11TH ERCOFTAC WORKSHOP ON REFINED TURBULENCE MODELLING

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GENERAL

The 11th Workshop on Refined Turbulence Modelling took place at Chalmers University of Technology, Göteborg, Sweden on the 7-8 of April 2005 under the auspices of the ERCOFTAC Special Interest Group for Turbulence Modelling, SIG-15, and in association with Volvo Aero Corporation, Volvo Car Corporation, and DESider, a 6th Framework Programme for Industrial CFD. The purpose of this series of workshops is to contribute to the further development and refinement of turbulence models for flow and heat transfer. Within the framework of the workshop this is done by comparing computational results obtained by different groups with the results of carefully executed and very well documented experiments.

The workshop attracted a total of 35 participants, 30 from 6 European countries, and 5 from USA and Canada. The participants represented the academic sector (21), the industrial sector (8), and research organizations (6).

The meeting was conducted in an informal and friendly atmosphere and was characterized by extensive and fruitful discussions.

The general pattern of the workshop was first to select four test cases characterized by both being very well documented experimentally and being challenging for the turbulence models in use today. Researchers from all over Europe and elsewhere were then invited to carry out computations on these cases, using turbulence models and numerical schemes of their own choice, and to submit them to the organizing committee. The next phase was to compile, cross-plot and compare the results obtained by different researchers using different turbulence models and different numerical schemes, and to the experimental results. These results were available to the participants before the workshop.

During the workshop each case was presented and discussed, one at a time. During the presentations the experimental results were first presented, in most cases by a person that actually had been part of doing the experiment. This was followed by an overview and comparison of the various computational and experimental results. Finally each contributor made a short presentation of his own results. Discussions of the results were made an integral part of the presentations throughout the workshop.

TEST CASES

Four test cases were selected, one of them a two-dimensional flow, the other three were strongly three-dimensional. The four test cases are described briefly below.

Test case 11.1: Wall-mounted two-dimensional hump with oscillatory zero-mass-flux jet or suction through a slot

The experimental data for this test case were obtained at NASA Langley Research center, Hampton, VA, USA. The case was considered by two groups. In total seven turbulence models were used. One of the computations was a large-eddy simulation.

Description

This is a carry-over test case from the March 2004 workshop at NASA Langley. Experimental data are available for three cases: the baseline without any control, the flow with steady suction, and the flow with a zero-efflux oscillatory slot jet.

These test cases are all nominally two-dimensional, although end plates bring some 3D effects. The hump was 420 mm long with the crest of 53.7 mm and was mounted on a splitter plate of thickness 12.7 mm, which extended 1935 mm upstream from the hump leading edge and 1129 mm downstream from the hump leading edge. The hump with the splitter plate was placed in a wind tunnel of 771 mm width and 508 mm height, but the nominal test section height (between the splitter plate and the top wall) was 382 mm and the nominal hump width (between the two end plates) is 584 mm. The characteristic Reynolds number, based on the hump length, was about 10^6 and the Mach number was 0.1. Results containing base plate pressure and friction factor, and PIV of the mean velocity components in the main flow direction, $\overline{U}$, and the wall-normal direction, $\overline{V}$, and of two normal Reynolds stresses, $\overline{u^2}$, $\overline{v^2}$, and the shear stress, $\overline{uv}$ are available at different stations for the three cases: Baseline results (no control), suction control (steady suction rate through the slot of 0.01518 kg/s at Re=929000) and zero-efflux oscillatory forcing trough the slot, with nominal peak velocity of 26.6 m/s and frequency of 138.5 Hz (other cases are also available, but not considered in the workshop).

A detailed account of the experiment can be found on the internet at:

http://cfdval2004.larc.nasa.gov/case3.html,

and in an AIAA conference paper:

David Greenblatt, Keith B. Paschal, Chung-Sheng Yao and Jerome Harris, "A Separation Control CFD Validation Test Case, Part 2. Zero Efflux Oscillatory Blowing", 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV 2005.

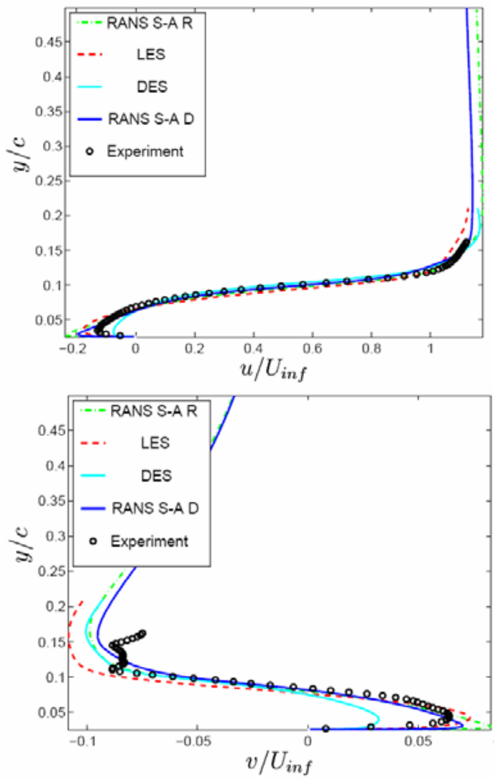

Figure 1: Mean velocity in the main flow direction, u/U_{inf}, and in the wall-normal direction, v/U_{inf}, for the baseline case. x/c = 0.8.

Baseline (no control)

A few examples of the computational results are shown in figure 1. The position *x/c* = 0.8 is downstream of the slot, approximately half-way down the rear part of the hump.

The axial mean velocity was well predicted in this position by all turbulence models. Farther downstream the predictions were less favorable. The wall-normal mean velocity was also reasonably well predicted here, but was severely in error in the more downstream positions. In more upstream positions the predictions were much better.

Oscillatory jet

This case is much more complicated and requires the computation of the mean velocity components and the Reynolds stresses for all phases of the oscillation. A few example results are shown in figure 2.

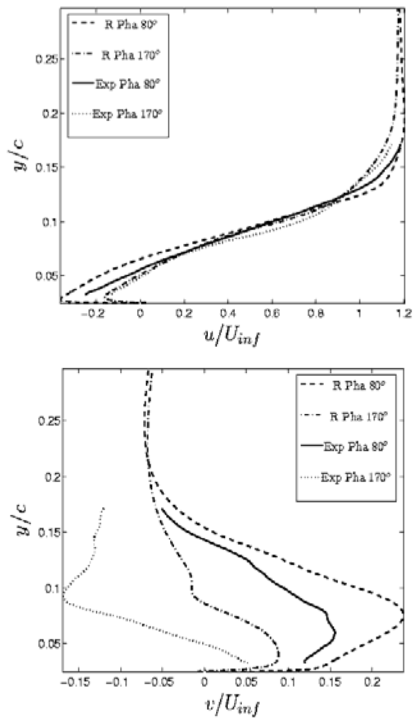

Figure 2: Mean velocity components for the oscillatory jet for two phase angles. x/c = 0.8.

The mean velocity in the main flow direction, u/U_{inf}, is fairly well predicted. Although not demonstrated in this figure, a common problem found in more downstream positions was a lack of sensitivity to the phase of the oscillation. The predictions of the wall-normal mean velocity component were generally severely in error. At more upstream positions the predictions were generally better.

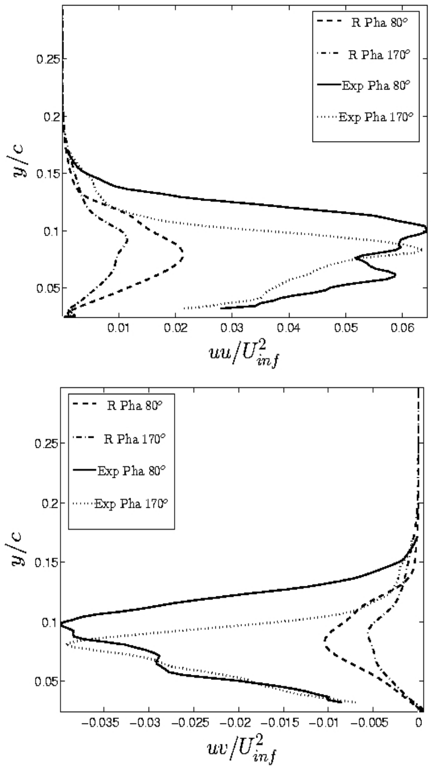

Figure 3: One normal Reynolds stress component and the Reynolds shear stress component for the oscillatory jet. x/c = 0.8.

The Reynolds stresses were generally poorly predicted. A lack of sensitivity to the phase of the oscillation was manifested throughout.

Steady suction through the slot

A few computational results are shown in figure 4.

The mean velocity component $\overline{U}$ is again well predicted in the *x/c*=0.8 position. The wall-normal component is less well predicted. At more upstream positions the predictions are generally good, but further downstream they are worse. Especially the predictions of the wall-normal component deteriorate.

Teat case 11.1 has shown that, upstream of the slot, the mean velocity components are well predicted. Far down on the rear part of the hump the predictions are generally poor. There are of course differences between the results using different turbulence models, but in most cases the main difference is between computational results on the one hand, and the experimental results.

Test case 11.2: Flow over an axisymmetric three-dimensional hill

The experimental data for this case were obtained at Virginia Polytecnic and State University, Blacksburg, VA, USA. Eight groups submitted computational results. In total 17 different solutions were contributed.

Description

Detailed three-component LDA measurements of velocity, surface mean pressure, oil-flow visualization in a flow field with challenging three-dimensional separation. The flow serves as a test case in the EU project DESider in which LES based computations are also in progress.

A bell-shaped hill is placed in a wind tunnel, and extensive flow visualization and measurements of wall pressure, wall friction, the mean velocity field and the Reynolds stress field were carried out using oil-film technique and laser-Doppler anemometry. A detailed description can be found in *Simpson, R.L, Long, C.H., Byun, G., "Study of vortical separation from an axisymmetric hill", Int. J. Heat and Fluid Flow, 23(5) 582-591, 2002*. Additional in formation is available on the internet at:

http://www.aoe.vt.edu/~gbyun/.

The structure of this flow field is very complex. It is therefore impossible to give more than a few examples of the computational results. See figures 4-6.

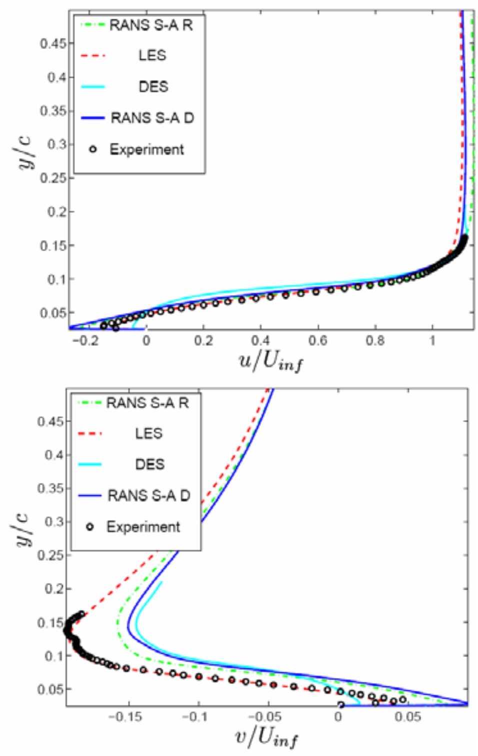

Figure 4: Mean velocity components for the case with steady suction. x/c = 0.8.

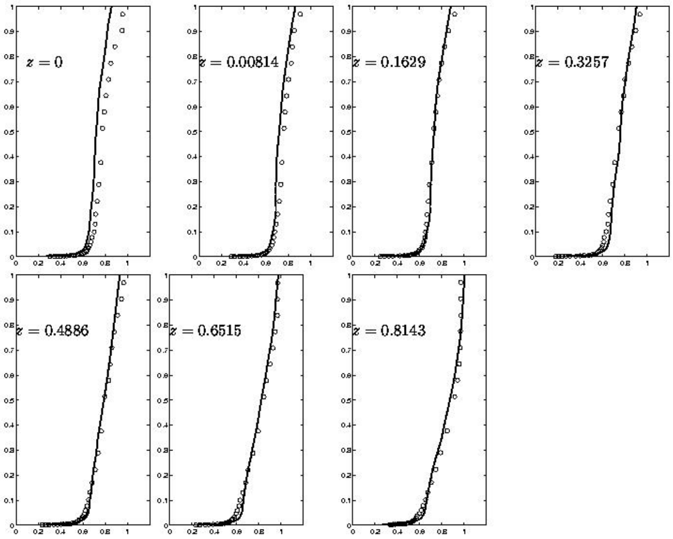

Figure 4: Example of mean axial velocity profiles for different transverse positions.

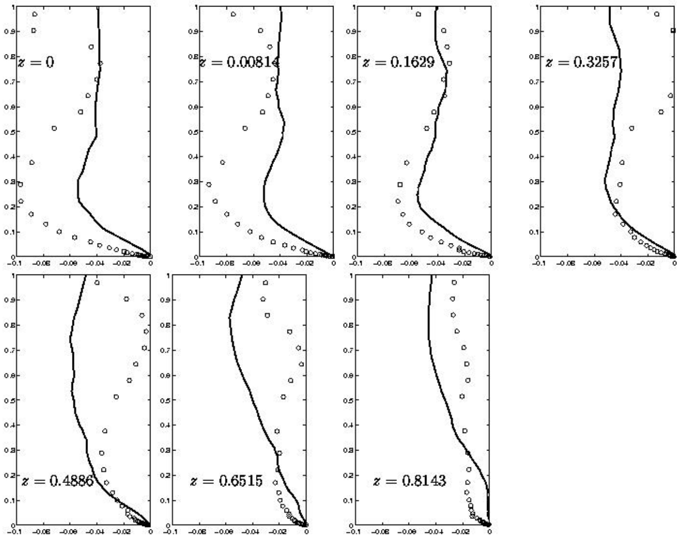

Figure 5: Example of mean vertical velocity component for different transverse positions.

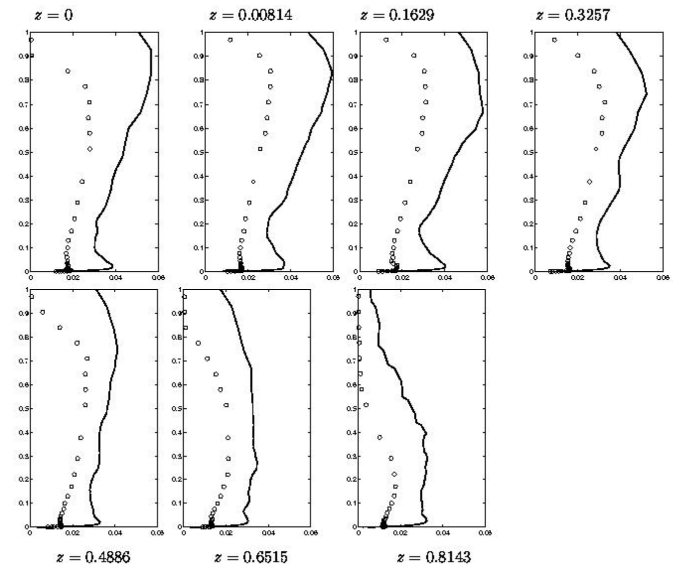

Figure 6: Example of the normal streamwise Reynolds stress component for different transverse positions.

The computational results for the 3D hill are mixed. The mean velocity component in the main flow direction is well predicted in the example given here. On the other hand, the mean velocity component in the vertical direction and the normal streamvise Reynolds stress are poorly predicted. The accuracy of the computational results varies considerably in different regions of the flow fields, which is to be expected given the complexity of the flow field.

Test case 11.3: Slanted jets in cross-flow

The experimental data for this case were obtained at Chalmers University of Technology, Göteborg, Sweden. Three groups submitted computational results. Seven different solutions were contributed.

Description

In a full coverage film cooling experiment a large number of jets were injected from a side wall into a main stream parallel to the wall. Measurements were performed on one of the jets located in the third row of cooling jets.

The measurements were done in about 35 000 points using a three-component laser-Doppler anemometer. In every point 5000 samples were collected. The LDA-system worked in hardware coincidence mode, i.e. all three velocity component were sampled simultaneously. Results are reported for all three mean velocity components, all Reynolds stresses, and all third order moments. The measurement volume of the LDA was nearly spherical in shape with a diameter of 45 µm (side-scatter mode).

Details of the experiment can be found in the following publications:

Gustafsson, K.M. B., Experimental Studies of Effusion Cooling, PhD Thesis, Department of Thermo and Fluid Dynamics, Chalmers University of Technology, SE-41296 Göteborg, Sweden. Available as pdf-file at http://www.tfd.chalmers.se/~gujo/WS11_2005 /Slanted_jet/Gustafsson-Thesis.pdf (15.9 MB).

Gustafsson, K.M.B. and Johansson, T.G., "Turbulence and Velocity Fields of Slanted Jets in Crossflow - Measurements and CFD Simulations", Turbulence, Heat and Mass Transfer 4, Oct 12-17, 2003, Antalya, Turkey.

Detailed experimental data can be found on the internet at:

http://www.tfd.chalmers.se/~gujo/WS11_2005 /Slanted_jet/INDEX.HTM.

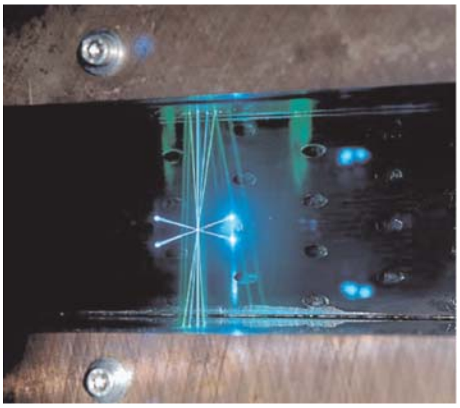

Figure 7: The experimental set-up of the slanted jets in cross-flow. The laser beam configuration used in the experiment is also shown.

Some computational results

This case is very complex in its topology (see figure 8), and is, like the previous case, impossible to describe in any detail in a short summary report. None of the computations manage to describe the complexity of the flow field. Shortly following the injection hole a pair of focal points is at hand. Only Gustafsson's k-ω model manages to predict the existence of this essential topological structure. It is noteworthy that another contributor's computations using the same turbulence model fails to predict this feature of the flow field. The strength of the vertical mean velocity component is also severely underestimated by all computations, again with the exception of Gustafsson's k-ω model.

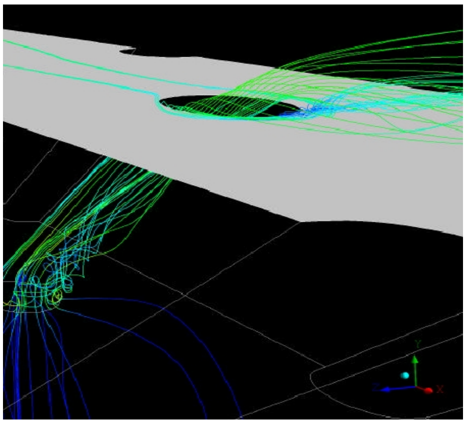

Figure 8: Computational results with SST-k-omega model. Streamlines through the pipe and in the jet emanating from the pipe illustrates the complexity if the flow.

Test case 11.4: Multiple-impinging jets: flow and heat transfer

The experimental data for this test case were obtained at Delft University of Technology, Delft, The Netherlands. Three groups submitted computational results, and eight different solutions were contributed.

Description

PIV measurements were carried out yielding mean flow and turbulent second-moments. Surface temperature and heat transfer for the two jet array configurations were also measured at the Delft University of Technology.

The first case consisted of 9 jets in an in-line arrangement. The second case consisted of 13 nozzles in a hexagonal arrangement. Both cases are characterized by full three-dimensionality, high anisotropy, and strong variation of heat transfer over the impingement plate.

Details about the experiment can be found in *L.F.G. Geers, Ph.D. 2003 Delft Univ. Technology* and in *Geers, L.F.G., Tummers, M.J., Hanjalic, K. "Experimental investigation of impinging jet arrays", Experiments in Fluids Vol. 36, pp. 946-958 (2004).* Information is also available on the internet at:

http://tmdb.ws.tn.tudelft.nl/workshop11/case11.4.html.

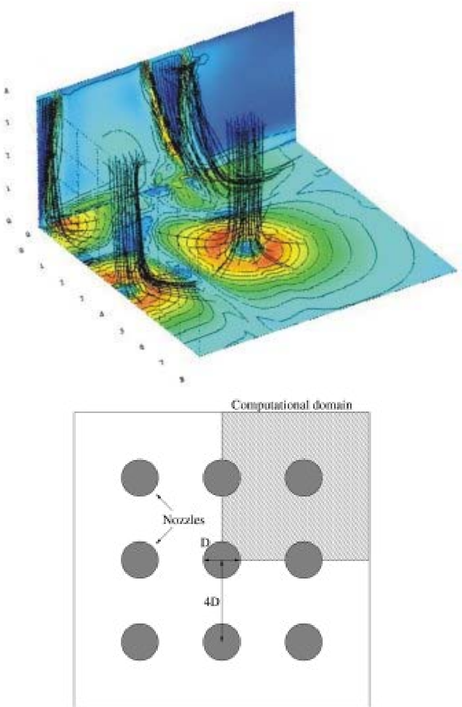

Figure 9: Impinging jets in in-line arrangement, showing mean velocity streamlines and the heat transfer rate on the surface.

Additional information can also be found in the RANS computations for this case that have been reported by:

L. Thielen, K. Hanjalik, H. J.J, Jonker, and R. Manceau, "Predictions of flow and heat transfer in multiple-impinging jets with an elliptic-blending second-moment closure", Proc CHT-04, ICHMT International Symposium on Advances in Computational Heat Transfer, Norway, April, 2004.

A sector of the in-line arrangement is shown in figure 9 and a few computational results are shown in figure 10.

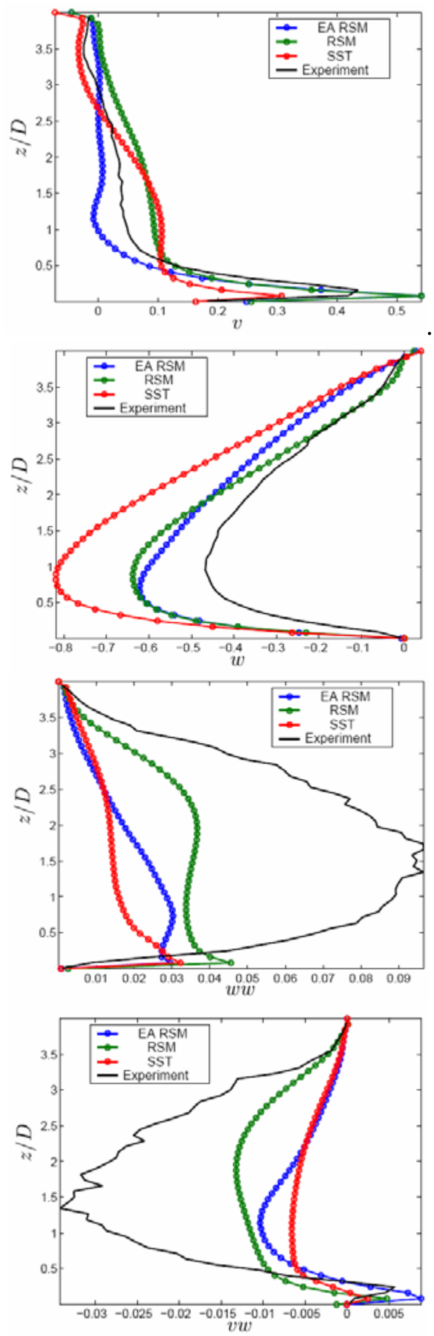

Figure 10: Top: Mean velocity field. Bottom: Reynolds stresses. Computations and experimental results from the plane y/D=0.5, in-line arrangement.

This case demonstrates clearly the difficulties with computations of complex flow fields. The computational results of the mean velocity field show the general features of the flow field correctly. They predict the magnitude of the y-component fairly well, but not the z-component. The Reynolds stresses are poorly predicted.

Some results of computations of the Nusselt numbers are shown in figure 11.

The computations of the Nusselt numbers show qualitatively correct distributions. The magnitudes vary though in a way that is not in agreement with the experimental results. The experiments show approximately equal Nusselt numbers for each jet, but this is not the case for the computations.

SUMMARY

The 11th ERCOFTAC Workshop on Refined Turbulence Modelling was a very intense and productive meeting, with a lot of fruitful discussions.

2D flow fields are computed with reasonable accuracy, at least mean velocity fields.

3D fields are still very difficult to compute.

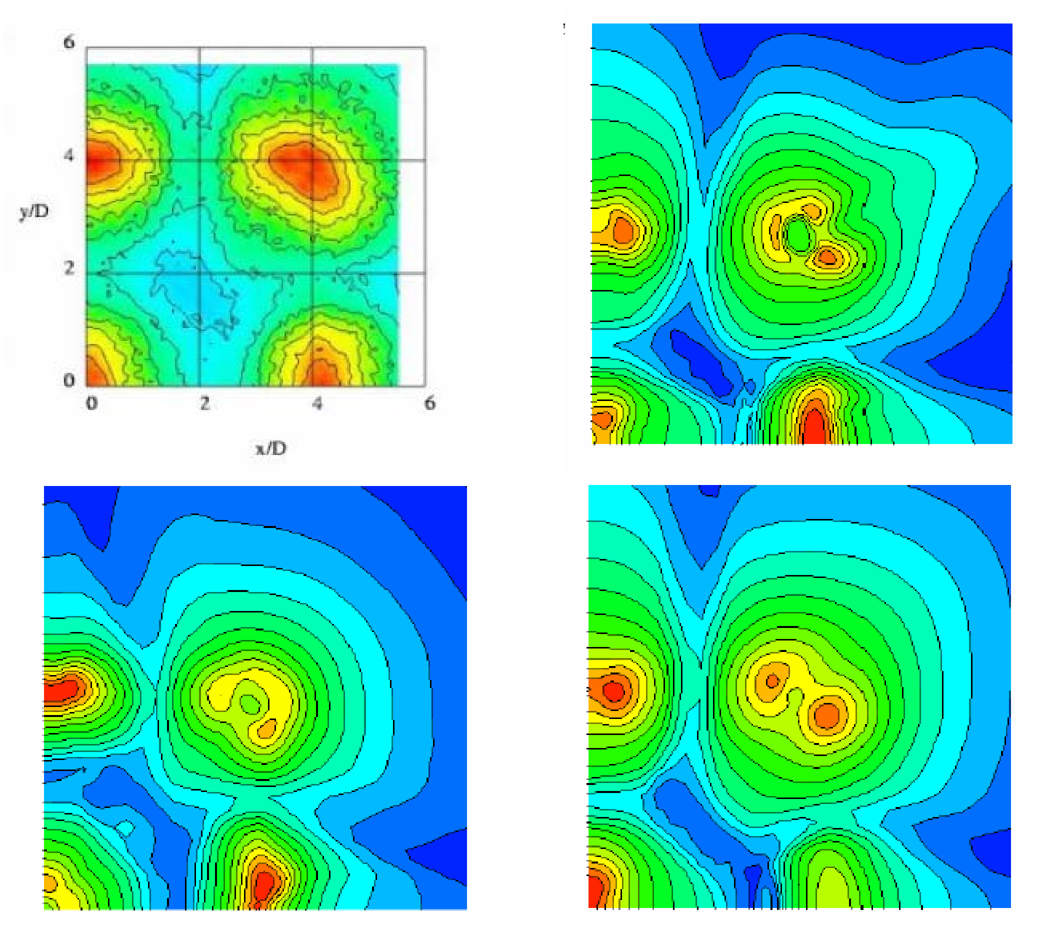

Figure 11: Experimental and computational results of the Nusselt number distribution on the surface. Top left is experimental results, top right is computational results using the SST model. Bottom left and right show computational results using RSM and EARSM models respectively.