PHOENICS Implementation of the Spalart-Allmaras Turbulence Model

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Introduction

The Spalart-Allmaras (SA) model is a one-equation turbulence model designed for aerodynamic applications involving wall-bounded flows. First introduced in 1992 [1], it is a low-Reynolds number (LRN) model that solves for the undamped turbulent kinematic viscosity. Whilst it has been calibrated and widely used for wall-bounded aerodynamic and turbomachinery applications, it is unable to model free shear flows and decaying turbulence with accuracy.

Its main advantage is its simplicity, requiring less computation time than more complex 2-equation models. The model is also considered more robust than the LRN k-ε model, providing reasonable results on relatively coarse grids compared to the finer grids required by more complex LRN models. However, this simplicity means that in some flows, accuracy is lost compared to the 2-equation models.

Although designed as a LRN model, the SA model can be adapted for use with wall functions in a high Reynolds-number closure. In addition, a number of variants of the original model have been proposed, such as modifications to account for rotation and curvature effects, and handling negative viscosity values. A full list of the variations with detailed descriptions can be found at [2]. These modifications can be applied individually or in combinations to the original model.

This article reports on the provision of the SA turbulence model as a standard option in PHOENICS Classic 2025. The motivation for including this model in PHOENICS stems not only from its popularity, but also from its ability to provide cost-effective solutions for wall-bounded flows. The remainder of this article provides brief details on the implementation, activation, verification and validation of the model. Some concluding remarks are provided in section 4.

PHOENICS Implementation and User Activation

In PHOENICS, the SA model is implemented without any trip terms following standard practice. The original model includes two trip terms, but both are generally omitted, assuming free-stream turbulence. A rotation correction [3] is included in the production term of the undamped turbulent kinematic viscosity, with a lower limit [2] imposed to avoid the numerical problems which would arise if the term became zero or negative. The rotation correction reduces eddy viscosity in regions where vorticity exceeds strain rate.

The model is available in both high- and low-Reynolds number forms within PHOENICS. The high-Reynolds number model uses equilibrium wall functions and the value of the undamped turbulent kinematic viscosity at the wall is dependent on the friction velocity. The low-Reynolds number model integrates down to the wall with zero turbulent kinematic viscosity at the wall, requiring y+ values near 1.

The SA model has been implemented for Cartesian, polar and BFC meshes, and can be used with both SPARSOL and PARSOL. Users can activate the model from the VR menu, in *Main Menu > Models > Turbulence models*. The options for the high- and low-Reynolds number models are selected as "Spalart-Allmaras" and "Spal-Allm-lowRe" respectively (**Error! Reference source not found.**). The undamped turbulent kinematic viscosity is stored as ENTI with default whole-field solution.

The model has been tested on the Stones solver in serial and default parallel solver in PHOENICS. Convergence is generally good provided near-wall velocity values remain stable. It is recommended to apply linear relaxation to ENTI, with values of 0.3-0.5 giving good convergence during model verification and validation.

Several example cases are included in the PHOENICS library (see Applications section), and a full technical description is included in POLIS at https://www.cham.co.uk/phoenics/d_polis/d_enc/turmod/enc_t322.htm.

Applications

This section will present the validation cases and 3D time comparisons to demonstrate the advantages of the SA model over the more complex 2-equation models.

3.1. Validation

The model has been successfully validated in PHOENICS for a selection of cases, including channel and pipe flow, flow past a backward-facing step, flow over a flat plate, flow past a blunt flat plate and flow over a surface-mounted square rib. These cases have all been validated for both model variants. Additional cases for aerofoils and 3D flow past a surface-mounted cube have been validated for the high-Reynolds number form of the model. Due to time constraints, these cases have not included grid-sensitivity studies.

The results for flow over a flat plate, flow over a backward-facing step and flow past a blunt flat plate will be presented here.

Flow over a Flat Plate: The problem considered is steady, incompressible, turbulent flow across a smooth flat plate with zero pressure gradient. Since this is one of the cases on which the original model was calibrated, we would expect the SA model predictions to be in strong agreement with the expected values, and this is the case for all predicted quantities. **Error! Reference source not found.** shows the predicted u+ profile near the wall compared to theoretical values. The PHOENICS prediction shows excellent agreement. Additionally, **Error! Reference source not found.** shows the predicted skin friction coefficient compared to the correlation of Schlichting [5], again showing excellent agreement.

Backward-facing step: This case is 2D flow over a backward facing step in a channel, with an expansion ratio of 1.125, and Reynolds number of 36,000 based on step height H. The SA model captures the separation region well, predicting a reattachment length x/H of 6.4 and 6.0 in the low- and high-Reynolds cases respectively, in good agreement with experimental results of 6.26. **Error! Reference source not found.** shows the pressure coefficient compared to the data of Driver and Seegmiller [6], again demonstrating good agreement.

Flow past a Blunt Flat Plate: The case considered is 2D, incompressible, turbulent flow past a thick flat rectangular plate with a sharp leading edge, with Reynolds number 50,000 based on plate thickness H. The flow separates at the leading edge of the plate, forming a long separation zone over the top of the plate, which reattaches further downstream. The SA model predicts reattachment length x/H of 4.8 and 4.5 for the low- and high-Reynolds number models respectively, consistent with the experimental result of 4.7. **Error! Reference source not found.** shows the velocity contours and filtered vectors around the separation zone on top of the plate.

3.2. 3D Time Comparison

A selection of 3D cases have been run in order to compare the computer time needed for the SA model with that required for more complex 2-equation models.

The first comparison is for a steady case using the high-Reynolds closure of the SA model. This was run for an aerofoil, and compared to the Chen-Kim k-ε model. The SA model gave around a 30% decrease in computer time compared to the Chen-Kim k-ε model. Both models gave very similar results, with predicted lift and drag coefficients in agreement.

A steady electronics-cooling case was run, using the low-Reynolds form of the SA. This was done in comparison to the two-layer k-ε model. The SA model showed superior convergence over the two-layer model, with a saving of approximately 70% computer time. The accuracy of the SA model in this case was compromised, as the electronics-cooling case involved circular inlets, such that the air entered the case in jets. The SA model showed increased spreading of these jets, as expected since the model is not designed for this type of flow, leading to higher temperature predictions. However, the computer savings show the potential for this model in other electronics cooling applications.

Finally, a comparison between SA and the Chen-Kim k-ε model was conducted for a transient case. This case was the flow past a surface-mounted cube, using the high-Reynolds form. Both models gave similar results, with the

SA model predicting a slightly shorter (and more accurate) separation length. The SA model also gave savings of over 50% computer time compared to the Chen-Kim k-ε model.
These results show that the SA model gives significant savings in computer time compared to more complex models, especially for transient cases and in the low-Reynolds form, with convergence more easily procured in the low-Reynolds form than other models.

Conclusion

The SA turbulence model has been successfully implemented into the PHOENICS code in high- and low-Reynolds-number forms, both of which can be activated from the VR menu. It is available for Cartesian, polar and BFC meshes, and can be used with both SPARSOL and PARSOL. The implementation has been validated for a number of cases, with results showing good agreement with expectations. The SA model was initially designed for external flows, and as such performs especially well in these cases. Its computational efficiency and robustness make it a good choice for many applications, although it may sacrifice some accuracy relative to more complex two-equation models. Caution is advised when using the SA model for untested industrial applications, and in flows with free shear and decaying turbulence, such as jets where the model is known to be unsuitable. With the model now available for use with equilibrium wall functions and integration down to the wall, future work will investigate the use of an automatic wall treatment to make the solution less sensitive to near-wall mesh refinement.

References

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