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ASSESSMENT OF TURBULENCE MODELS FOR FLOW SIMULATION AROUND THE AHMED BODY

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Abstract

This paper presents numerical simulations for the prediction of the flow around the Ahmed body, with the 25° and 35° slant angles, obtained with the flow solver ISIS-CFD. Two RANS (Reynolds Averaged Navier-Stokes) turbulence models, as the $k - \omega$ SST and the EARSM (Explicit Algebraic Stress Model) and two hybrid RANS-LES models, as DES (Detached Eddy Simulation) and IDDES (Improved Delay Detached Eddy Simulation) models, are used. The use of a hybrid RANS-LES model, and more particularly the IDDES model, offers an advantage over RANS models in term of the force coefficients, and general flow field.

1 Introduction

The external aerodynamics of a car determines many relevant aspects of an automobile such as stability, comfort and fuel consumption at high cruising speed, e.g. Hucho (1998). The flow around vehicles is characterized by highly turbulent and three-dimensional separations. There is a growing need for more insight into the physical features of these dynamical flows, on the one hand, and powerful numerical tools to analyze them on the other hand. Computations based on RANS equations are common in industry today. Although they are very successful in predicting many parts of the flow around a vehicle, they are unable to predict unsteadiness in the wake regions. The failure in predicting the base pressure is the major reason for large discrepancy in drag prediction between experiments and numerical simulations.

In an attempt to improve the predictive capabilities of turbulence models in highly separated regions, Spalart et al. (1997) proposed a hybrid approach which combines features of classical RANS formulations with elements of Large Eddy Simulations (LES) method. This concept has been termed Detached Eddy Simulation (DES) and is based on the idea of covering the boundary layer by a RANS model and of switching the model to a LES mode in detached regions. Compared to classical LES methods, DES save orders of magnitude of computing power for high Reynolds number flows, due to the moderated costs of a RANS model in the boundary layer region, but still offers

some of the advantage of a LES method in separated regions. A variant of the DES model, like Improved Delayed DES, IDDES, seems to be attractive. The numerical simulations, with these turbulence models, are carried out with the ISIS-CFD flow solver.

The purpose of this paper is to conduct a validation of the flow around the Ahmed body, see Ahmed et al. (1984), to compare RANS model and hybrid RANS-LES methodologies. Both the 25° and 35° slant back angles are investigated in this study to assess the capability of each turbulence model to capture the important changes in flow physics. The flow is at a Reynolds number of 2.8×10^6 , based on the length of the model, L , and the upstream velocity $U_\infty = 40$ m/s.

2 ISIS-CFD at glance

ISIS-CFD, developed by the Ecole Centrale de Nantes and CNRS and available as a part of the FINE/Marine computing suite, is an incompressible unsteady Reynolds-averaged Navier-Stokes (URANS) method. The solver is based on the finite volume method to build the spatial discretization of the transport equations. The unstructured discretization is face-based, which means that cells with an arbitrary number of arbitrarily shaped faces are accepted. A second order backward difference scheme is used to discretize time. The solver can simulate both steady and unsteady flows. The velocity field is obtained from the momentum conservation equations and the pressure field is extracted from the mass equation constraint, or continuity equation, transformed into a pressure equation. In the case of turbulent flows, transport equations for the variables in the turbulence model are added to the discretization. A detailed description of the solver is given by Queutey and Visonneau (2007).

RANS results shown in this paper are obtained using two turbulence models: the classical two-equation SST model of Menter (1994) ($k - \omega$ SST) and the anisotropic two-equation Explicit Algebraic Reynolds Stress Model (EARSM) presented by Deng and Visonneau (1999). For this turbulence model, the turbulent velocity and length scales are determined by using two transport equations, the $k - \omega$ BSL model proposed by Menter (1994). One hybrid RANS-LES method used is the Detached Eddy Simulation (DES), based on the $k - \omega$ model as proposed by Menter et al.

(2003). Recently, some modifications of this formulation proposed by Gritskevich et al. (2012) includes recalibrated empirical constants in the shielding function and a simplification of the original Spalart-Allmaras-based formulation. This new model is called Improved Delayed Detached Eddy Simulation (IDDES).

3 Numerical set-up

The computational domain starts 2L in front of the model and extends to 5L behind the model. The width of the domain is 1.87 m and its height is 1.4 m. These dimensions are recommended for the ERCOF-TAC workshop on Refined Turbulence Modelling, see Manceau and Bonnet (2002). The mesh is generated using Hexpress, an automatic unstructured mesh generator. This software generates meshes containing only hexahedrals. For the surface of the car model and the floor, a no-slip boundary condition is used and the wall normal resolution is set 0.0007 mm, i.e. $y^+ \leq 0.7$. For the 25° slant angle, the mesh consists of 23.1×10^6 cells and the model is described by 384,090 faces. For the 35° slant angle, the mesh consists of 22.2×10^6 cells and the model is described by 379,358 faces.

In this paper, for the RANS turbulence models, the time step is $\Delta t = 0.001$ s and the numerical simulation converge to a steady flow. For the hybrid RANS-LES models, the time step is $\Delta t = 2.5 \times 10^{-4}$ s and the flow is unsteady and the averaging time, $t \times U_\infty / L$ is 40 (160,000 time steps).

4 Results

The flow in the symmetry plane obtained with all turbulence models is reported in Figure 1 and Figure 2 for the 35° and 25° slant angles, respectively. For the 35° slant angle, see Figure 1, the main characteristic of the flow is a massive separation in the wake of the body. With the EARSM turbulence model, the separation is the higher than that obtained by all turbulence models. With the hybrid RANS-LES models, a small separation at the end of the slant. In the experiments, it is difficult to say if this recirculation is present. However, the separation obtained with the hybrid RANS-LES models is in good agreement with the experimental data. For the 25° slant angle, see Figure 2, a massive separation is always present in the wake of the Ahmed body with the RANS turbulence models. With the EARSM model, this separation is approximately the same as the one obtained with the 35° slant angle. With the hybrid RANS-LES models, the wake is different. The massive separation does not exist, only small separations are present. On the slant, a recirculation bubble is predicted with the IDDES model while with the DES model, this separation completely covers the slant. The wake of the Ahmed body predicted with the hybrid RANS-LES models is in good agreement with the experimental data.

Figure 3 shows a comparison of the streamwise velocity component on the rear slant in the symmetry plane. The experiment profiles are those obtained by Lienhart and Becker (2003). For the 35° slant angle, all turbulence models predict correctly the flow, a fully separated flow. The IDDES approach gives a better agreement with the experimental data at the shear layer region. For the 25° slant angle, as expected by the previous figure, the agreement with experiments on the slant is not good for the results obtained with the EARSM turbulence model. The hybrid RANS-LES approaches provide a good estimation of the boundary layer thickness at the end of the roof. However, with the IDDES model, the boundary layer thickness becomes less thick than that obtained with the DES model and this evolution is so in better agreement with experiments. The same observation is true for the 35° slant angle.

A comparison of the streamwise velocity component in the wake of the model is presented in Figure 4. For the 35° slant angle, all numerical simulations give a good agreement with the experimental data with a least good agreement for the EARSM turbulence model due to the size of the recirculation zone which is larger than that obtained with the other turbulence models. A difference between the profiles obtained with the RANS models and those obtained with the hybrid RANS-LES approaches is an overestimation of the underbody flow with the RANS models. For the 25° slant angle, as the RANS turbulence models predict a massive separation, the agreement with the experimental data is not good. With the hybrid RANS-LES turbulence models, as the separation is smaller, the results are in better agreement with the experiments. The results obtained with the IDDES approach match very well the experimental data.

The thickness of the boundary layer thinner with the IDDES model than the other turbulence is due to a separation present at the beginning of the roof, as shown Figure 5. Some experimental studies, see Spohn and Gilliéron (2002) or Sims-Williams and Dominy (1998), and numerical results, see Krajnović and Davidson (2005a) or Minguez et al. (2008), have recorded these recirculation on the front part of the body. Nevertheless, the most of the studies only focus on the slant part and the near wake of the model and do not provide any available data for the upstream flow. For the 25° slant angle, the streamlines issued from the lateral side of the model separate along the lateral edges of the rear window, roll up into the longitudinal vortex and reattach themselves on the rear window. This clearly visible in Figure 6(a) which presents the streamlines around the back of the Ahmed body obtained with the IDDES model. Then a portion of the fluid moves toward the side edge and separates again along a separation line. The flow in the middle part of the slant surface separates at the upstream edge. The reattachment point is located at 77% of the slant

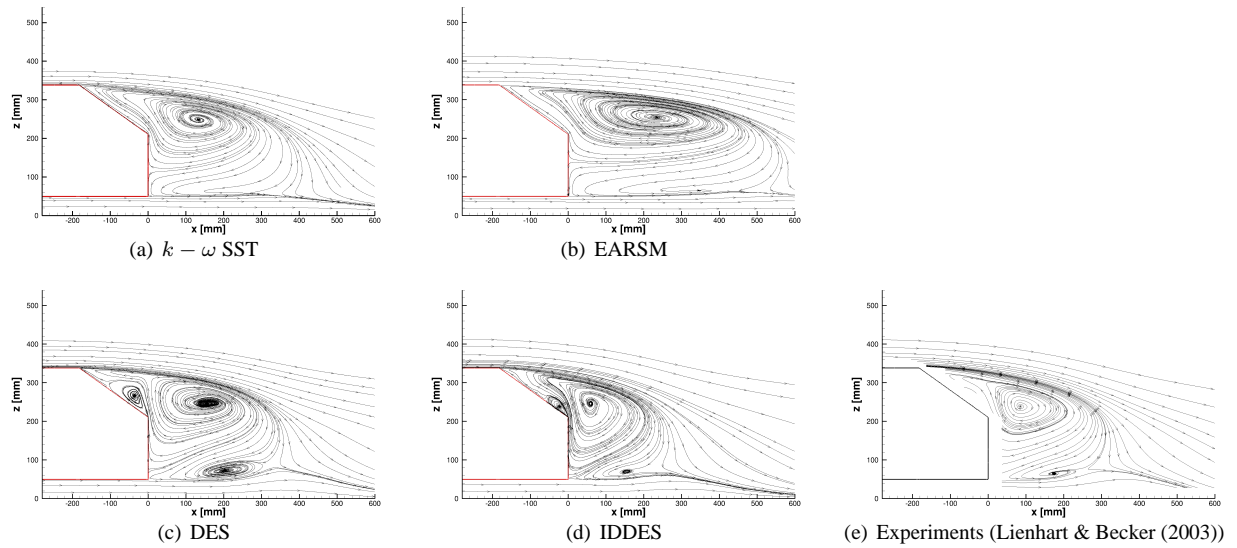


Figure 1: 35° slant angle - Streamlines in the symmetry plane.

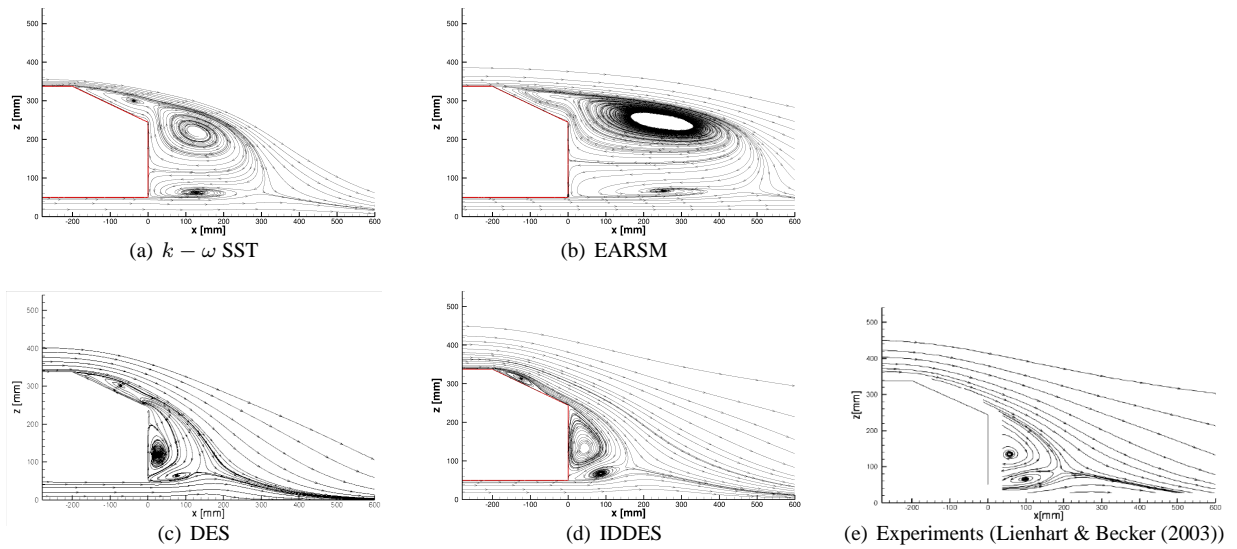


Figure 2: 25° slant angle - Streamlines in the symmetry plane.

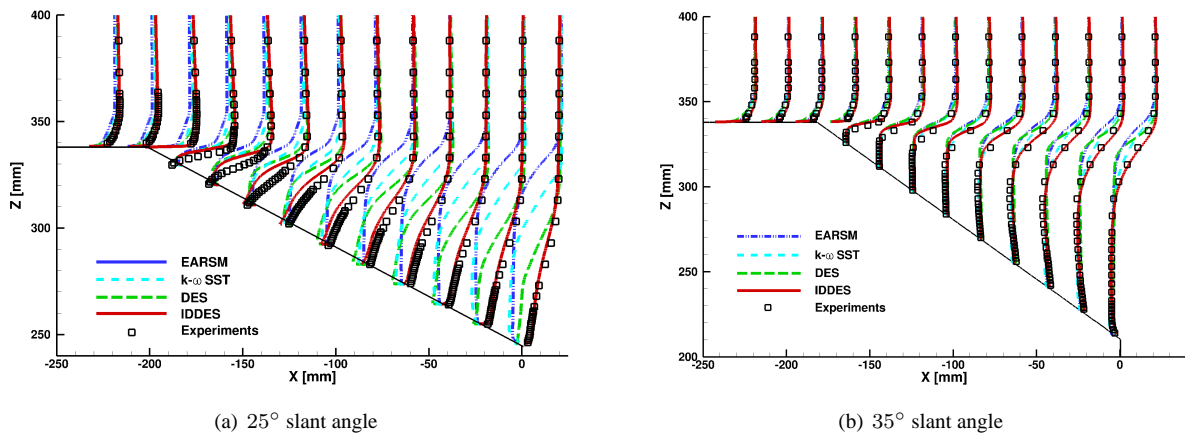
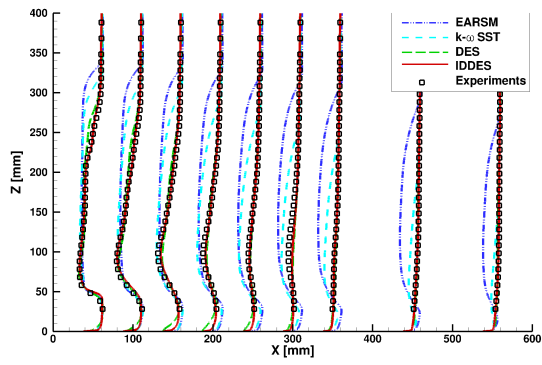
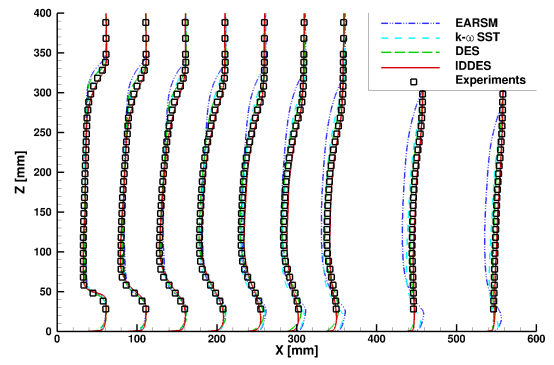


Figure 3: Comparison of the streamwise velocity component on the rear slant in the symmetry plane.

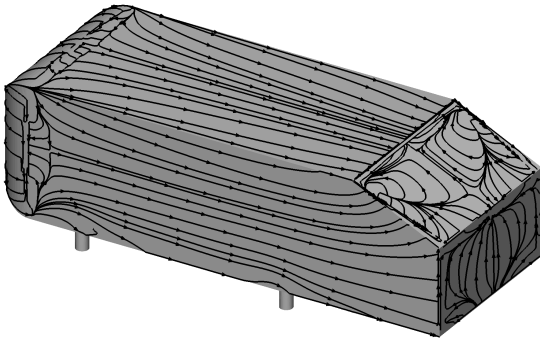


(a) 25° slant angle

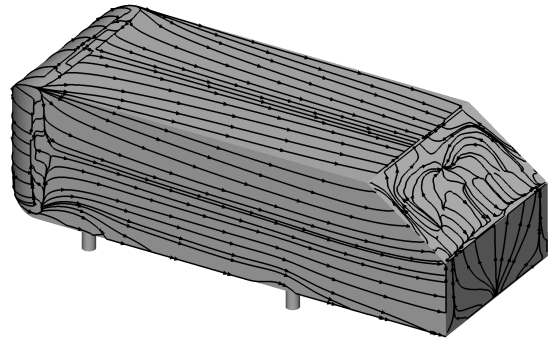


(b) 35° slant angle

Figure 4: Comparison of the streamwise velocity component on the rear slant in the symmetry plane.

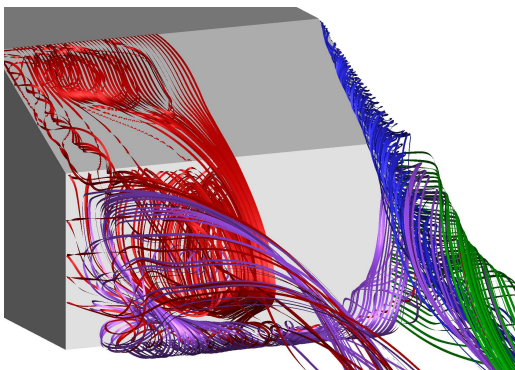


(a) 25° slant angle

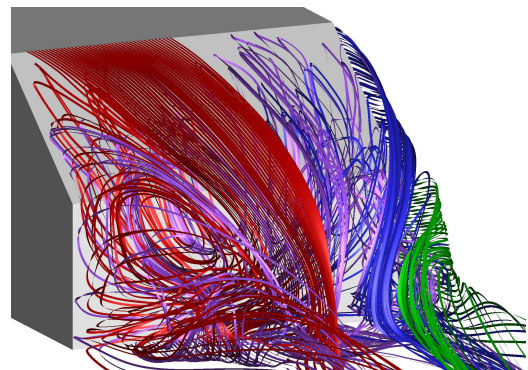


(b) 35° slant angle

Figure 5: Frictionlines on the Ahmed body obtained with the IDDES model.



(a) 25° slant angle



(b) 35° slant angle

Figure 6: Stream-ribbons from the edge between the roof and the rear window (purple), between the underbody and the base (red), from the upper part (blue) and the lower part (green) of the side of the Ahmed body obtained with the IDDES model.

length while in experiments, see Thacker (2010), this point is located at 72% of the slant length. The friction lines indicate the existence of secondary counter-rotating longitudinal vortices along the lateral edge as observed by Krajnović and Davidson (2005b)

For the 35° slant angle, the shear layer, predicted by the IDDES model, developed on the roof of the model separates near the upper edge of the rear window, as shown in Figure 6(b). The streamlines issued from the lateral side of the model do not roll up into a longitudinal vortex and so the C-pillar vortex is not present.

Figure 7 presents a comparison of the turbulent kinetic energy (TKE) over the rear slant for the 25° and 35° slant angles. For the 35° slant angle, the agreement with experiments is quite good. However, near the region of the shear layer of the external zone of the separation, close to the end of the rear window, the level of TKE is overestimated while for the other positions, the agreement is better. For the 25° slant angle, with the RANS turbulence models, the results are underestimated just after the upper edge of the rear window. This means less turbulent mixing and thus a greater recirculation region. With the hybrid RANS-LES models, the TKE is overestimated and particularly at the end of the slanted surface. However, for the first X-positions on the slant, the results obtained with the IDDES model are in relatively good agreement with the experimental data.

The evolution of the pressure coefficient, C_P , in the symmetry plane of the model for $Z \geq 194$ mm, which corresponds to the upper half of the Ahmed body, is drawn in Figure 8. Until $X = -600$ mm, the evolution of C_P is similar for both slant angles. A high pressure at the front of the model is observed. On the front part, the flow speed increases and the pressure decreases. Before the end of the front, the pressure increases, followed by a small variation only with the IDDES model, which indicates the presence of a recirculation. Then, the pressure rises slowly until $X = -600$ mm. After this abscissa, the evolution depends on the slant angle. For the 35° slant angle, the pressure decreases slowly until the edge of the rear window. On the slanted surface, the pressure is practically uniform. For the 25° slant angle, the pressure decreases until the edge of the rear window, except with the EARSM turbulence model where the pressure is almost uniform. Close to the edge of the rear window, the low level of pressure is only predicted by the IDDES model. Then, on the slanted surface, the evolution of pressure is only predicted with the same model. With the DES model, as this modelization predicts a large bubble, the increase of the pressure is shifted in X direction while with the $k - \omega$ SST model, the pressure evolution has a very mild slope.

Similar to Ahmed et al. (1984) did, the pressure drag from the front, C_K , for the rear slant, C_S , and for the base of the model, C_B , are presented in Table 1.

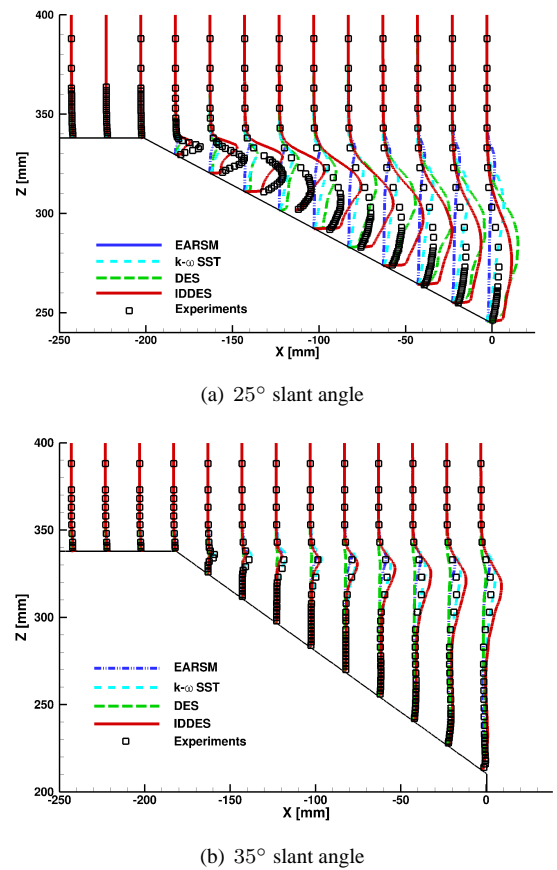


Figure 7: Comparison of the turbulent kinetic energy on the rear slant in the symmetry plane.

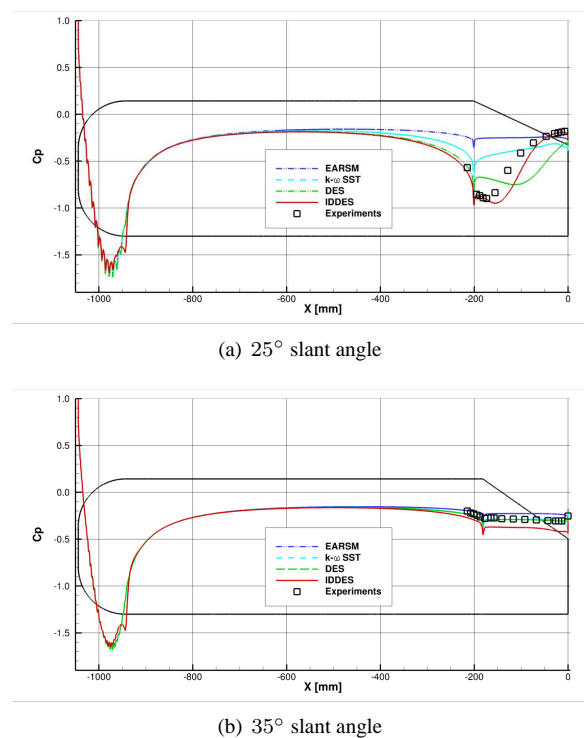


Figure 8: Pressure coefficient in the symmetry plane for the upper part of the Ahmed body.

Table 1: Ratio of pressure force coefficients.

	25° slant angle			35° slant angle		
	$C_B/C_{d,P}$	$C_S/C_{d,P}$	$C_K/C_{d,P}$	$C_B/C_{d,P}$	$C_S/C_{d,P}$	$C_K/C_{d,P}$
$k - \omega$ SST	48.27%	48.02%	3.70%	46.48%	49.92%	3.61%
EARSM	59.05%	35.49%	5.46%	50.11%	45.33%	4.57%
DES	42.56%	54.08%	3.36%	50.38%	47.03%	2.58%
IDDES	38.96%	58.25%	2.79%	46.65%	51.25%	2.11%
Experiments	35.10%	57.55%	7.35%	44.28%	48.26%	7.46%

The total pressure drag coefficient, $C_{d,P}$, represents the sum of C_K , of C_S and of C_B . In this table, the experimental values of Ahmed et al. (1984) are also indicated. For the 25° slant angle, in experiments, the pressure drag on the rear window, C_S , is the greater part of the pressure drag. Only, the hybrid RANS-LES models predict this behavior. However, the values obtained with the IDDES model are in good agreement with the experimental values, except for C_K which is underestimated. This is true for all turbulence models. For the 35° slant angle, in experiments, the force on the rear slant surface, C_S , is slightly above the force on the base of the model, C_B . For the numerical simulations, this is true only for the results obtained with the $k - \omega$ SST and the IDDES models. As for the previous slant angle, the contribution of C_K is smaller in the numerical simulations than in experiments.

5 Conclusions

An investigation of RANS and hybrid RANS-LES turbulence models for the Ahmed body at 25° and 35° slant angle cases has been conducted. The RANS turbulence models used are $k - \omega$ SST model and the EARSM. For the hybrid RANS-LES models, the use of DES and IDDES models, are investigated. This paper shows that the IDDES model offers an advantage over the other turbulence models used in terms of flow field and in pressure force coefficients.

For the 35° slant angle, all simulations are in agreement with the experimental data. However, the IDDES model gives a better agreement, in particular at the shear layer of the separation and also for the ratio between the pressure drag for the rear slant and the pressure drag for the base.

For the 25° slant angle, the numerical results are highly dependent on the turbulence model used. The RANS approach fails to capture the separation bubble on the slant. The IDDES approach is the only one to predict correctly the bubble on the slant as well as its size. Therefore, the velocity profiles and the turbulent kinetic energy are in agreement with the experimental data. Moreover, this model is the only one that predicts the correct ratio on the pressure drag on the slanted surface and on the base surface.

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