16th ERCOFTAC Workshop on turbulence modelling
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S. Benhamadouche[1], M. Dular[2], C. Flageul[3], C. Katsamis[4], R. Krpan[5], D. Laurence[4], I. Tiselj[5,6]

cedric.flageul@enpc.fr rok.krpan@ijs.si

1 : Fluid Mechanics, Energy and Environment Dept., EDF R&D, Chatou, France
2 : Faculty of Mechanical Engineering, The University of Ljubljana, Ljubljana, Slovenia
3 : CEREA, École Nationale des Ponts ParisTech, Champs-sur-Marne, France
4 : The University of Manchester, Manchester, United Kingdom
5 : Reactor Engineering Division, Institut Jožef Stefan, Ljubljana, Slovenia
6 : Faculty of Mathematics and Physics, The University of Ljubljana, Ljubljana, Slovenia

Abstract

A short report is given on the 16th ERCOFTAC SIG 15 Workshop on Turbulence Modelling, which was organized at the Jožef Stefan Institute of Ljubljana on 15th and 16th of October 2019. The workshop was focused on turbulent natural convection. The test cases were differentially heated vertical channel flows and differentially heated square cavities.

1. Introduction

The role of the ERCOFTAC SIG 15 (Special Interest Group for Turbulence Modelling) series of workshops on refined turbulence modelling is closely connected to intensive verification and systematic validation of CFD software. The latter are used for tackling problems of fundamental importance and industrial relevance. These workshops bring together researchers, users and developers form industry and from the academic field. They promote discussion and conclusions about predictive performance of variety of models such as LES, RANS and hybrid LES/RANS. The outcome of the workshops is also a large database of simulation results along with a detailed comparison with reliable reference data (experimental, DNS and highly-resolved LES databases). Credible, reliable and robust numerical methods and turbulence models are the keys making CFD one of the most versatile and powerful workbench to study turbulent fluid flows.

The 16th ERCOFTAC SIG 15 workshop was held on 15th and 16th October, 2019 at the Jožef Stefan Institute of Ljubljana, Slovenia. Similar to the previous workshops in Lyon (1991), Manchester (1993), Lisbon (1994), Karlsruhe (1995), Chatou (1996), Delft (1997), Manchester (1998), Helsinki (1999), Darmstadt (2001), Poitiers (2002), Gothenburg (2005), Berlin (2006), Graz (2008), Rome (2009) and Chatou (2011), some cases have been chosen for this workshop by the steering committee of the SIG 15. The following two flows involving turbulent natural convection and numerous features of scientific and engineering relevance (e.g. laminarization, transition to turbulence, ...) were finally selected as test cases for this workshop.

As a general framework, fluids considered in this report are incompressible Newtonian fluids with constant properties (i.e. density, viscosity and thermal conductivity), their Prandtl number is 0.71, the low Mach number assumption holds and buoyancy effects are taken into account using the Boussinescq approximation. Although not discussed here, simulations with variable properties or without the low Mach number assumptions were presented and discussed during the workshop.

2. Case 16.1: Differentially heated vertical channel flow

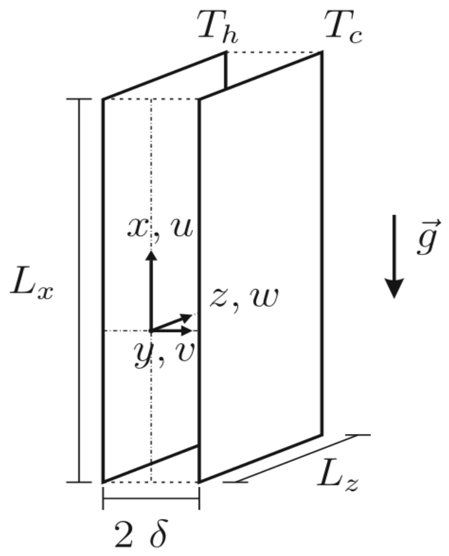

Figure 1: Sketch of the differentially heated vertical channel, [1].

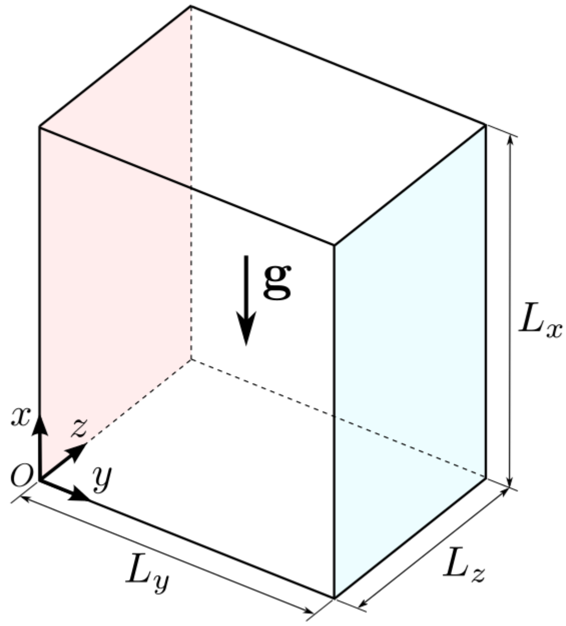

Figure 2: Sketch of the differentially heated square cavity, [4].

Regarding turbulent channel flows, a large number of studies focus on forced convection or natural convection in a horizontal channel (Rayleigh-Benard convection). For a horizontal channel, production / destruction of turbulent kinetic through buoyancy effects involves the wall-normal heat flux. For a vertical channel, buoyancy effects on turbulent kinetic energy involve the wall-parallel heat flux. This fundamental difference can be of prime importance.

For instance, simpler RANS turbulence models use a simple gradient diffusion hypothesis for both the turbulent convection in the temperature equation and for the buoyant term in the turbulent kinetic energy equation. For a horizontal periodic channel flow, the outcome of those hypotheses is the absence of any stream-wise turbulent heat flux, thus discarding buoyancy effects from impacting the turbulent kinetic energy.

Regarding the vertical channel flows considered in the workshop, the cases with a Grashof number of 2.10^6 and 3.10^6 from *Kiš and Herwig* ([2]) were considered. Among the 9 datasets submitted for the first case, 4 were selected:

- A LES using the standard Smagorinsky model (and Van Driest near-wall damping) combined with a constant subgrid-scale Prandtl number
- A RANS simulation using the Launder and Sharma model combined with a Simple Gradient Diffusion Hypothesis
- A RANS simulation using a cubic non-linear k-ε model combined with an algebraic heat flux model
- A RANS simulation using a Reynolds stress model combined with a Generalized Gradient Diffusion Hypothesis

Some of the corresponding results are given in Figure 3 and in Figure 4. The spread regarding the Nusselt number is quite large, and is naturally reproduced on the wall-normal turbulent heat flux. A general trend – not shown here – impacting all the RANS datasets submitted is the underestimation of the turbulent kinetic energy in the channel for both cases considered. Regarding LES, the datasets submitted compared very favorably with the DNS. This was expected as advanced RANS quantities such as ε, ε_θ or terms in their budget equation were not investigated during the workshop.

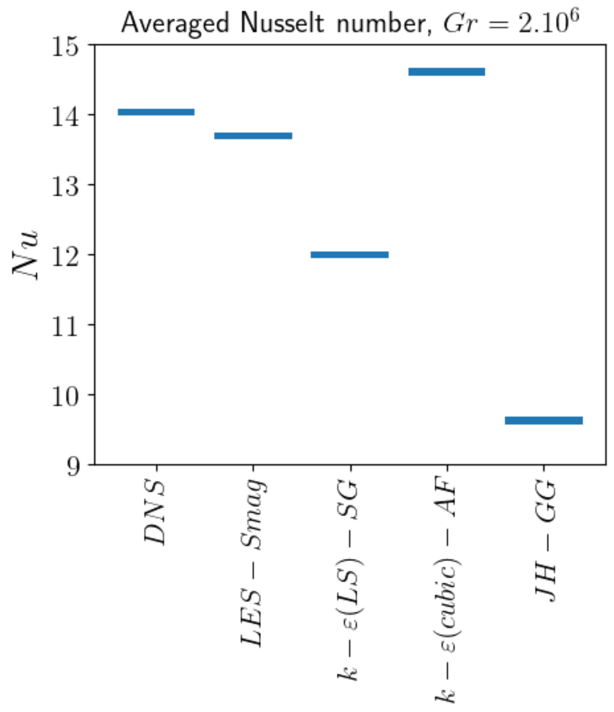

Figure 3: Averaged Nusselt number for the vertical channel flow at Gr=2.10^{6}.

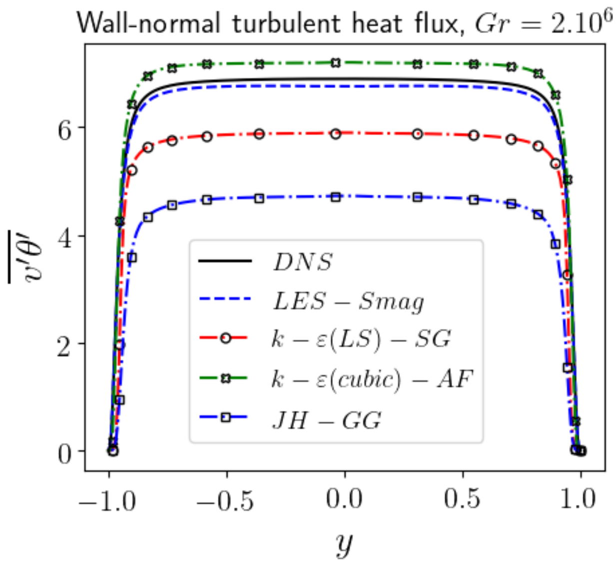

Figure 4: Wall-normal turbulent heat flux for the vertical channel flow at Gr=2.10^{6}.

3. Case 16.2: Differentially heated square cavity

The challenging test case of this workshop is the square cavity with a differential heating at side walls, as described in *Sebilleau et al.* ([4]). In the present report, only a subset of the datasets submitted at the intermediate Rayleigh numbers are presented. For the case with Ra=1.58e9, the DNS is compared with a LES (Filtered Structure Function, [1], [3]) and several RANS simulations including both High-Reynolds number (HRN) models with wall function (k-ε with SGDH (Single Gradient Diffusion Hypothesis), SSG with the GGDH (generalized gradient diffusion hypothesis) and some recently developed Low-Reynolds number (LRN) schemes with elliptic blending (BL-v^2k with SGDH and EBRSM with GGDH). Regarding the case at Ra=1e10, the DNS is also compared with a LES (FSF), a Delayed Detached Eddy Simulation and several RANS simulations (BL-v^2k+SGDH, EBRSM+GGDH and EBRSM+EBDF).

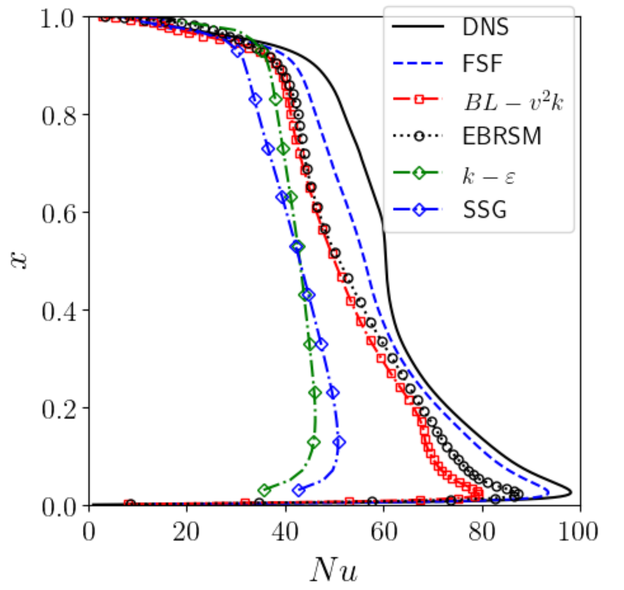

Figure 5: Averaged Nusselt number on the hot wall, square cavity at Ra=1.58e9.

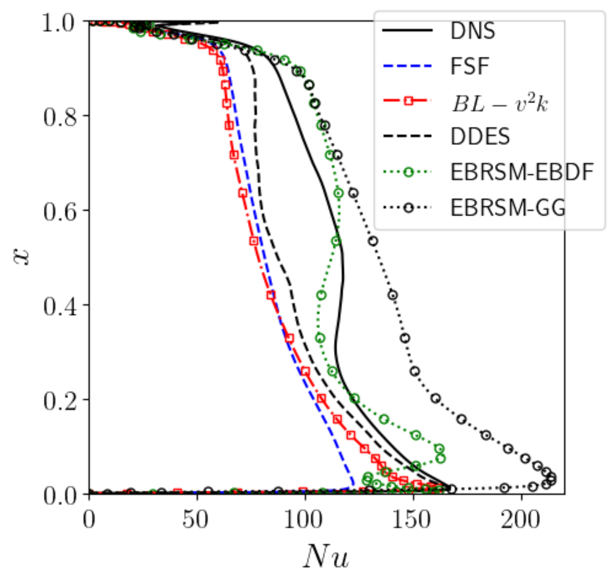

Figure 6: Averaged Nusselt number on the hot wall, square cavity at Ra=1e10.

The steep near wall velocity gradients that arise as the fluid impinges on the active walls challenges both class of Eddy Viscosity and Reynold Stress transport closures which were initially developed for forced convection. The log-law based wall function used alongside the HRN models is the main cause of the underestimation of the Nusselt number (Figure 5) which is proved inappropriate and very sensitive to the near wall cell height. At Ra=1.58e9, compared with the HRN models, the LRN ones perform slightly better, but still exhibit their deficiency in handling transitions, leading the flow to become laminar at this Ra number and predicting the turbulence enhancement location to occur at a different location from the DNS (see the peak of the Nusselt at x=0.6 in Figure 5). At Ra=1e10, the more advanced second-order LRN models no longer underpredict the Nusselt number, thus showing that their complexity is rewarded.

At the lower Rayleigh number presented here, the LES clearly outperforms the RANS ones. However, at the higher Rayleigh number, it is slightly under-resolved and the DDES outperforms the LES. Indeed, the presence of zones where laminarization / transition to turbulence can occur is a challenge for RANS models. The selected results show that it is also a challenge for LES due to the mesh requirement. When the grid becomes fine enough, the LES outperform RANS simulations and compare very favorably with DNS. However, it must be stressed that for such a 2D steady case, the computing time needed for a RANS simulation is well below the computing time needed for a wall-resolved LES on a refined grid.

4. General comments and remarks

It is important to stress that the comparison made in this report is qualitative as the mesh and the CFD code used vary between datasets. Datasets submitted to the workshop were produced by the following CFD codes:

- In-house LES / DNS code from the University of Cyprus
- *Code_Saturne* version 5.0 and 6.0 (open-source)
- In-house STREAM code from the University of Manchester

Although not exposed here, some interesting results based on new turbulence models were discussed:

- The dual-mesh hybrid RANS/LES method in which simultaneous URANS and under-resolved LES simulations are run and are corrected towards each other as suggested by Xiao and Jenny ([6]) and Tunstall et al. ([5]).
- The Eddy-viscosity based turbulence models are sensitized to the effects of buoyancy by introducing the influence of buoyancy production in the Boussinesq relation. This extended constitutive relation is implemented in the BL-v^2k and k-ω-SST models as presented in Saad Jameel et al. ([7]).

5. Conclusions

In the square cavity, most severe modelling challenges arise due to the significant unsteadiness and the strong gradients at the boundaries where the larger scales are being developed. Regarding the RANS simulations, the HRN schemes maintain the flow turbulent even with the log-law based wall function which its assumption does not apply for this case. Although the more advanced LRN schemes with the blending approach seem more promising, transition to turbulence will probably remain a difficult challenge for RANS models.

Acknowledgments

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