Wall-bounded flow separation computed by a second-moment closure model

*S. Jakirlić and R. Maduta

Darmstadt University of Technology, Department of Mechanical Engineering, Institute of Fluid Mechanics and Aerodynamics / Center of Smart Interfaces, Alarich-Weiss-Strasse 10, D-64287 Darmstadt, Germany

*Presenting and corresponding author: s.jakirlic@sla.tu-darmstadt.de

Abstract

It is well-known that the separation process is inherently a highly unsteady phenomenon. To capture it correctly LES-relevant models – conventional LES (Large-Eddy Simulation) and hybrid LES/RANS (Reynolds-Averaged Navier Stokes) models (see e.g., Jakirlic and Maduta, 2015 for an overview) - have to be applied. However, all these methods require the governing equations to be integrated in time under conditions of appropriately high spatial and temporal resolutions. Accordingly an increased computing power is required followed by a correspondingly long computational time, both being not straightforwardly affordable for simulating turbulent flows of industrial relevance featured by complex geometries and high Reynolds numbers. Therefore, from the point of view of the practical application, it would be highly beneficial if a correctly predicted time-averaged turbulence field and consequently the mean velocity field could be achieved in the framework of the steady RANS computations. On the other hand, apart from the backward-facing step flow geometry characterized by the “sharp-edge” separation of a flat plate boundary layer, which can be reasonably well solved by an advanced steady RANS model, the flows involving separation are in general beyond the reach of the conventional RANS method independent of the modeling level. The separation region exhibits high level of intermittency, being especially pronounced in the flows separated from continuous curved surfaces, but also from rib-shaped and fence-shaped obstacles. An intensively oscillating separated shear layer is characterized by a broader frequency range. Typical outcome of application of a steady RANS model (temporal integration of this model in the framework of a conventional unsteady RANS framework ends up traditionally in a steady solution) is a low turbulence activity level in the separated shear layer and a correspondingly enlarged recirculation zone. The latter issues motivated the present work demonstrating the possibility to appropriately improve the computational results pertinent to the flow configurations featured by wall-bounded separation in the “Steady RANS” framework.

An appropriately designed term modeled in terms of the von Karman length scale (adopted from the so-called SAS modeling strategy for sensitized ”unsteady” flow computations, Menter and Egorov, 2010; SAS – Scale-Adaptive Simulation), denoted by P_{SAS}, was introduced into the scale-supplying equation governing the homogeneous part of the inverse time scale ($\omega_h = \varepsilon_h / k$). It is firstly recalled that the introduction of the “positive” SAS-term in the instability-sensitized second-moment closure model version in the Unsteady RANS framework contributed strongly to the turbulence activity enhancement (originating from the resolved motion) in the region around the separation point, Jakirlic and Maduta (2015). Accordingly, the production of the ω_h- i.e. ε_h-variable, enhanced selectively by the SAS term, led to suppression of the unresolved residual turbulence allowing subsequent evolution of structural features of the associated turbulence and development of the resolved motion. The capability of this “instability-sensitized” model to account for the large-scale structures and bulk unsteadiness caused consequently a correctly predicted intensification of the fluid entrainment into the separated shear layer region. Final outcome is the locally increased magnitude of the turbulence kinetic energy followed by improved shape of the mean velocity profiles and correctly predicted reattachment length. However, in the present turbulence model, employed within the steady RANS framework, an opposite action is necessary: the scale-supplying variable has to be appropriately reduced acting towards an appropriate increase

of the fully-modeled (RANS) turbulence intensity. Accordingly, the same SAS-term was introduced into the ω_h-equation but this time with the "negative" sign, representing actually a sink term. Similar as in the instability-sensitized model version this sink term is active only in the narrow area of the separation region. It finally resulted in a correct mean velocity development and proper size of the recirculation zone. Improved predictive performances of the proposed ω_h model equation solved in conjunction with appropriate Reynolds stress model equation are demonstrated by computing several configurations featured by boundary layer separation including the flow over a periodical arrangement of smoothly contoured 2-D hills in a range of Reynolds numbers and the flow over a wall-mounted fence. Figures 1-2 illustrate exemplarily some relevant results obtained by computing the 2D hill flow configuration. It should also be noted that this additional term doesn't influence the predictive capabilities of the model in the attached wall-bounded flows (as e.g. fully-developed flow in a plane channel) and a mixing layer originating from the boundary layer separation at a backward-facing step; the results obtained by both model versions, with and without the P_{SAS} term, are identical. Because the additional term depends only on the mean velocity field, kinetic energy of turbulence k and its specific dissipation rate ω_h, it could be beneficially used also in conjunction with the eddy-viscosity model group.

Keywords: Turbulent flow separation, Steady RANS framework, Reynolds stress model

References

Fröhlich, J., Mellen, C.P., Rodi, W., Temmerman, L. and Leschziner, M.A. (2005) Highly resolved large-eddy simulation of separated flow in a channel with streamwise periodic constrictions, *J. Fluid Mech.* **526**, 19-66

Jakirlić, S. and Maduta, R. (2015) Extending the bounds of "steady" RANS closures: towards an instability-sensitive Reynolds stress model, *Int. J. Heat and Fluid Flow* **51**, 175-194.

Menter, F.R. and Egorov, Y. (2010) The Scale-Adaptive Simulation Method for Unsteady Turbulent Flow Predictions: Theory and Model Description, *Flow, Turb. and Combust.* **85**, 113-138.

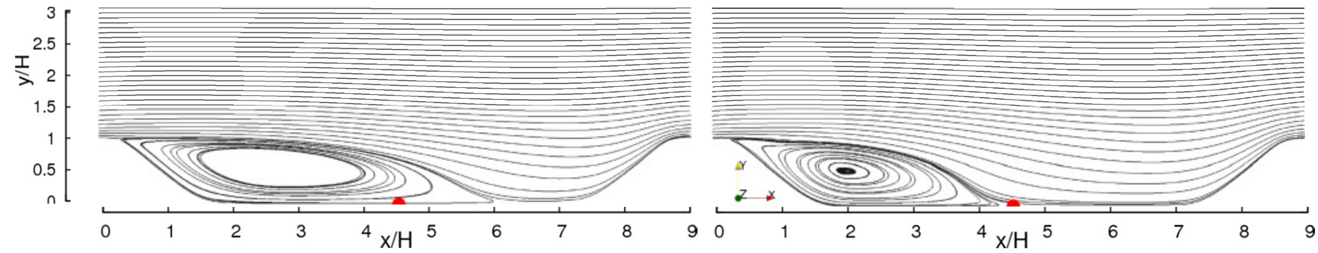

Figure 1: 2D hill flow, Re$_H$=10600 – mean streamline patterns obtained by the present RSM model without (left) and with "$-P_{SAS}$" (right) term. Red point denotes the reattachment point at $(x/H)_{RP} \approx 4.6$ obtained by the reference LES (Fröhlich et al., 2005).

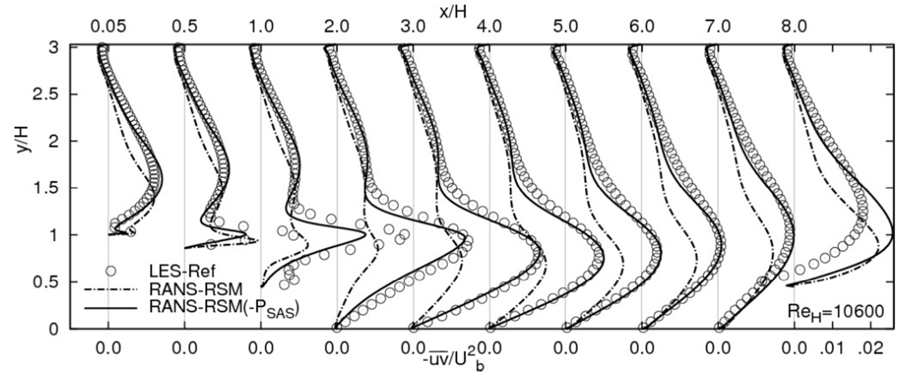

Figure 2: 2D hill flow at Re$_H$=10600 - evolution of the shear stress component profiles (reference LES is by Fröhlich et al., 2005). The introduction of the negative production term P_{SAS} into the scale-supplying equation contributed to the turbulence intensity enhancement in the separated shear layer and appropriate shortening of the recirculation zone (Fig. 1)