaches a critical value, further increasing a_1 is not advisable. This trend of the drag coefficient can be observed similarly at different Mach numbers. Thus, according to the experimental results, the best drag coefficient result, which is closest to the experimental ones can be chosen for the k–ω SST turbulence model at the corresponding Mach number.

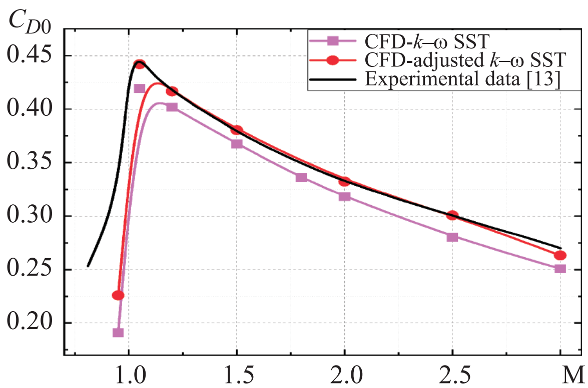

Figure 5. Comparison of Drag coefficient between different methods

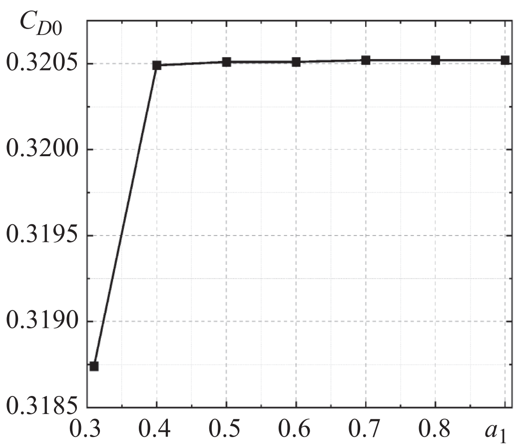

Figure 6. Effects of a_1 on the model drag coefficient at $\beta^* = 0.09$

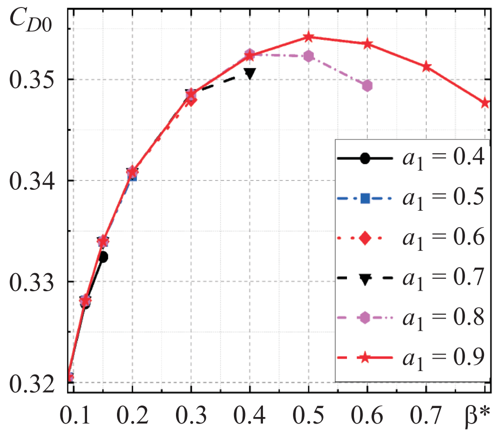

Figure 7. Effects of a_1 and β^* on the model drag coefficient at M = 2.0

The results with the smallest error when compared to experimental data across various transonic and supersonic conditions are summarized in Table 2.

Figure 5 shows the drag coefficient results obtained from different methods for the research model at transonic and supersonic velocity ranges. The results indicate that the adjusted k–ω SST turbulence model provides the best results across all different Mach numbers. Specifically, at the velocity range M = 1.2–2.5, the error compared to experimental results is nearly zero. At the velocity range M = 0.95, although the error is relatively high (33 %), it is still the best result when compared to other research models. At this velocity range, significant turbulence may be the direct cause of the errors in the simulation calculations. Therefore, further research needs to be conducted in this velocity range to address the remaining limitations.

Validation by 130 mm projectile model. The research applied adjusted k–ω SST turbulence

Table 2

The values of a_1 and β^* of the adjusted k–ω SST turbulence model at different Mach number

M	a_1	β^*	C_{D0}		Differences (%)
			Adjusted k–ω SST	Experiment [13]	
0.95	0.9	0.50	0.2259	0.3412	33.79
1.05	0.6	0.15	0.4440	0.4457	0.38
1.20	0.5	0.12	0.4169	0.4177	0.18
1.50	0.4	0.12	0.3804	0.3801	0.06
2.00	0.4	0.15	0.3324	0.3330	0.17
2.50	0.7	0.40	0.3008	0.3005	0.09
3.00	0.9	0.50	0.2633	0.2700	2.49

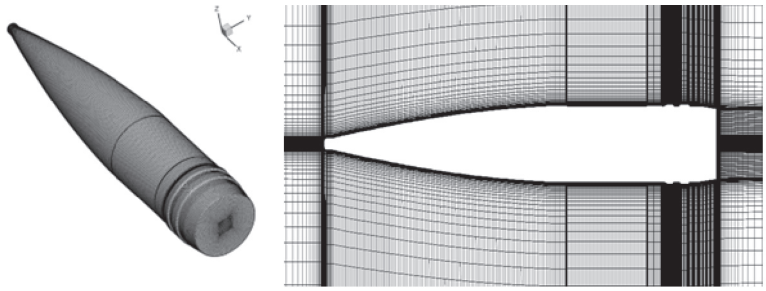

Figure 8. The 130 mm projectile model and mesh around model

model for a 130 mm projectile model (Figure 8). The numerical results of drag coefficient are compared with those using the standard k–ω SST turbulence model (Figure 9). The results show that when using the adjusted k–ω SST turbulence model, the drag coefficient increases in all Mach numbers.

From the aerodynamic coefficient results, the flight trajectory and maximum range of the model were calculated. The detailed results are presented Table 3. It can be seen that the results of the maximum range calculations for the 130 mm projectile model using adjusted k–ω SST turbulence model is more accurate than the standard k–ω SST model. The calculation error in maximum range (compared to the experimental results in the 130 mm projectile firing table) decrease from 9 to 4 %. Furthermore, the drag coefficient of the 130 mm model at 996.1 and 1003.1 m/s using the adjusted k–ω SST model is closer to the experimental data [15] (Table 4).

Thus, based on the 57 mm and 130 mm model, the adjusted k–ω SST turbulence model is evaluated to provide closer aerodynamic calculations to

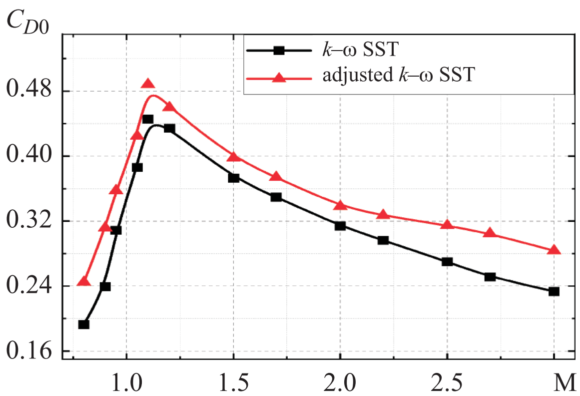

Figure 9. Comparison of Drag coefficients between adjusted k–ω SST and standard k–ω SST turbulence models

Table 3

The values of a_1 and β^* of the adjusted k–ω SST turbulence model at different Mach number

Turbulence model	Max range (m)	Error (%)
Standard k–ω SST	29.902	8.77
Adjusted k–ω SST	26.406	–3.94
Experiment data (from fire-table)	27.490	–

Table 4

Comparison of the drag coefficient of the 130 mm projectile model with experimental results [15] at supersonic speed

Speed (m/s)	Turbulence model	C_{D0}	Error (%)
996.1	Standard k–ω SST	0.2482	19.94
	Adjusted k–ω SST	0.2871	7.39
	Experiment data [15]	0.3100	–
1003.1	Standard k–ω SST	0.2470	11.79
	Adjusted k–ω SST	0.2885	3.04
	Experiment data [15]	0.2800	–

experimental data than the standard k–ω SST model. This is achieved by adjusting the parameters a_1 and β^* at different Mach numbers. It is showed that the the adjusted k–ω SST turbulence model has advantages in calculating aerodynamic coefficients for axisymmetric boattail model.

Conclusions

1. In this study, the method of adjusting the k–ω SST turbulence model at transonic and supersonics conditions is presented. The values of the drag coefficient of the boattail model were closer to the experimental data when using the adjusted model. The values of a_1 and β^* for the adjusted k–ω SST turbulence model at different Mach number were collected. These values are applicable for determining the drag coefficient of the axisymmetric boattail models at transonic and supersonic conditions. Especially, at M = 1.2–2.5, the gap between numerical and experimental results is approximately zero.

2. The adjusted k–ω SST turbulence model was also evaluated by the 130 mm projectile model and it provided better aerodynamic calculations than the standard k–ω SST model. This is considered a valuable contribution of the study in developing a turbulence model for axisymmetric flying objects. Additionally, this turbulence model adjustment method can be applied to other flying models when experimental results are available.

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