5^{th} ERCOFTAC Workshop on Refined Flow Modelling for Turbulent Flows

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1. Introduction

This is the 5^{th} of a series of yearly Workshops aiming at testing mainly turbulence models, and also performances of numerical methods. The 4th Workshop in Karslruhe, 1995 [1], concluded a CEC "Science Project" aimed at assembling a large database of detailed and reliable experimental data for turbulent flow (http://fluindigo.mech.surrey.ac.uk). The interest of the community in code validation was demonstrated again by the broad participation to this 5th Workshop: 65 participants, mainly West Europeans, but also coming from as far as Finland, Russia or USA. Most teams (see table 1) contributed to 2 or 3 test cases and applied 2 or 3 different models for each case, resulting in 2000 graphs and 600 pages of proceedings that were put together by only 2 students : Isabelle DAUTIEU and Sonia RICHOUD with admirable patience. The first three test cases were selected from the ERCOFTAC Database :

- Rectangular duct with a curved 90° bend,
- 2D plane turbulent wall jet,
- Natural-convection boundary layer,
- Natural convection in tall cavities.

2. Workshop programme

Each case was analysed in three steps, presentation of the reference data by the authors of the experiments when present (Pr. R. Karlsson, Pr. P. Betts), or DNS database (V. Maupu, H. Dol), presentation of the calculation methods and turbulence models by the participants, and comparison between the results. The local LNH organising committee (D. Laurence, J-P Chabard, G. Pot) is thankful to the Scientific committee (Pr. K. Hanjalic, Pr. B. Launder, Pr. M. Leschziner, Pr. W. Rodi, Pr. R. Karlsson) who helped conduct and present this analysis.
During the workshop Pr. Rodi presented the conclusions of the previous Workshop in Karlsruhe and the SCIENCE DATABASE project, while Pr. Hanjalic gave a lecture on turbulence modelling in natural convection flows.

3. Curved Channel

The duct has a rectangular cross section of width H=20.2 cm and height 6H. The inner wall around the 90° bend has a radius of 3H. W.J. Kim and V.C. Patel [2] provide hot wire and pressure probe measurements of axial and secondary velocities as well as Reynolds stresses in 6 cross sections. The Reynolds number based on freestream velocity and width H is Re=224 000.
Surprisingly for a 3D flow, up to 10 teams submitted 25 numerical solutions. The objective in considering again this case after the Karlsruhe workshop was to clarify why the same (k-epsilon) models used by different teams could give different results, and to invite more contributions with Reynolds stress transport models (RSTM). Also it was discovered at the 4th workshop that it was necessary to include at the inlet of the computations a pair of vortices along the floor that are generated by the contraction of the lateral walls upstream of the bend.

Universities from Göteborg, Nantes, Georgia, Helsinki, Lulea, Delft, Karlsruhe, Manchester, and also Vattenfall, presented solutions on meshes of about 250 000 nodes. Some were using commercial codes like CFX-Flow3D, but many "in house" codes now also have 3D body-fitted features. 12 solutions with RSTM models were presented (standard IP model with or without wall echo terms, Speziale Sarkar Gatski model, Clarke & Wilkes, and also Launder & Li's "Cubic" closure for the pressure-strains).

In the lower part of the channel, the low momentum fluid on the floor of the duct is pushed by the pressure gradient toward the inner side of the curvature (which in a meandering channel, causes sediment transport to the inner side of the curve). The vector plots on Fig 1. show this secondary motion in the lower part of a cross section of the duct after it has turned by 75°. The experiment shows a fairly complex structure with sharp features, whereas computations show a more diffused picture, especially for the k-epsilon computations (6-7-8). The Reynolds stress transport models (2-3-4) seem to perform better, but the non-linear k-epsilon model of Lien & Leschziner (5) does just as well. Also, the cubic RSTM of Launder and Li (2) (used here by a Swedish team in a commercial code) does show an improvement over the simpler RSTM (3-4). Still, differences are also due to numerical procedures (e.g. 6 & 7 using the same model). Although turbulence levels, with either RSTM or EVM, were similar, anisotropies were better predicted with RSTM or non-linear EVM which explains the differences in the secondary flow pattern.

At medium height in the channel, the problem can be considered two-dimensional, but in contradiction to our expectations, the RSTM did not clearly behave better than k-epsilon models as concerns the asymmetry of the kinetic energy profile from the inner wall (where curvature has a damping effect) to the outer wall (with the opposite effect of curvature through normal stresses anisotropies, ignored by standard EVM). On fig 2. are selected the best eddy viscosity and RSTM overall predictions for the friction coefficient. The RSM seem to better predict the increase of friction on the outer wall, halfway through, and just downstream of the bend. Two codes picked up instabilities of the mean flow on the outer wall which might have given rise to Gortler vortices, had much finer meshes been used. In the experiment, the energy of coherent structures may have been included in the turbulent kinetic energy, thus explaining the underestimation by all computations.

Wall jet

A slot is placed on the bottom of a pool, an a 2D wall jet develops along the floor (R. Karlsson et al. [3]), the Reynolds number based on the inlet is Re=10 000. 36 numerical solutions were submitted with models ranging from simple 1 eq. models, low Re 2 eq. models, to RSTM with wall functions.

The major problem for this case is that each participant had "guessed" different values for the dissipation at the inlet (where the flow exhibited a laminar mean velocity behaviour, although non zero fluctuations had been measured), and also the flow entertainment condition was dealt with by various procedures, while others decided to compute the whole pool. At x/b=70 (70 inlet diameters downstream) however, the jet reaches a self similar state and influence of inlet conditions is diminished.

Fig. 3 shows some of the better results by B. Huurdeman from Stuttgart (ICA) using finite elements, and B. Hemstrom from Vattenfall (VUAB). Fortunately, participants submitted results from different models using the same code, so comparisons could be made without bias effects from different numerical methods or inlet conditions. Here we see that away from the inlet, the use of a low Reynolds model (Launder-Sharma) does not show any difference with calculation using wall functions. At the 2 last stations (x/b = 150 and 200), the 2 different RSM computations are consistent with each other in their capacity in predicting better the maximum velocity while the k-epsilon models show a more diffused velocity profile. The kink in the VUAB profile on the left (x/b = 20) is characteristic of problems many participants had with the inlet conditions: standard mixing-length assumptions for the dissipation at inlet often led to a relaminarisation since the inlet turbulence level was very low. Left of Fig 3. shear stress profiles are shown at x/b = 200. It is well known that in a wall jet the position of the zero value of the shear stress does not coincide with the maximum of the velocity profile. This is due to the turbulent transport terms in the Re stress transport equations, which is large because of the strong asymmetry of turbulence levels between the near wall shear layer and the free shear layer.

Natural convection along a vertical hot plate.

The experiment by Tsuji & Nagano [4] was chosen because of the very detailed data available which include turbulent stresses, heat fluxes and their budgets. A variety of zero, one and 2 equation models (k-eps by Chien, k-omega, by Menter, eddy viscosity transport by Spalart-Almeras) provided acceptable results for engineering purposes such as Nusselt number predictions, although none of these models represent the detailed interaction between turbulence and gravity. The full RSM model by Peeters & Henkes, on the other hand yielded excellent results, quite as expected since it was devised for natural convection flows.

One of the outcomes of these workshops is also to determine up to what degree of accuracy experiments can be trusted. The audience debated the fact that the experiments show a zero shear stress around y+ = 10 while all models naturally predict it to be negative in the region where the velocity gradient is positive. Other experiments (Kato-Murakami-Yoshie, Karlsson et al.) yielded results in opposition with that of Tsuji & Nagano, and experimentalists present at the workshop concluded that measurement so close to the wall were extremely difficult to achieve. Although the hot and cold wire experiments by Tsuji & Nagano are probably the most detailed and reliable away from the wall, the discrepancies below y+ = 10 should be attributed to experimental uncertainties.

Natural convection in a tall cavity.

A recent experiment by Betts & Bokhari in a tall cavity, with vertical walls heated or cooled provided mean and fluctuating quantities for velocity and temperature, at Raleigh numbers Ra = 8.5 and 15.3 10^5 , with a remarkable symmetry of the profiles, which was not the case for many other such experiments. The aspect ration of 28.6 made possible the comparison of the experimental results with the DNS obtained at LNH (Boudjemadi, Maupu, Laurence [5]) assuming an infinite cavity. The DNS provided insight into detailed budgets of the stresses and fluxes and was confirmed by an independent DNS by Niewstadt & Versteegh (Delft TU). They indicate however that the relatively small size of the domain in the spanwise direction used by LNH leads to a slight overestimation of the maximum velocity. Though the DNS were conducted at Ra = 1 and 5.4 10^5, they compared very well with the experimental data for mean quantities while the DNS showed higher values of rms fluctuating temperatures. This is however consistent with Dr. Betts's observation that (non-dimensionalised) rms temperature profiles tend to decrease with increasing values of Ra numbers.

The predictions for mean quantities were reasonable even with 1 and 2 equation models. The 3 equation algebraic flux model by Kenjeres & Hanjalic, where in addition to k and epsilon, a transport equation for the temperature variance (used for the gravity contribution to the algebraic model of the heat fluxes) was used by both TU Delft team and EDF/TTA. Though implemented in two entirely different codes, this model consistently provided better results than standard low Re k-epsilon models, equivalent to the full RSM (Fig 4).

A term by term comparison for the budgets, with models and DNS, was conducted but would require a full paper by itself [5]. The shear and gravity production terms, of comparably similar magnitude, were naturally well predicted. Near the wall the shear production becomes negative (because the shear stress keeps a constant sign while the velocity gradient changes) but is almost compensated by the positive gravity contribution to the turbulent kinetic energy. This explains why simple one or two equation models, ignoring both features, still yielded acceptable results for mean temperature and velocities, as obtained by the team from Saint-Petersburg (Fig. 4).

As concerns the pressure-strains, for the wall normal component, it was found that the models actually compare better if the pressure diffusion is added to pressure-strain, (i.e. thus forming the velocity/pressure-gradient correlation) since each term shows large variations of opposite sign in the DNS while the models have smoother profiles.

Conclusions

There seemed to be a tendency for more sophisticated models to yield somewhat superior result, but this was not always obvious to all. For three-dimensional flows for which discretization errors still cannot be excluded, the full Reynolds stress closures did not clearly stand out of the large number of results, except for the details of the secondary flow. Surprisingly good results were obtained in natural convection with simple one or two equation models, while the RSTM show that these miss entirely the complex interaction between trubulence and gravity leading to non gradient fluxes and stresses.

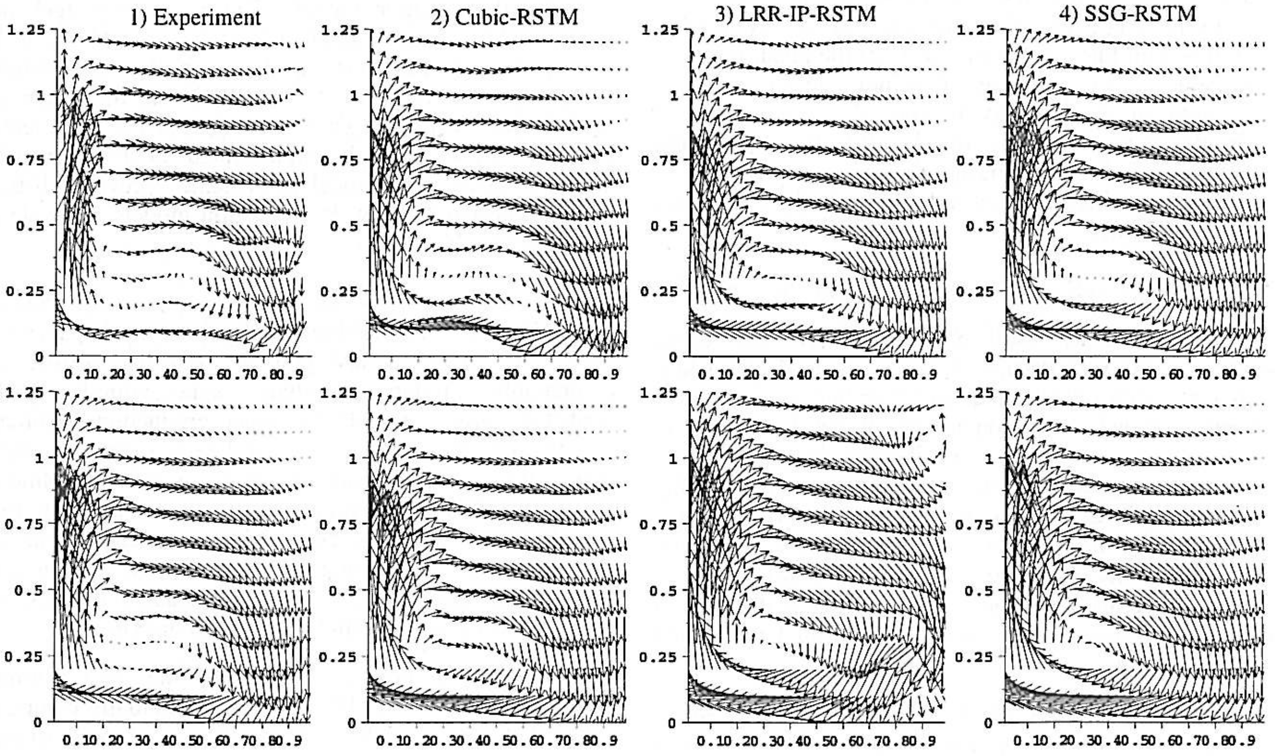
More conclusions were reached concerning the organisation of future workshops. Because of the increasing number of participants, rightfully concerned by code and model validation, such workshops would require more time for analysis, or fewer test cases.
Other suggestions relate to prescribing the mesh, or qualitative degree of mesh resolution, and inlet conditions for missing parameters (like dissipation) should also be prescribed. All this requires that the organisers actually complete their own numerical study, and try to define reference solutions, before the test case description is even sent to participants! Help from the community to define such reference solutions, apart from the yearly workshop events, is welcome.

References

[1] Bonnin, Buchal, Rodi. ERCOFTAC bulletin n 28, March 1996.
[2] W.J. Kim, V.C. Patel. J. of Fluids Engineering, 116, 45, 1994.
[3] R. Karlsson, J. Erisson, J. Persson. 6th I. S. on Applications of Laser Techniques to Fluid Mechanics, pp 1.5.1-1.5.6. , 1992.
[4] Tsuji T., Nagano Y., Tagawa M. 8th Turb. Shear Flow, Munich, 1991.
[5] R. Boudjemadi, V. Maupu, D. Laurence, and P. Le Quéré, J. Heat & Fluid Flow **18**, 1, Feb 1997.

Table 1: Teams contributing results :

APCH_rus:	Russian center for Applied Chemistry; M. Shur & M. Strelets, Bassina
CHALM:	Chalmers UT; S. Perzon, L. Davidson, M. Ramnefors.
ECL_SCIT:	Ecole Centrale de Lyon LMFA; S. Parpais
ECN_VD:	Ecole Centrale Nantes; Visonneau & Deng
EPFL:	E. Polytechnique Fed. Lausanne; T. Jongen, Y. Marx
GATECH:	Georgia Inst. of Technology; F. Sotiropoulos,
HUT_KH:	Helsinki UT; S. Laine, A Hellsten, P. Kaurinkoski
HUT_SR:	Helsinki Univ. Tech.; P. Rautaheimo, T. Siikonen
ICA3:	Inst. for Computer Applic. 3; B. Hurdeman
LNH_DLBA:	EDF, Lab Nat Hydraulics; Dauthieu, Laurence, Bonnin, Archambeau
LUTH_JB:	Lulea University of Technology; J. Bergstrom
TUD_HHS:	DELFT UT; H. Dol,I. Hadzic, K. Hanjalic, N. Stosic, S. Kenjeres
TUD_MZ:	DELFT UT, M. Zijlema
UKA:	U. Karlsruhe, Inst. fur Hydromechanik; T. Buchal, D. Lakehal, W. Rodi
UMIST:	U. Manchester IST; F.S. Lien, T. Craft, M. Lechziner, B. Launder
VUAB_BH:	Vattenfall Utveckling; B. Hemstrom
VUAB_SJ:	Vattenfall Utveckling AB; S. Jansson
VUB:	Vrije Univ. Brussels, N. Hakimi, A. E. Khodak and C. Hirsch



1) Experiment 2) Cubic-RSTM 3) LRR-IP-RSTM 4) SSG-RSTM

5) non-linear k-eps 6) standard k-eps 7) standard k-eps 8) low Re k-eps

Fig. 1: Curved Duct, secondary motions near the floor in a cross section after the channel has turned (left) by 75°.
2)- CHALM; 3)- CHALM; 4)- VUAB; 5)- UMIST; 6)- GATECH; 7)- UKA; 8)- ECN.

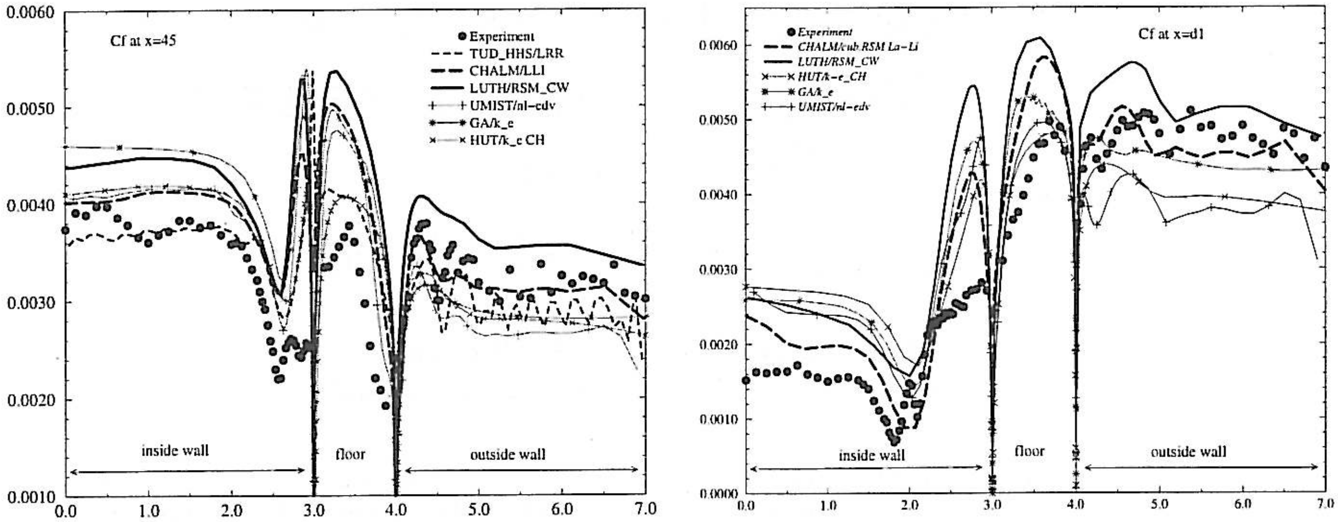


Fig. 2 : Curved Duct, friction coefficient in cross section at 45° and just after the bend.

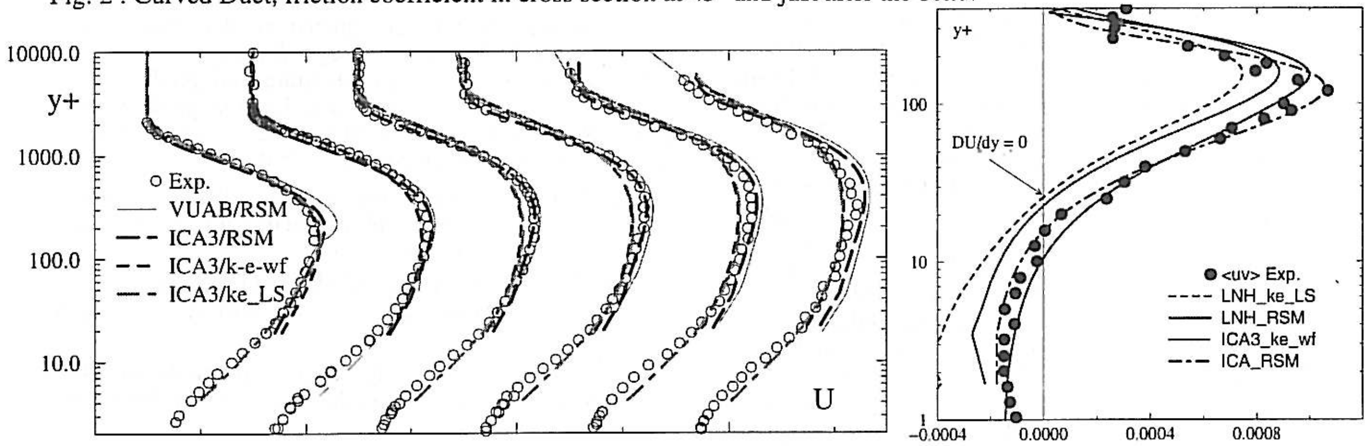


Fig 3 Mean velocity profiles across the wall jet at stations ranging from x/b=20 to 200. Left: Shear stress profiles across the jet v/s y+ . The EV models predict <uv>=0 only when the velocity is maximum.

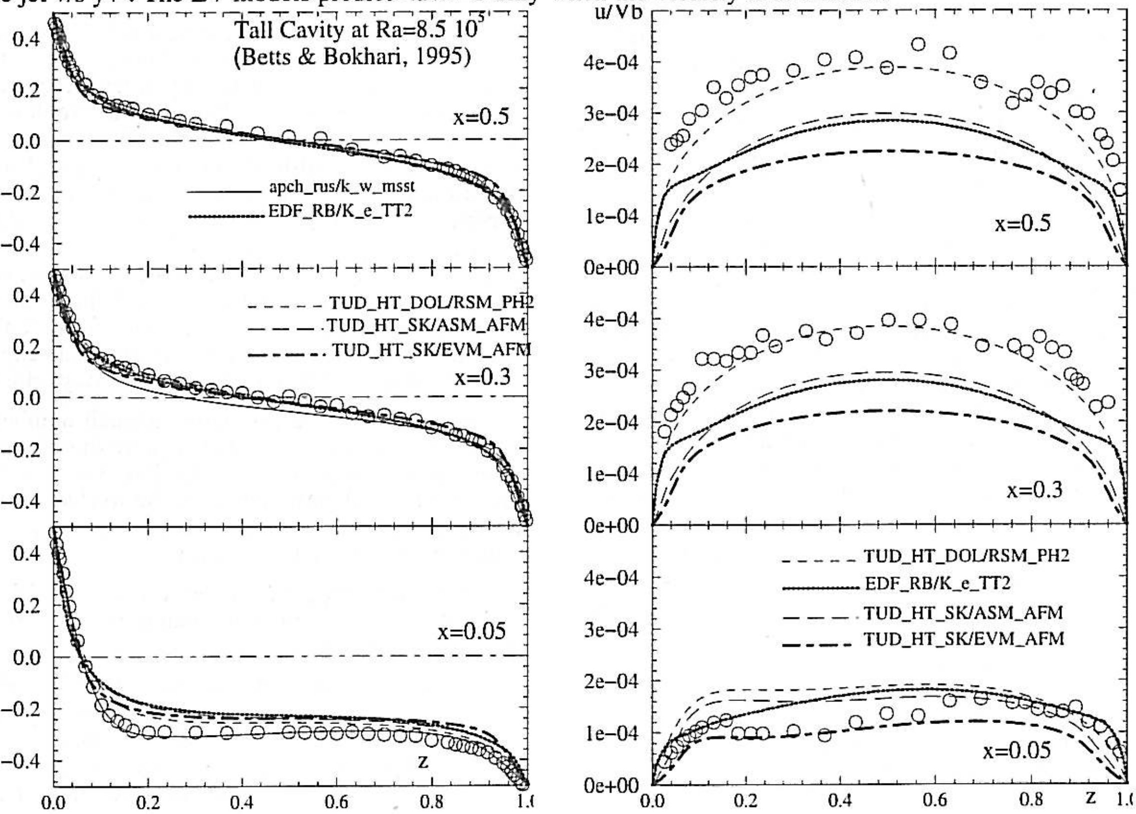


Fig. 4 : Natural convection in a tall cavity, Temperatures (well reproduced by a simple 2 eq. model), and r.m.s velocity profiles, well reproduced only by the RSTM.