9th ERCOFTAC/IAHR/COST Workshop on Refined Turbulence Modelling

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Introduction

Computational Fluid Dynamics (CFD) has developed to a key technology which plays an important role in design, development and optimization in engineering practice. Although increasing computer capacities enable a broader use of highly resolved computational schemes such as Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES), the statistical turbulence modelling used in the framework of the Reynolds Averaged Navier-Stokes (RANS) approach represents the current industrial standard. However, it is generally recognized that the statistical turbulence models remain the largest source of errors and inaccuracy in the CFD codes[1]. Keeping in mind the wide use of CFD technology for solving the problems of industrial relevance, questions about the credibility and reliability of both the numerical methods and mathematical models simulating turbulence can only be tackled (and possibly answered) by intensive verification and systematic validation. The role of the ERCOFTAC/IAHR series of workshops on refined turbulence modelling is closely connected to the latter. The workshops aim at bringing together scientists, researchers, users and developers from industry and from the academic field. A large data-base of simulation results assembled in such a way, as well as their detailed comparison with the reliable reference data obtained experimentally, by means of DNS but also by highly-resolved LES, enable discussion and conclusions about predictive performances of variety of turbulence models in a broad range of well-documented flow configurations.

The 9th ERCOFTAC/IAHR/COST Workshop was held on 4 and 5 October at the Darmstadt University of Technology, Germany. The workshop is a continuation of the joint activity of the ERCOFTAC Special Interesting Group for Turbulence Modelling (SIG 15) and of the IAHR Working Group on Refined Turbulence Modelling. Similar to the previous eight workshops in Lyon (1991), Manchester (1993), Lisbon (1994), Karlsruhe (1995), Chatou (1996), Delft (1997), Manchester (1998) and Helsinki (1999), some fundamental phenomena, but also some industrially relevant problems have been chosen as test cases for this workshop. The selection of test cases was made by the standing committee of the SIG 15 (Profs. K. Hanjalić, D. Laurence, B.E. Launder, M.A. Leschziner and W. Rodi) and the Local Organizing Committee (S. Jakirlić, R. Jester-Zürker, Profs. C. Tropea and J. Janicka) at the Darmstadt University of Technology. The following four flows involving numerous features of scientific and engineering relevance (three-dimensionality, unsteady wake regions, periodicity, separation and reattachment, swirling effects, etc.) were finally selected as test cases for this workshop:

9.1 Swirling flow in a model combustor. Exp.: Roback and Johnson (1983), LES: Pierce and Moin (1998). *Coordinator: Dr. S. Jakirlic, Darmstadt University of Technology*

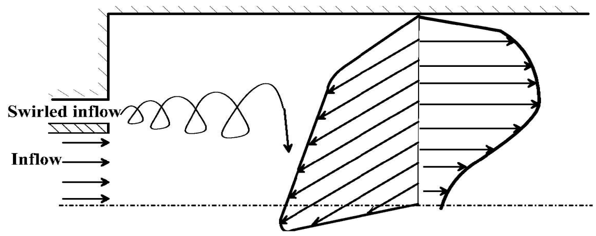


Figure 1: Schematic of the swirling flow in a model combustor

9.2 Periodic flow over a 2-D hill. LESs: Mellen, Fröhlich and Rodi (2000), Temmerman and Leschziner (2001). *Coordinator: Prof. M.A. Leschziner, Imperial College London*

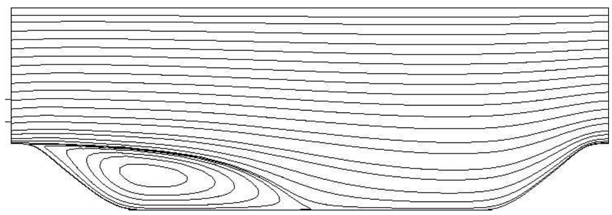


Figure 2: Typical streamline pattern

9.3 Periodically perturbed separated flow over backward-facing step. Exp.: Yoshioka, Obi and Masuda (2001). *Coordinator: Prof. S. Obi, Keio University*

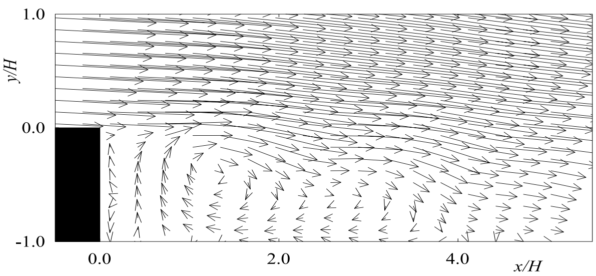


Figure 3: Phase averaged velocity field at max. injecting phase

[1]This statement should not be related only to the modelling level reflecting the flow physics, which is supposed to be captured, but also to the uncertainties with respect to the model implementation into a computer code and corresponding numerics. See e.g. Fig. 16 and corresponding discussion

9.4 Flow around a simplified car body (Ahmed body). Exp.: Lienhart, Stoots and Becker (2000). *Coordinator: Dr. B. Basara, AVL List GmbH, Graz*

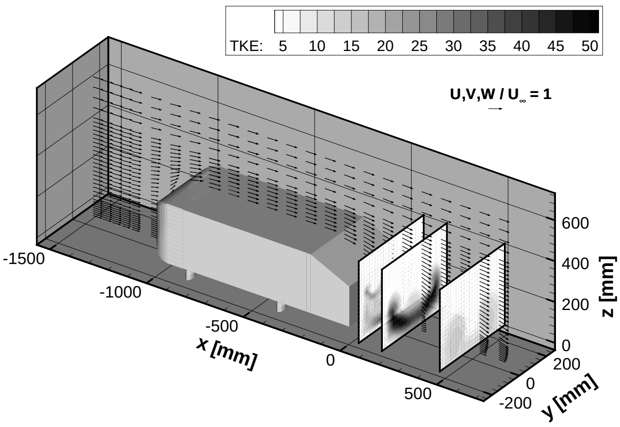


Figure 4: Overview of velocity distributions and TKE around the 25^o slant Ahmed body

None of the flows listed was previously considered in the framework of the ERCOFTAC Workshops. The final processing of all results and assembly of the plots was conducted by S. Jakirlić, R. Jester-Zürker and S. Šarić.

The workshop was attended by 52 participants from 10 countries from Europe and Asia (Austria 2, Belgium 1, Finland 2, France 8, Germany 25, Greece 1, Japan 1, Swiss 2, The Netherlands 4 and United Kingdom 6). 27 computational contributions from 21 groups (see Table 1) were submitted. Most participants (39) came from universities. Three computational contributions were submitted from CFD vendors directly (AVL List GmbH, FLUENT and ICCM GmbH), whereas several university groups (Thesaloniki, Poitiers, Hamburg-Harburg) used commercial codes (FLUENT, Star CD, COMET) for their computations. Two attendants were from large national scientific/industrial research centers (CNRS and Swiss Federal Institute for Snow and Avalanche) and the remaining 11 participants came from industry (Peugeot S.A., ALSTOM Power Technology Centre, Bombardier Transportation, TECOSIM GmbH, etc.). Parallel to the workshop, an exhibition of several CFD vendors (CD Adapco Group, AVL List GmbH, FLUENT Deutschland GmbH and NUMECA) was also organized.

A large variety of turbulence models ranging from the Spalart-Allmaras (SA) one-equation model, standard linear (KE-STD) and non-linear $k-\varepsilon$ (NLKE) and $k-\omega$ (KW) models, via the Durbin's three equations $k-\varepsilon-v^2$ model (KE-V2F), explicit (EARSM) and implicit algebraic Reynolds-stress models (ARSM) up to differential Reynolds-stress models (RSM) and LES was used in this workshop.

The proceedings of the workshop (two volumes with about 600 pages) containing a summary of the test cases with all details necessary for their computations, a review of turbulence models and numerical methods used by each participant, as well as cross-plots of results for all four test cases were distributed to all participants. The contributors were offered a possibility to correct or refine their results and to re-submit them after the workshop. Only few took advantage of this opportunity. The updated proceedings are available on the workshop www-site: *http://www.sla.maschinenbau.tu-darmstadt.de/workshop01.html.*

Contributors		Test Cases			
		1	2	3	4
AUTH	Aristotle University and Enervac-Flutec Ltd., Thessaloniki, Greece; Prinos, Sofialidis		x		
AVL-SWIFT	AVL List GmbH, Graz and TU Darmstadt; Basara, Jakirlić				x
ECN	Ecole Centrale de Nantes; Deng, Visonneau, Queutey, Guilmineau	x		x	x
EDF	Electricité de France, Chatou; Tekam, Laurence, Buchal				x
FLU-ENT	FLUENT Deutschland GmbH; Lanfrit, Braun, Čokljat				x
GU	Ghent University; Merci, De Langhe, Vierendeels, Dick	x	x		
HUT	Helsinki University of Technology; Hellsten		x		
IC	Imperial College, London; Jang, Temmerman, Leschziner		x		
IFH	Institute for Hydromech., Karlsruhe University; Mellen, Fröhlich, Hinterberger, Rodi		x		x
KU	Keio University, Yokohama; Obi			x	
SLA	Strömungslehre und Aerodyn., TU Darmstadt; Jakirlić, Jester-Zürker	x			
SUT	Science University of Tokyo; Yamamoto			x	
TUB	Technical University, Berlin and Bombardier Transportation; Rung, Thiele	x			
TUDF	Delft University of Tech.; Popovac,Ničeno, Stawiarski, Oulhous, Khier, Liu, Hanjalić		x	x	x
TUHH	TU Hamburg-Harburg and ICCM GmbH; I. Hadžić, H. Hadžić, Muzaferija		x		
TUM	Munich University of Tech.; Skoda, Schilling		x		
TUT	Tampere University of Technology; Ahlstedt	x			
UMIST	UMIST Manchester, Craft, Gant, Iacovides, Launder, Robinson				x
UMIST -EDF	UMIST Manchester and Electricité de France; Guime, Laurence		x		
UP	Université de Poitiers; Manceau		x		
VINAS	VINAS Co. Ltd., Osaka; Lei (Obi)			x	

Table 1: Groups contributing results[2]

Workshop Programme

Each test case was presented in three steps: presentation of the reference data by the authors of the experiments[3] (case 9.3 was introduced by Prof. S. Obi and the case 9.4 by H. Lienhart) and LES

[2]The persons, whose names are underlined, attended the workshop.
[3]with exception of the case 9.1, which was presented by its coordinator.

database (case 9.2 was presented by Dr. J. Fröhlich), presentation of the computational methods by the contributors, and comparison of the results by the corresponding coordinator.

Summary of Results and Discussion

Flow description, instructions for calculations, detailed specification of the shape and dimensions of solution domains, as well as of the inlet data and boundary conditions for all four test cases considered, are given in the workshop proceedings. Here, only a summary of some specific outcomes and the most important conclusions is given.

9.1: Swirling flow in a model combustor

Five groups computed this case. A total of 17 sets of results were submitted. The most important feature of this confined, swirling jet discharging into a sudden expansion is a large, free recirculation zone situated in the combustor core, Fig. 5.

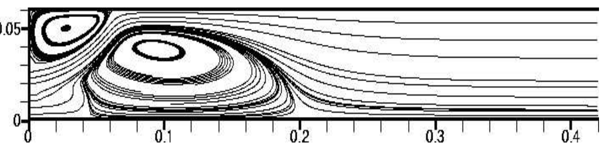


Figure 5: Swirling flow in a model combustor; computationally obtained (GLm) streamlines in the $r-z$ plane. GLm - Gibson, Launder model, modified to account for non-linearity in the pressure strain and dissipation terms

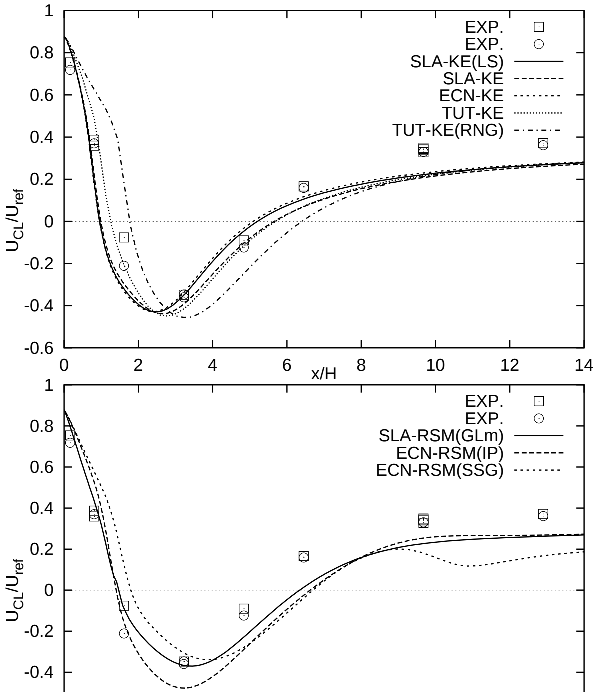


Figure 6: Swirling flow; centerline velocity evolution along the model combustor obtained by the $k-\varepsilon$ (upper) and Reynolds-stress (lower) model groups. RNG - Renormalization Group Theory; IP - Isotropization of Production; SSG - Speziale, Sarkar, Gatski

Thanks to the joint action of the strong adverse pressure gradient due to high expansion ratio ($ER = 2.1$) and the annular swirling inflow, the free bubble is reproduced even using the standard $k-\varepsilon$ models. One possible explanation for this feature is that the superposition of the two flow phenomena, flow separation and swirl, which are both incorrectly predicted by the standard $k-\varepsilon$ model, results in a compensation. Fig. 6 shows evolution of the centerline velocity along the model combustor obtained by the $k-\varepsilon$ and Reynolds-stress model groups. The $k-\varepsilon$ models result in the almost correct length of the free recirculation zone, which is shifted slightly upwards. The onset of the free separation zone is correctly predicted by the Reynolds-stress model groups, but its length is somewhat larger compared to the experimental data.

The computational results in the near field ($x < 200$ mm) close to the combustor entrance are strongly influenced, and to a certain extent "fixed" by the prescribed input data. This led to reasonable agreement of the mean velocity components with the experimental data (not shown here). The results obtained are virtually independent of the model applied. Only in the far field ($x \geq 200$ mm), the differences in the results obtained by different model groups become significant. This is especially related to the circumferential velocity component, whose profile shape follows the well-known "solid body rotation" solution, obtained traditionally by the linear $k-\varepsilon$ models, Fig. 7 (left). A modification of the SA model (TUB), accounting for the streamline curvature effects, cured this anomaly. Only downward of this cross-section, the models based on the solutions of the transport equations for the Reynolds-stress tensor proved their superiority, Fig. 7 (right).

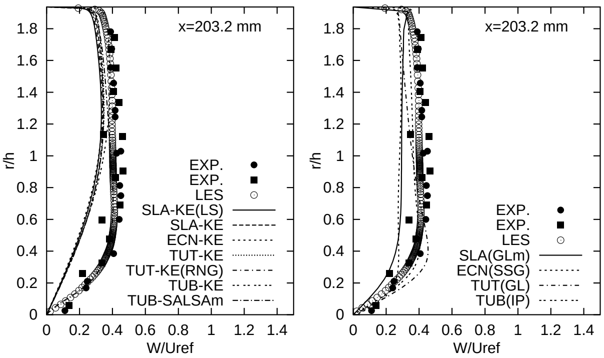


Figure 7: Swirling flow; circumferential velocity components in the recovery region of the flow in combustor obtained by the $k-\varepsilon$ (left) and Reynolds-stress (right) model groups. SALSAm - Spalart, Allmaras model, modified to account for streamline curvature

This test case was in the past very often used for turbulence model validation, in spite of the uncertanties with respect to the completeness and accuracy of the inlet conditions. This is especially related to the specification of the dissipation rate of kinetic energy of turbulence. The data prescribed at the inlet cross-section (end of the central pipe, $x = 0$ mm) were usually obtained by extrapolating the experimental results from the first measuring station in the interior of the combustor to its inlet. Dissipation rate was estimated from the length scale, which was also provided by the measurements. The inlet data, generated in such a way, were proposed to be used for the computations at this workshop. The aforementioned uncertainties were eliminated to a large extent by applying the results of the recently performed LES (Pierce and Moin, 1998) for the position $x = -1$ mm as the inlet data. Pierce and Moin (1998b) have also proposed a method for generating the equilibrium swirling inflow conditions. It was shown[4], however, that the choice of inlet data was

[4]The LES results were not avaliable until after the workshop and their suitability to be applied as the inlet data was checked

not of decisive importance. According to this finding, but also to the fact that the computational results were almost indistinguishable in the large portion of the flow (in particular in the mixing zone) regardless of the model scheme applied, this flow configuration can be regarded as not especially challenging for turbulence models (similar configurations with lower expansion ratio offer more sensitivity to the predictive properties of turbulence models, see e.g., Jakirlić et al., 2002). Nevertheless, the Roback and Johnson experimental configuration, enriched now by the high quality LES results, proved to represent a very important database for the turbulent model validation, especially if the emphasis is to be placed on turbulent mixing (passive scalar statistics are also avaliable) and heat release (reacting flow with fast chemistry).

9.2: Periodic flow over a 2-D hill

This configuration represents a periodic segment of a channel constrained by 2-D hills positioned along the lower wall. This test case offers a number of important features challenging for turbulence models. The separation takes place from a (continuous) curved surface and the flow reattaches between succesive hills, providing also a significant post-reattachment recovery region on the flate plate separating them. Streamwise periodicity of the flow was enforced by applying the periodic inlet/outlet conditions. Very important characteristics of such a flow treatment is a two-way coupling of these boundary conditions to the inner flow. This feature significantly increases the sensitivity of the prediction to the quality of the turbulence model.

A total of 37 solutions were contributed by 10 groups. For more details the work of Jang et al. (2001), whose conclusions are closely followed in the discussion given here, should be consulted.

Fig. 8 gives a selection of streamline patterns for 6 different models. The reference LES solution is shown in Fig. 2. Some substantial differences between different models are observed already at this global level. The reattachment point depends sensitively on the separation point and the angle of the mean dividing streamline at that point, but also in part on the streamwise periodicity. The reattachment length obtained by the reference LES ($x_r = 4.7h$) is, as expected, underpredicted by the linear $k-\varepsilon$ model ($x_r = 3.4h$, Fig. 8a). The majority of the more elaborate models overestimate the recirculation length, a feature connected closely to the insufficient turbulent mixing in the separated shear layer. It applies to most of the non-linear, ε-based eddy viscosity models (NLKE, see e.g., Figs. 8c and 9a) and the Reynolds-stress transport models (Fig. 8e). The results closest to the LES solution are those obtained with Durbin's $k-\varepsilon-v^2$ (KE2F) model (Fig. 8d). In addition to accounting for the kinematic wall blockage, this model employs a switch between the Kolmogoroff time scale and turbulent time scales k/ε in both the production and destruction terms of its ε-equation. This observation suggests that the precise form of the scale-supplying equation is extremely influential. This is clearly visible on the results obtained by the ω-based eddy viscosity models (Figs. 8b and 9b), which are both very close to those obtained by the reference LES. A somewhat shorter separation bubble was returned by applying the LES with wall functions, Fig. 8f. In spite of using wall functions in such a non-equilibrium flow region, the profiles of all mean flow and turbulent quantities obtained by this LES method are by far in the closest agreement with the referent LES, Fig. 10 (lower).

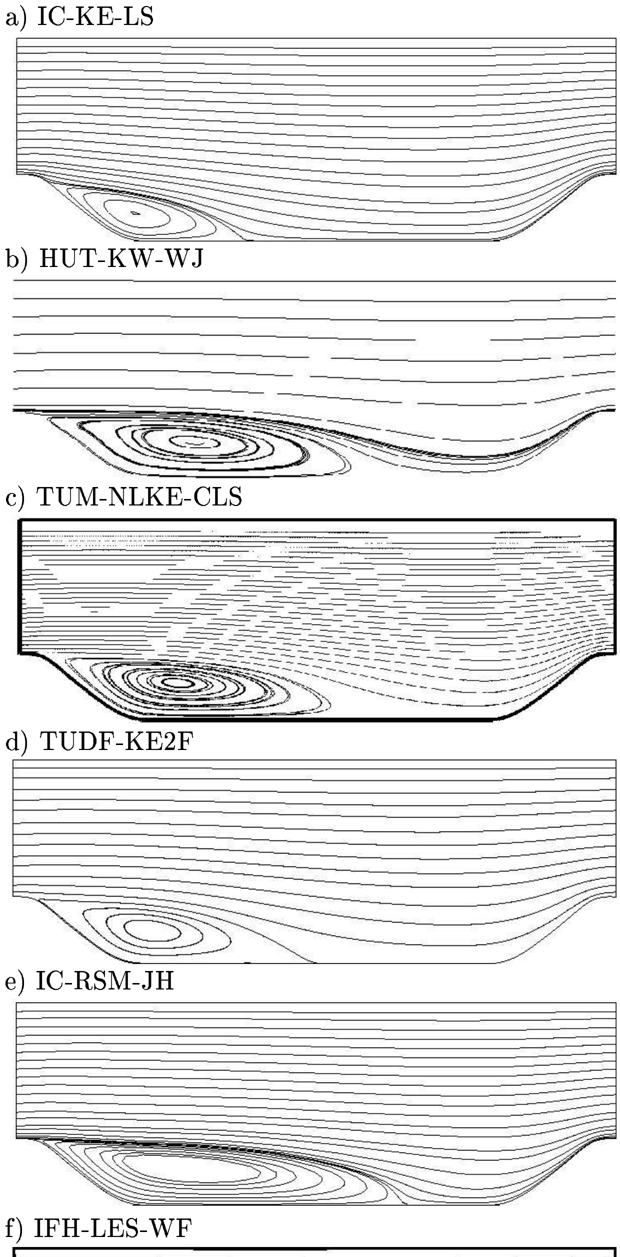


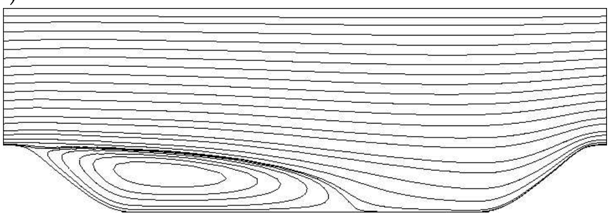
Figure 8: Flow over a 2-D hill; streamlines obtained by different turbulence models. LS - Launder, Sharma; WJ - Wallin, Johansson; CLS - Craft, Launder, Suga; JH - Jakirlić, Hanjalić; WF - Wall Functions

Fig. 10 shows the profiles of axial velocity (left) and shear stress component (right) at the position $x/h = 5$, located in the recovery region immediately after the reattachment point ($x_r/h = 4.7$), obtained by three different model groups: the ε (upper) and ω (middle) based eddy-viscosity models and differential Reynolds-stress models and LES with wall functions (lower). Here, a delayed reattachment, indicated by

by the authors of this report.

the near-wall momentum deficit, is obvious. This momentum deficit in the recovery region causes a slow and thick boundary layer close to the hill crest. This consequently leads to a poor representation of the separated shear layer, affecting, as already mentioned, to a large extent the flow in the recirculation zone and further downstream. The discussion about the differencies between the model results for the mean velocity profiles at reattachment corresponds closely to that given for the streamline patterns.

a) IC-NLKE-AL



b) IC-NLKW-AL

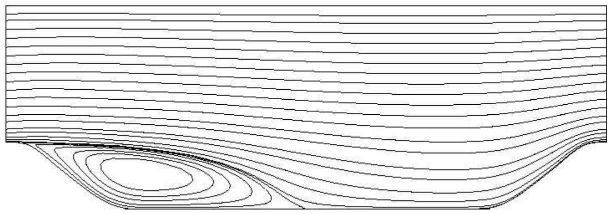


Figure 9: Flow over a 2-D hill; streamfunction contours obtained by the cubic low-Re model due to Apsley and Leschziner (AL), employing ε (a) and ω (b) as the length-scale variable

The majority of the shear stress profiles show a certain underprediction (much stronger underprediction occurs within the recirculation zone, not shown here) compared to the reference LES data, pointing out once more a weak mixing in the shear layer bordering the separation bubble. Contrary to this situation, the shear stresses overestimate the LES results at positions on the wind ward side of the hill, where the flow is accelerated (not shown here). As already indicated, the results of the LES with wall functions agree very well with the reference LES, an outcome connected closely to accounting for the dynamic of large-scale, unsteady motion. This feature is essential for proper capturing of the separated shear layer.

It has been decided to repeat this case for the upcoming 10th workshop on refined turbulence modelling, which is to be held at LEA, Université de Poitiers on 10 and 11 October, 2002. The streamwise periodicity should be removed this time. Possible accumulation of model errors should be avoided by fixing the inlet conditions and taking the zero-gradient outlet conditions. The 2x9h long solution domain, comprising two hills and the space between them, should start at the position $x/h = 6$ corresponding to the post-reattachment recovery region. The results from the reference LES at this cross-section will be adopted for inlet conditions.

9.3: Periodically perturbed separated flow over backward-facing step

The significance of this test case is that the temporal variation is superimposed onto the mean flow, so that time-dependent RANS computations are necessary. As depicted in Fig. 3, the sinusoidal per-

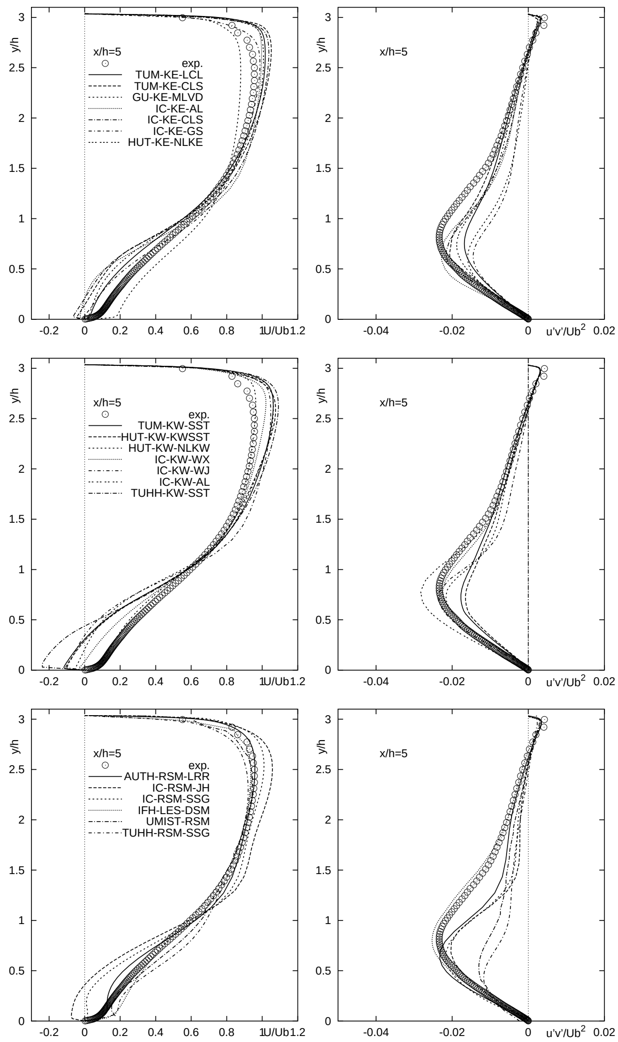


Figure 10: Flow over a 2-D hill; axial velocity and shear stress profiles at reattachment. LCL - Lien, Chen, Leschziner; MLVD - Merci et al., GS - Gatski, Speziale; SST - Shear Stress Transport; WX - Wilcox, LRR - Launder, Reece, Rodi; DSM - Dynamic Smagorinsky Model; RSM - Reynolds-stress model

turbation introduced at the edge of the step results in the wavy pattern in velocity vector along the separated shear layer. The experiment (Yoshioka et al., 2001) indicates that the Reynolds shear stress is increased due to the perturbation, and as a consequence, the reattachment length is reduced by, at most, 30 percent from the case without perturbation. The key of this test case is, therefore, how the RANS models respond to the unsteady perturbation, and whether the reduction of the reattachment is reproduced.

There were 10 contributions from five institutions. The turbulence models used included one-equation SA model, k-ε and k-ω model schemes, as well as three different Reynolds-stress models. Because of the fairly low Reynolds number (Re=3,700 based on the step height and the maximum velocity at the inlet), all computations were performed by using low-Re models. The inlet flow condition was a fully developed channel flow, so that the ambiguity in describing the inlet conditions was avoided.

Fig. 11 (upper) shows the profiles of streamwise mean velocity and Reynolds shear stress at the location ($x/H = 4$), well upstream of the reattachment point for the flow without perturbation. It is obvious that there is already a certain scatter in the computational results, concerning both the mean velocity and shear stress. In spite of that, the velocity profile shape, indicating a low-intensity back flow is returned by all models applied. By imposing the perturbation, as shown in Fig. 11 (lower), the size of the separation bubble is reduced and reattachment point is shifted upstreams. At the same location $x/H = 4$, the flow already reattachs, as indicated by the measurements. However, none of the computational results follow this behaviour. Accordingly, the computations do not capture the experimentally obtained rate of increase in the Reynolds shear stress due to the imposed perturbation.

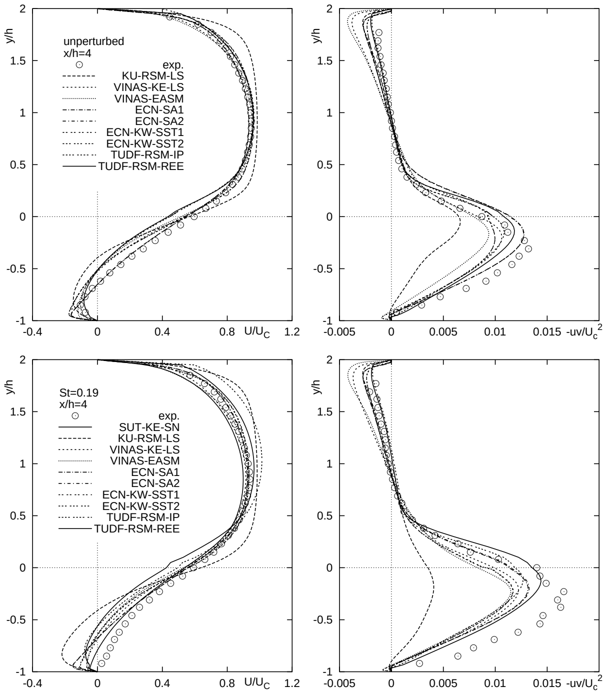


Figure 11: Case 9.3, axial velocity and shear stress profiles at reattachment for two selected frequencies St. RSM-LS - Launder, Shima; KE-LS - Launder, Sharma; REE - two scale RSM; SN - Shimada, Nagano

The variation of the reattachment length x_r/H as a function of the normalized frequency of imposed perturbation St is presented in Fig. 12. Although the quantitative agreement is rather poor, it is surprising that most of the models reproduced reduction of the reattachment length with respect to the steady case (St=0.0), and that the reattachment length minimum is reached at the position corresponding to St=0.15. Comparison with experiment, which indicates the most pronounced effect near St=0.2, reveals a slight discrepancy. It is difficult to judge, which model is superior to others, but it is clear that the models giving the correct reattachment length for the flow without perturbation, reproduce the reduction of x_r/H.

On the whole, the RANS computations presented here are capable of capturing the experimentally observed reduction of the reattachment length for the perturbed conditions, although the detailed flow parameters like individual Reynolds-stress components are not well represented (not shown). To escape the ambiguity in experiment, further investigations based on additional contribution by, e.g., LES of similar flow configurations would be recommended.

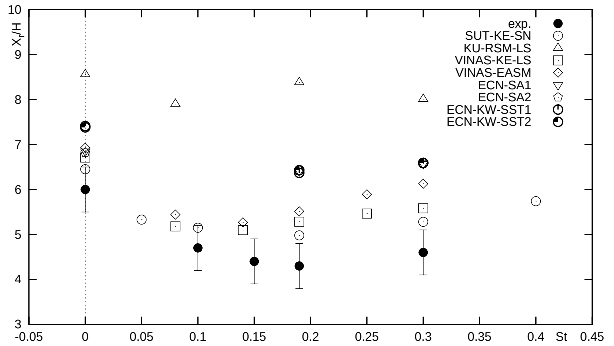


Figure 12: The variation of the reattachment length x_R/H with the normalized frequency St

9.4: Flow around a simplified car body (Ahmed body)

This test case was the only three dimensional case presented at the Workshop. The flow is characterized by a transverse vortex at the rear of the car model being influenced by the strong radial movement along the both sides of the model, creating finally a pair of the ring-formed edge vortices when flowing over the rear pillars. Seven groups contributed 18 different solutions. The calculations were performed for two slant angles, 25^o and 35^o. Fig. 13 depicts the region of attachment/detachment and recirculation at the rear of the Ahmed model for the two slant angles studied. The main difference between these two cases is that the flow detaches and reattaches along the slanted surface for the lower slant angle value, while for the 35^o slant angle the flow detaches and forms a fairly large, single recirculation region along the entire slanted surface, turning into a wake region behind the body.

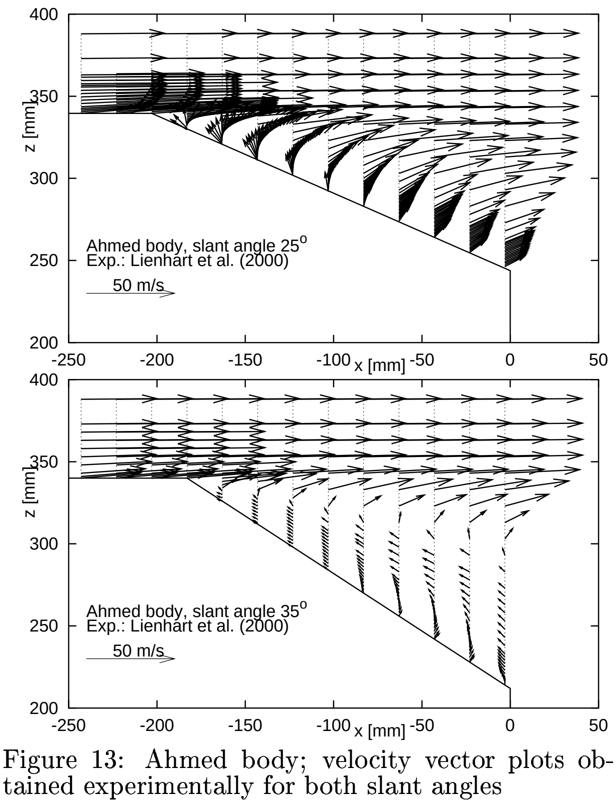


Figure 13: Ahmed body; velocity vector plots obtained experimentally for both slant angles

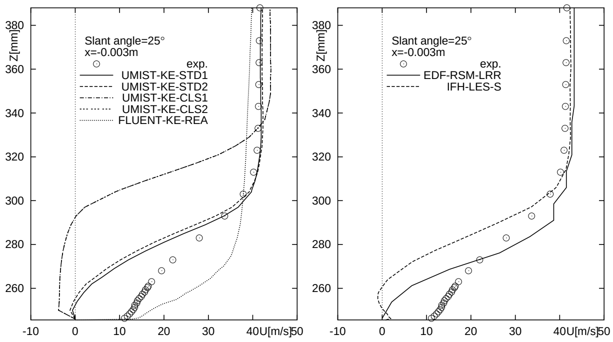


Figure 14: Ahmed body; slant angle 25^o: axial velocity profiles obtained by the $k-\varepsilon$ (left) and Reynolds-stress (right) model groups at a selected location. REA - Realizable $k-\varepsilon$ model; S - Smagorinsky

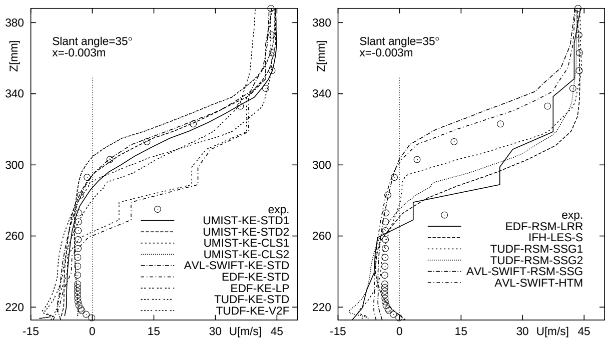


Figure 15: Ahmed body; slant angle 35^o: axial velocity profiles obtained by the $k-\varepsilon$ (left) and Reynolds-stress (right) model groups at a selected location. LP - Linearized Production

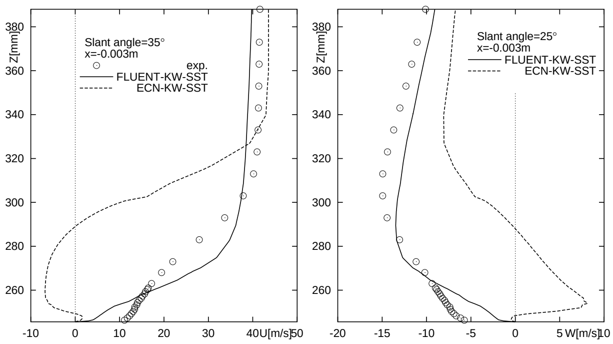


Figure 16: Ahmed body, slant angle 25^o; axial (left) and spanwise (right) velocity profiles obtained by the $k-\omega$ model group at a selected location

Figs. 14-15 show the streamwise velocity profile for both slant angles, obtained by the $k-\varepsilon$ (left) and Reynolds-stress models and LES (right), at the location corresponding to the end of the slanted surface ($x = -0.003\ mm$). Fig. 16 displays the streamwise (left) and spanwise (right) velocity profiles obtained by the KW-SST model group.

Seven groups obtained very different results even with the same turbulence models, see e.g. the $k-\varepsilon$ results in Fig. 14 (left) (notation STD in the UMIST's results is related to the REA model, which was also used by FLUENT), the $k-\varepsilon$ and RSM model results in Fig. 15, and especially the KW-SST results in Fig. 16. The reason can be attributed to insufficient grid resolution (the grid size varied from 150.000 to 2.3 millions cells for RANS and 8.8 millions for LES calculations), but also to not fully converged solutions and probably to coding errors as well. This is obvious at almost all positions and all computed profiles of various variables (see the workshop proceedings for more details). UMIST and IFH were the only groups, who submitted results for both test cases. It is very difficult to judge the predictive properties of turbulence models in such a situation. Almost all results (the only exception are the results obtained by FLUENT using the REA and KW-SST models[5], however it must be stressed that these results are very different compared to the results of some other groups obtained using the same models) exhibited a fairly similar flow pattern for both slant angles, with a recirculation zone surrounding complete end part of the car model, including the wake region. Whereas some models returned low intensity of this back flow for the 25^o case, among them were suprisingly the linear $k-\varepsilon$ model with wall functions (Fig. 14 left), some more complex models (e.g. NLKE-CLS) follow the same flow pattern with a large reverse-flow region, almost independent of the slant angle.

The predictions presented show in general, that Computational Fluid Dynamics "has a hard time" producing completely reliable and expected results when computing such complex, three-dimensional flows with high industrial relevance. The reason for the poor RANS results was sought by analysing the LES results (IFH). One important conclusion made was that transient rather than steady RANS calculations should be performed. Such calculations have to be done for the domain with the full body, otherwise an unsteadiness might be suppressed by the employment of the symmetry plane at the mid section of the body. From the novelties, it was interesting to see that the use of LES for the calculation of external aerodynamics is more visible after the calculations of IFH and that there were some attempts to make complex turbulence models more usable for real-life applications, e.g. calculations by hybrid EVM-RSM model (HTM), employment of the newly developed non-equilibrium wall functions (UMIST), as well as using the anisotropy resolving K2F model (TUDF). Finally, due to unsatisfactory results, this test case is recommended for the repetition at the next ERCOFTAC Workshop.

Conclusions

Similar to the previous eight ERCOFTAC Workshops on Refined Turbulence Modelling, the 9th workshop held at the Darmstadt University of Technology followed the basic goals of bringing together computational method developers and users from industry and from academia, and of promoting the exchange of information between them. The final outcome of this series of meetings is a general understanding of the models potential and limitations. A large number of solutions (over 80 sets of solutions for all four flows) have shown also a high level of predictive variability with respect to both, differences between the solutions and the experimental/LES data but also difference among solutions. The consistency among the results obtained by the same model was unfortunately not always as expected, this was especially true for the Ahmed body case. Keeping in mind the experience from the previous workshops, it will probably never be possible to achieve fully consistent solutions by using the same model schemes. Accordingly, the conclusion drawn at the 5th workshop (Laurence, 1997), that a reference solution should be sent to participants together with the case description, becomes even more relevant. This would be

[5] Furthermore, FLUENT computed only the slant angle 25^o. Due to the large differences between results, a result for the slant angle 35^o could not be estimated reliably.

particularly appropriate for the "new" test cases that are to be considered for the first time. However, this "large scatter of solutions" (Hanjalić et al., 2002) could be also understand as a knowledge acquired with respect to the range of uncertainty of the results obtained.

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