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Implementation and validation of a second-moment RANS turbulence model in OpenFOAM®

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Background

- The no-slip condition at solid interfaces, creates a layered structure for a near-wall turbulent flow, where in the immediate vicinity called viscous sublayer, viscous effects on turbulence cannot be neglected.
- Moreover, the impermeability condition introduces a non-viscous in nature damping, that particularly dampens wall-normal velocity fluctuations.
- This *wall-blocking* effect along with the consequent reflection of pressure fluctuations in the wall, is also felt outside the viscous layer, in the fully turbulent wall region.
- The modeling of these effects it is important for overcoming deficiencies in nonequilibrium flows scenarios, primarily in strong pressure gradients, impinging flows, separation, reattachment, etc. are present.

Background

- Simple models of near-wall turbulence usually resort to damping functions that depends on the local turbulence Reynolds number and the wall distance that are not well suited to incorporate turbulence anisotropy effects.
- In the context of an eddy viscosity RANS model Durbin (1991) noted that kinematic constraints due to blocking can be introduced through an elliptic model of pressure-velocity fluctuations.
- In this model a separate transport equation was solved for a scalar surrogate of wall-normal velocity fluctuations (designated v^2), in conjunction with an *elliptic relaxation* parameter f , that has become known since as the $v^2 - f$ model.
- In Durbin (1993) the elliptic relaxation concept is applied, but now in the context of a full second-moment closure. In this latter method, the elliptic relaxation has a tensorial character, which boundary conditions near a solid wall introduce a source of of numerical stiffness and instability.

Background

- In Manceau and Hanjalić (2002), the authors proposed a model that reduces the tensorial character of Durbin's second-order model to a single scalar elliptic blending variable.
- This model maintains the solid theoretical basis and modeling properties of Durbin's model, while increasing the robustness and ease of implementation and adaptation to industrial CFD codes.

Second-order RANS equations

- Consider the Reynolds decomposition of the velocity into a mean U_i and a fluctuating part u_i .
- The *Reynolds averaged* momentum equation for an incompressible flow of kinematic viscosity ν in the absence of external forces reads as:

$$\frac{DU_i}{Dt} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \overline{u_i u_j} \right) \right]$$

- The Reynolds-stress transport equation reads as:

$$\frac{D\overline{u_i u_j}}{Dt} = P_{ij} + D_{ij}^\nu + D_{ij}^T + \phi_{ij}^* - \epsilon_{ij}$$

- ▶ P_{ij} : turbulent production.
- ▶ D_{ij}^ν : viscous diffusion.
- ▶ D_{ij}^T : turbulent diffusion by fluctuating velocity.
- ▶ ϕ_{ij}^* : fluctuating velocity-pressure gradient correlation.
- ▶ ϵ_{ij} : turbulence dissipation.

Elliptic Blending Method (EBM)

- Velocity-pressure gradient correlation, Manceau (2015):

$$\phi_{ij}^* = (1 - \alpha^3)\phi_{ij}^w + \alpha^3\phi_{ij}^h$$

- ▶ Homogeneous term:

$$\begin{aligned}\phi_{ij}^h = & - \left(g_1 + g_1^* \frac{P}{\epsilon} \right) \epsilon b_{ij} + \left(g_3 - g_3^* \sqrt{b_{kl}b_{kl}} \right) k S_{ij} \\ & + g_4 k \left(b_{ik} S_{jk} + b_{jk} S_{ik} - \frac{2}{3} b_{lm} S_{lm} \delta_{ij} \right) \\ & + g_5 k \left(b_{ij} W_{jk} + b_{jk} W_{ik} \right)\end{aligned}$$

where

$$\begin{aligned}b_{ij} &= \frac{\overline{u_i u_j}}{2k} - \frac{1}{3} \delta_{ij} \\ S_{ij} &= \frac{1}{2} \left(\frac{\partial U}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right), \quad W_{ij} = \frac{1}{2} \left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i} \right)\end{aligned}$$

- ▶ Wall reflection term:

$$\phi_{ij}^w = -5 \frac{\epsilon}{k} \left[\overline{u_i u_k} n_j n_k + \overline{u_j u_k} n_i n_k - \frac{1}{2} \overline{u_k u_l} n_k n_l (n_i n_j + \delta_{ij}) \right]$$

- Elliptic relaxation equation:

$$\alpha - L^2 \nabla^2 \alpha = 1$$

- ▶ Approximate wall normal vector:

$$\mathbf{n} = \frac{\nabla \alpha}{\|\nabla \alpha\|}$$

- Turbulent diffusion:

$$D_{ij}^T = \frac{\partial}{\partial x_l} \left(\frac{C_\mu}{\sigma_k} \overline{u_l u_m} T \frac{\partial \overline{u_i u_j}}{\partial x_m} \right)$$

- Time and length scales:

$$T = \max \left(\frac{k}{\epsilon}, C_T \left(\frac{\nu}{\epsilon} \right)^{1/2} \right), \quad L = C_L \max \left(\frac{k^{3/2}}{\epsilon}, C_\eta \frac{\nu^{3/4}}{\epsilon^{1/4}} \right)$$

- Dissipation tensor:

$$\epsilon_{ij} = (1 - \alpha^3) \frac{\overline{u_i u_j}}{k} \epsilon + \frac{2}{3} \alpha^3 \epsilon \delta_{ij}$$

- Turbulence dissipation rate equation:

$$\frac{D\epsilon}{Dt} = \frac{C'_{\epsilon_1} P - C_{\epsilon_2} \epsilon}{T} + \frac{\partial}{\partial x_l} \left(\frac{C_\mu}{\sigma_\epsilon} \overline{u_l u_m} T \frac{\partial \epsilon}{\partial x_m} \right) + \nu \frac{\partial^2 \epsilon}{\partial x_k \partial x_k}$$

where

$$C'_{\epsilon_1} = C_{\epsilon_1} \left[1 + A_1 (1 - \alpha^3) \frac{P}{\epsilon} \right]$$

- Model constants:

$$g_1 = 3.4; \quad g_1^* = 1.8; \quad g_3 = 0.8; \quad g_3^* = 1.3; \quad g_4 = 1.25; \quad g_5 = 0.4;$$

$$C_\mu = 0.21; \quad \sigma_k = 1.0; \quad C_T = 6.0; \quad C_L = 0.133; \quad C_\eta = 80.0;$$

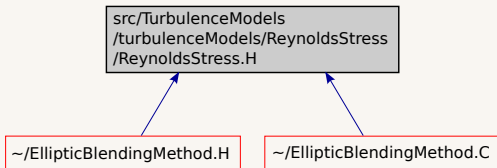
$$C_{\epsilon_1} = 1.44; \quad C_{\epsilon_2} = 1.83; \quad A_1 = 0.065; \quad \sigma_\epsilon = 1.15$$

- Wall boundary conditions:

$$U_i = 0; \quad \overline{u_i u_j} = 0; \quad \epsilon = 2\nu \lim_{y \rightarrow 0} \frac{k}{y^2}; \quad \alpha = 0$$

Implementation

- Implemented in OpenFOAM[®] v2012 as a class inherited from the ReynoldsStress class:



- We followed guidelines from the implementation that is described by Javadi (2016).
- Code Saturne Archambeau et al. (2004) also provides a publicly available implementation.

Results

- The implementation has been tested with three cases:
 - ▶ Low Reynolds flow in a plane channel.
 - ▶ Flow over periodic hills.
 - ▶ Flow in an asymmetric diffuser.
- RANS equations are discretized with a collocated second order cell-centered finite volume method and solved through the SIMPLE algorithm.
- Convergent residuals below 10^{-6} were noted in all variables, with the exception of pressure that stalled at $\approx 10^{-4}$ in most cases.
- With the aim of comparison results with a low Reynolds $k-\epsilon$ model Launder et al. (1974) were also obtained.

Plane channel flow

- Fully developed turbulent flow in a plane channel flow at low Reynolds number.
- Results are compared with DNS solutions presented in Kim et al. (1987).
- Reynolds number based on friction velocity corresponds to $Re_\tau = 180$ and $Re_\tau = 395$.
- First wall-normal cell height $\Delta y^+ \approx 1$.
- 300 cells in normal direction. One cell in streamwise direction with cyclic boundary conditions.

Plane channel flow

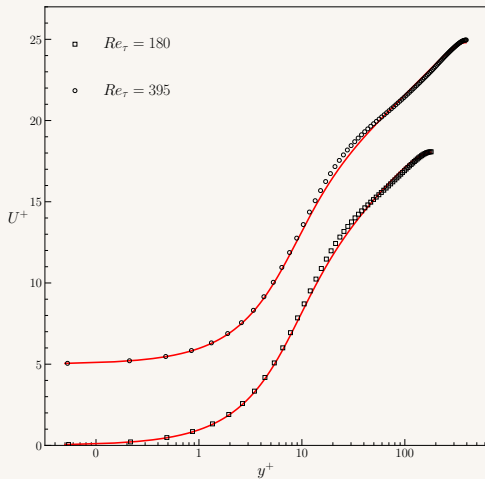
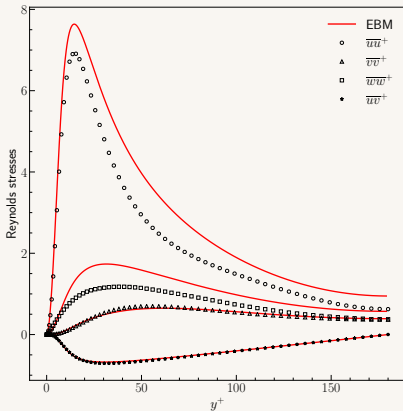
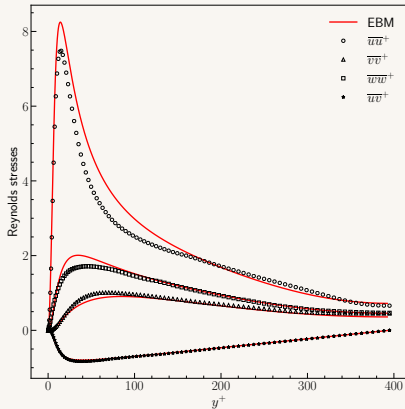


Fig. 1: Velocity profiles for a plane channel flow. Symbols: DNS, Kim et al. (1987); lines: computations with EBM model. Results shifted for clarity.

Plane channel flow



(a) $Re_{\tau} = 180$



(b) $Re_{\tau} = 395$

Fig. 2: Reynolds stresses for a plane channel flow. Symbols: DNS, Kim et al. (1987); lines: computations with EBM model.

Plane channel flow

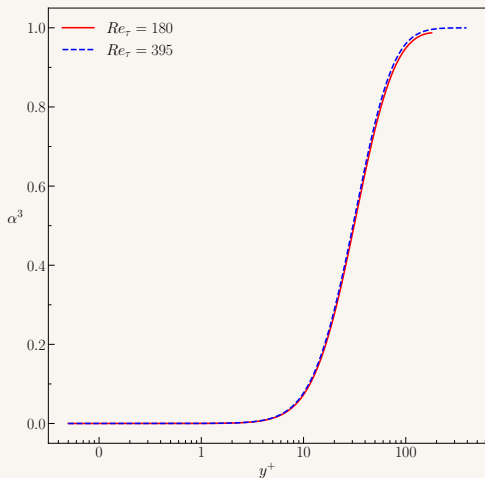


Fig. 3: Elliptic blending function profile for a plane channel flow.

Flow over periodic hills

- This test corresponds to the 2D turbulent flow over periodic hills numerically investigated by Temmerman et al. (2003)

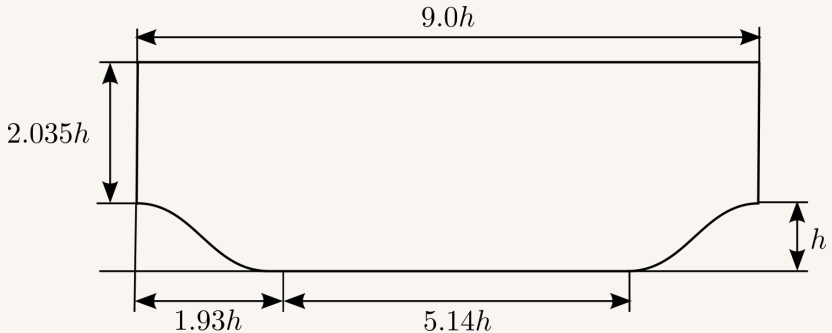


Fig. 4: Periodic hill case description.

Flow over periodic hills

- Fully developed turbulent flow in a plane channel flow at low Reynolds number.
- Results are compared with LES solutions presented in Temmerman et al. (2003).
- Reynolds number based on bulk velocity and the hill height is $Re_h = 10595$.
- Mesh convergence was evaluated in three meshes with increasing level of refinement.
- Coarse: 100 (streamwise) \times 70 (normal). Semi-coarse: 100×140 . Fine: 200×140 .
- First wall-normal cell height $\Delta y^+ \approx 1$ was kept constant in all meshes.

Flow over periodic hills

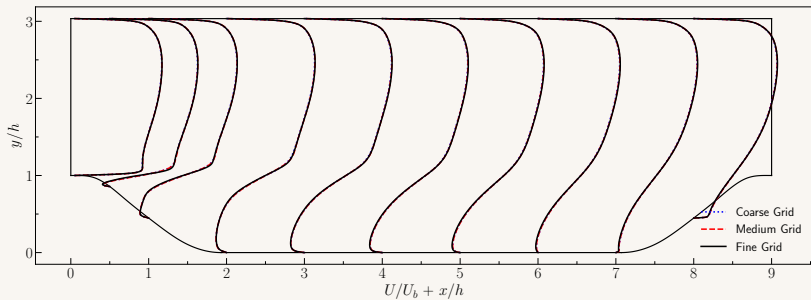
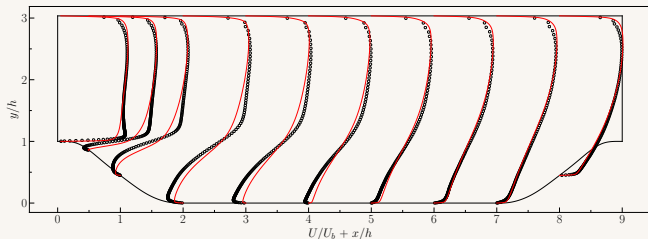
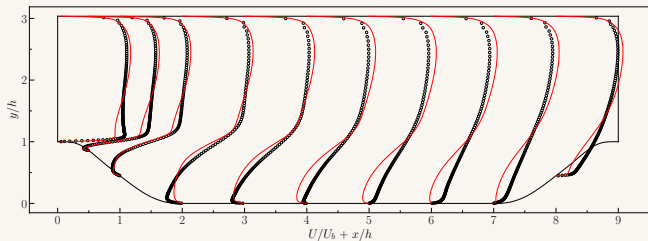


Fig. 5: Mesh convergence of flow over periodic hills simulations. Streamwise velocity profiles computed with EBM model.

Flow over periodic hills



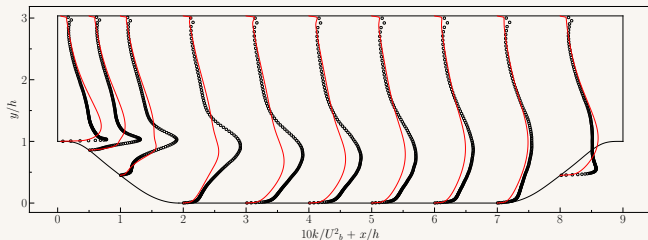
(a) Launder and Sharma low-Reynolds $k - \epsilon$ model



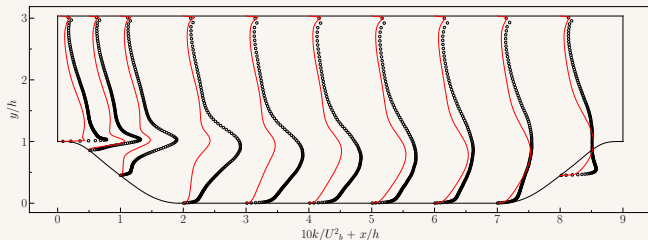
(b) Elliptic blending method

Fig. 6: Streamwise velocity profiles for a flow over periodic hills. Symbols: LES Temmerman et al. (2003); lines: computations.

Flow over periodic hills

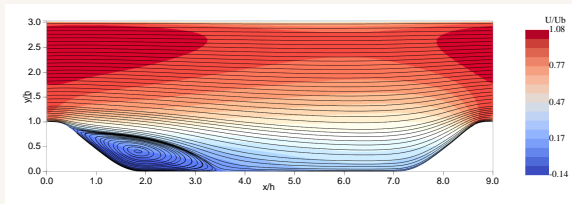


(a) Launder and Sharma low-Reynolds $k - \epsilon$ model

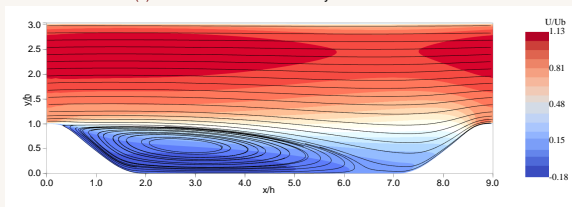


(b) Elliptic blending method

Fig. 7: Normal velocity profiles for a flow over periodic hills. Symbols: LES Temmerman et al. (2003); lines: computations.



(a) Launder and Sharma low-Reynolds $k - \epsilon$ model



(b) Elliptic blending method

Fig. 8: Streamline profiles for a flow over periodic hills.

| | Separation (h) | Reattachment (h) |
|-----------------------------|--------------------|----------------------|
| LES Temmerman et al. (2003) | 0.22 | 4.72 |
| Low Reynolds $k - \epsilon$ | 0.31 | 3.51 |
| Elliptic Blending Method | 0.26 | 6.35 |

Asymmetric diffuser

- This case corresponds to the separated 2D flow through the axisymmetric diffuser studied experimentally by Buice et al. (2000).

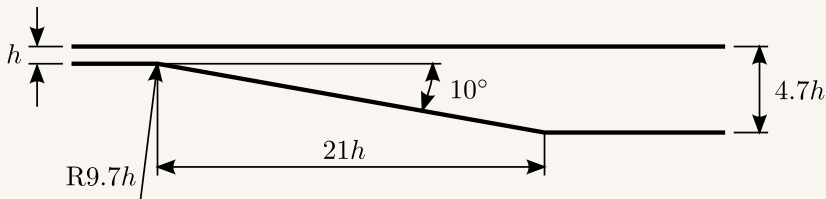
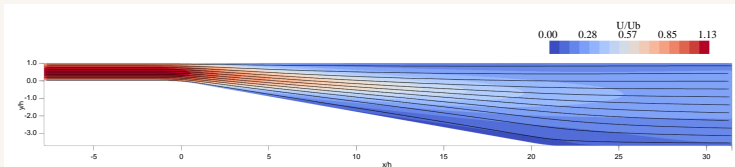


Fig. 9: Asymmetric diffuser geometry

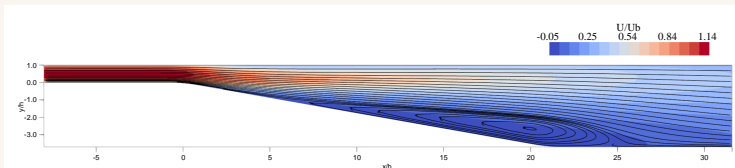
Flow over periodic hills

- Fully developed turbulent flow in a plane channel flow at low Reynolds number.
- Results are compared with experimental results presented in Buice et al. (2000).
- Reynolds number based on center line velocity and entrance channel height h is: $Re_h = 20000$.
- Mesh convergence was evaluated in three meshes with increasing level of refinement.
- Coarse: 160 (streamwise) \times 140 (normal). Semi-coarse: 210×190 . Fine: 320×240 .
- First wall-normal cell height $\Delta y^+ \approx 0.5$ was kept constant in all meshes.

Asymmetric diffuser

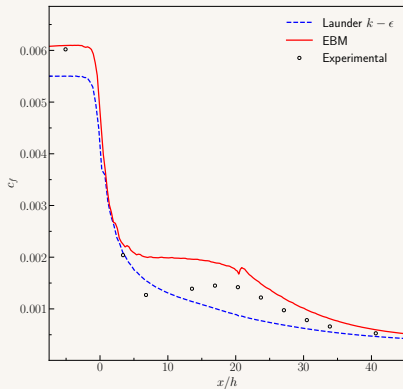


(a) Launder and Sharma low-Reynolds $k - \epsilon$ model

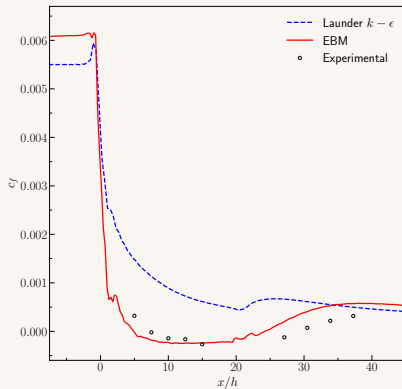


(b) Elliptic blending method

Fig. 10: Streamline profiles for the asymmetric diffuser



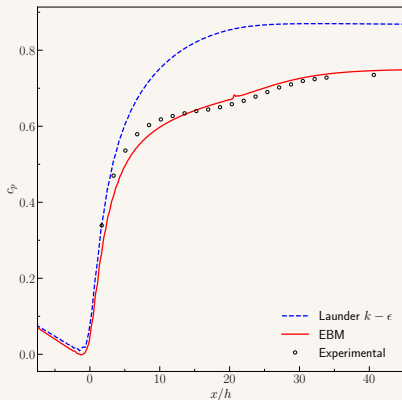
(a) Flat wall



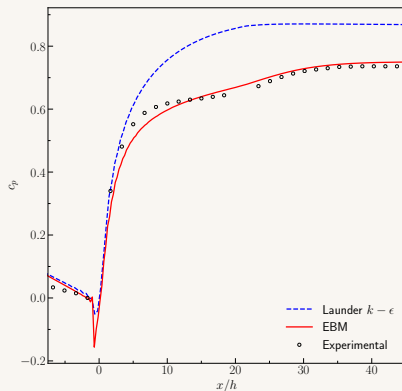
(b) Inclined wall

Fig. 11: Friction coefficient for the asymmetric diffuser.
 Symbols: experiments; lines: computations.

| | Separation (h) | Reattachment (h) |
|----------------------------------|--------------------|----------------------|
| Experimental Buice et al. (2000) | 7.3 | 29.2 |
| Low reynolds $k - \epsilon$ | NA | NA |
| Elliptic Blending Method | 4.56 | 24.8 |

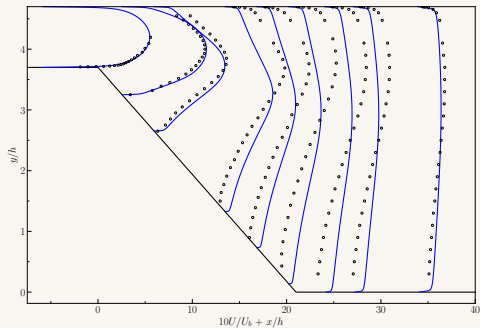


(a) Flat wall

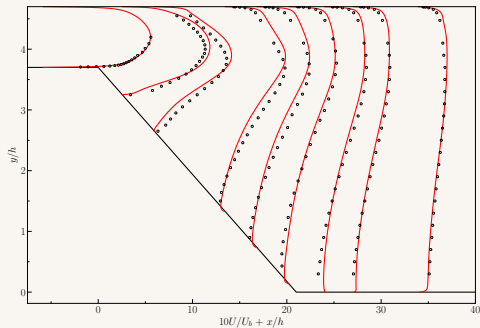


(b) Inclined wall

Fig. 12: Pressure coefficient for the asymmetric diffuser.
 Symbols: experiments; lines: computations.



(a) Launder and Sharma low-Reynolds $k - \epsilon$ model



(b) Elliptic blending method

Fig. 13: Streamwise velocity profiles for the asymmetric diffuser.
 Symbols: experiments; lines: computations.

Conclusions

- The implementation and validation of the Elliptic Blending Method in OpenFOAM[®] has been presented.
- Results were compared with high-fidelity numerical solutions corresponding to test cases involving flows with attached and separated boundary layers with streamline curvature effects.
- The performance of the model was also assessed in the separated flow in a 2D asymmetric diffuser where the low-Reynolds $k - \epsilon$ turbulence model was unable to capture the turbulent separation bubble.
- The implementation is considered satisfactory and as future work further testing in 3D separated flows problems will be considered.

¡Muchas gracias por su atención!