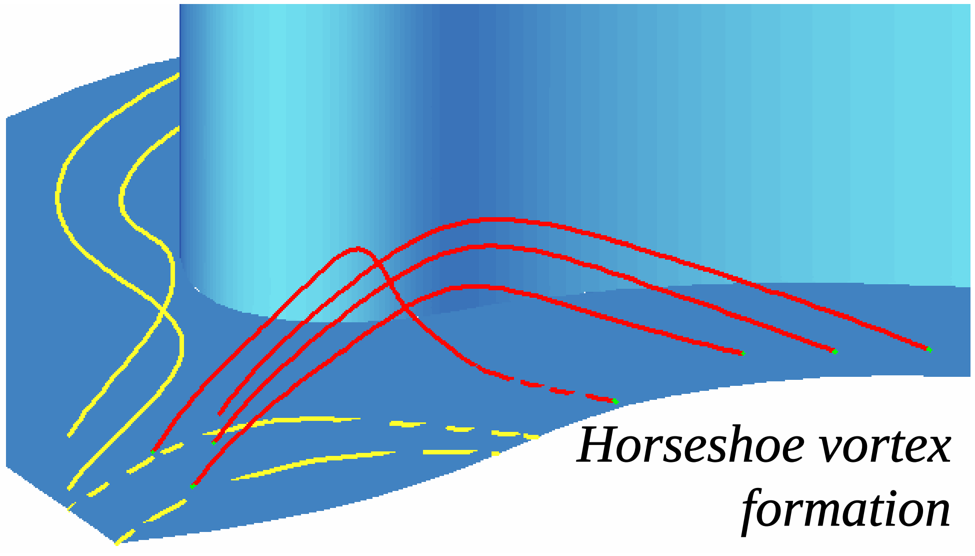
CFD-analysis of 3D flow structure and endwall heat transfer in a transonic turbine blade cascade: effects of grid refinement

Alexander M. Levchenya and Evgueni M. Smirnov

Saint-Petersburg State Polytechnic University
Department of Aerodynamics
E-mail: aero@phmf.spbstu.ru



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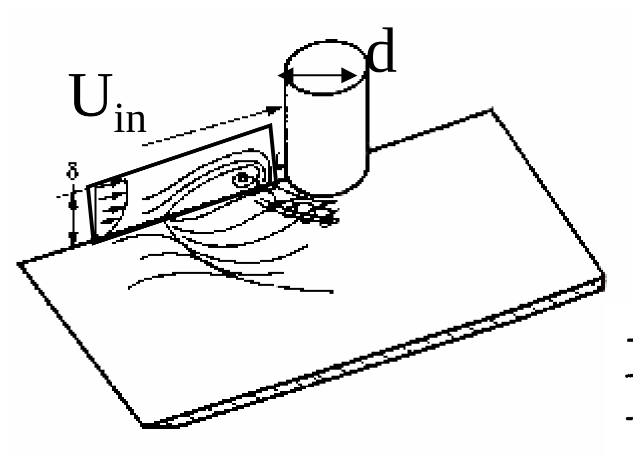
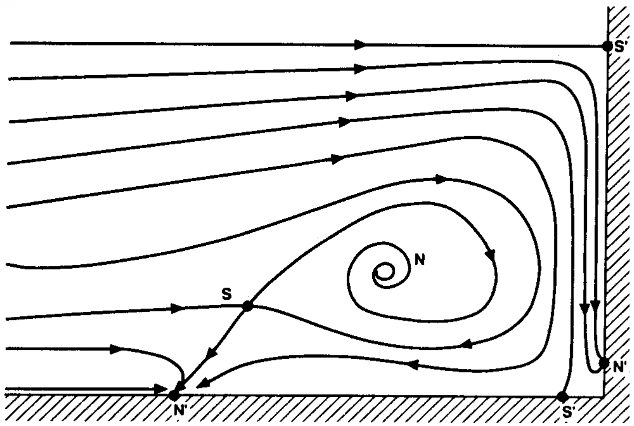
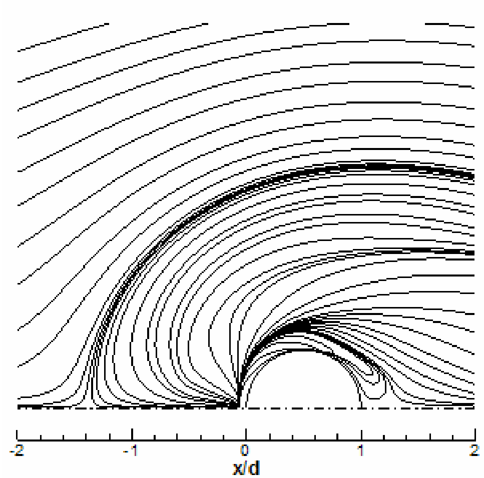
Laminar cylinder-plate junction flow

Results from: Chen, Hung (1992, AIAA Journal)
Levchenya, Smirnov (2007, submitted for publication)



Re=500



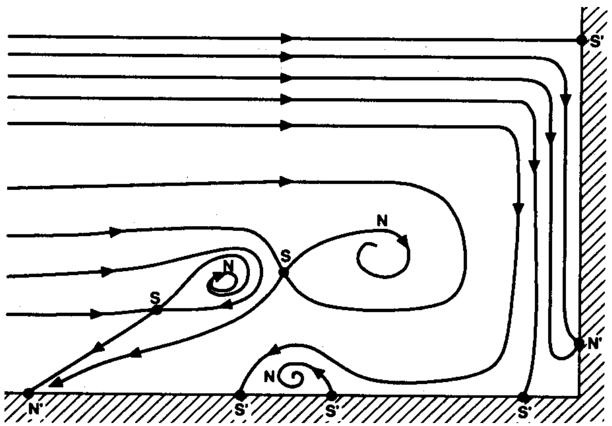


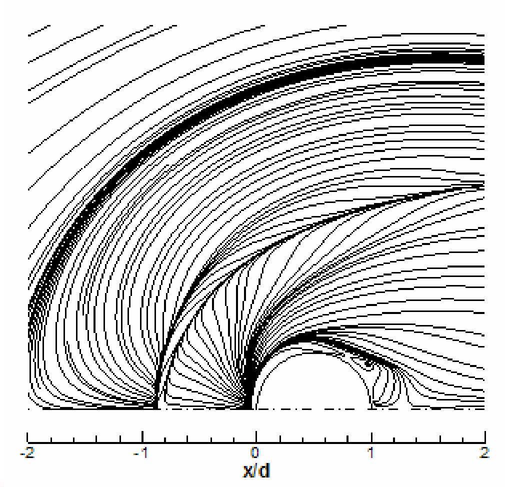
$$Re = \frac{U_{in} d}{\nu}$$

Streamline topology in the symmetry plane

Endwall streaklines

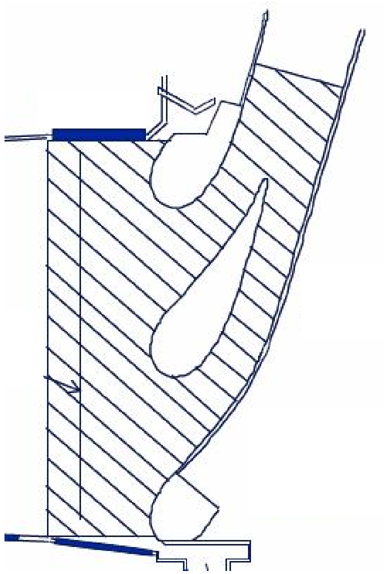
Re=1500

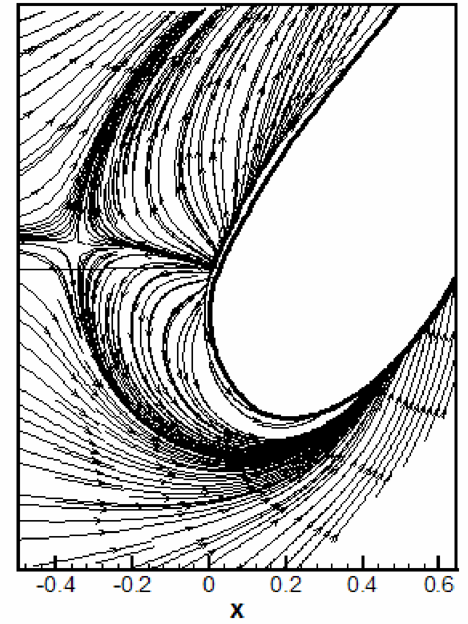




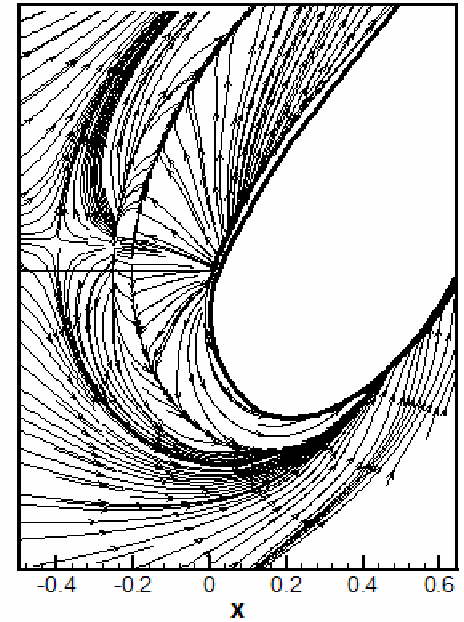
Our previous experience concerning numerical simulation of 3D turbulent flow in blade cascades

(Levchenya, Ris, Smirnov, 2006, Proc. 4th Russian Heat Transfer Conf.)





k-w



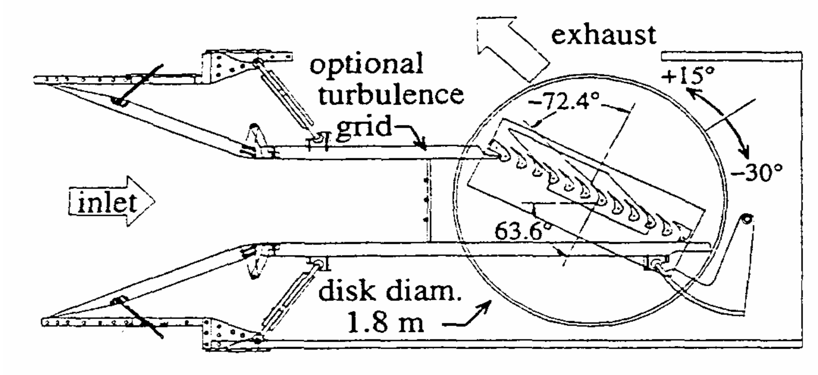
MSST

Experiment:
Kang *et al* (VPI), 1999

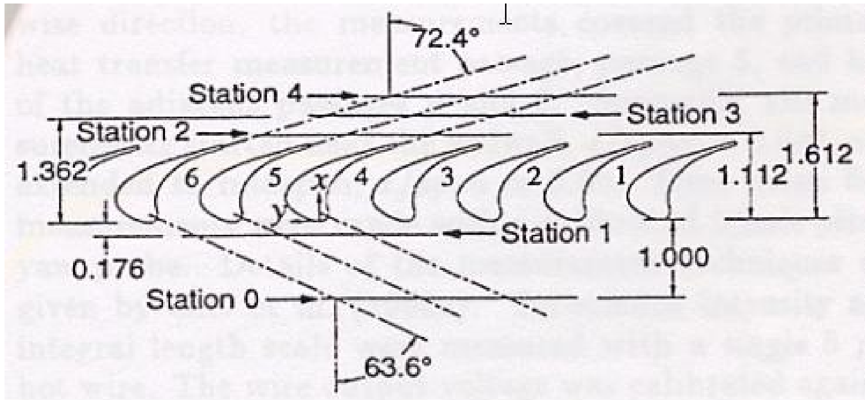
$$\mathrm{Re}_{\mathrm{eff}} = \frac{U_{\mathrm{in}} C}{\nu^{\mathrm{eff}}_{\mathrm{scale}}}$$

$$(\mathrm{Re}_{\mathrm{eff}})_{\mathrm{MSST}} > (\mathrm{Re}_{\mathrm{eff}})_{k\text{-}w}$$

NASA Glenn Research Center linear transonic blade cascade



Giel, P.W., Thurman, D.R., Van Fossen, G.J., Hippensteele, S.A, and Boyle, R.J. "Endwall heat transfer measurements in a transonic turbine cascade"
ASME Paper 96-GT-180 (1996)



Axial chord, *Cx*, cm	12.7
Pitch, cm	13.0
Span, cm	15.24
True chord, cm	18.42
Design inlet flow angle	63.6°
Total turning (at inlet flow angle)	136°
Prandtl number, *Pr*	0.72
Inlet Reynolds number, *Re*	1.0×10^6
Inlet Mach number, *M*in	0.38
Exit Mach number, *M*ex	1.32
Inlet boundary layer thickness, cm	3.2
Inlet turbulence intensity, %	0.25
Inlet turbulence length scale, cm	0.127

Mathematical model and computational aspects

- Reynolds-averaged Navier-Stokes and energy equation for turbulent compressible perfect gas flow
- Turbulence modeling:
  - *k*-*w* model by Wilcox
  - the SST version of the Menter model
  - the “code-friendly” version of the v^2-f model by Durbin

- High-order version of the Jameson’s H-CUSP scheme
- Regularization technique removing the difficulties of compressible flow computations in low-Mach-number regions

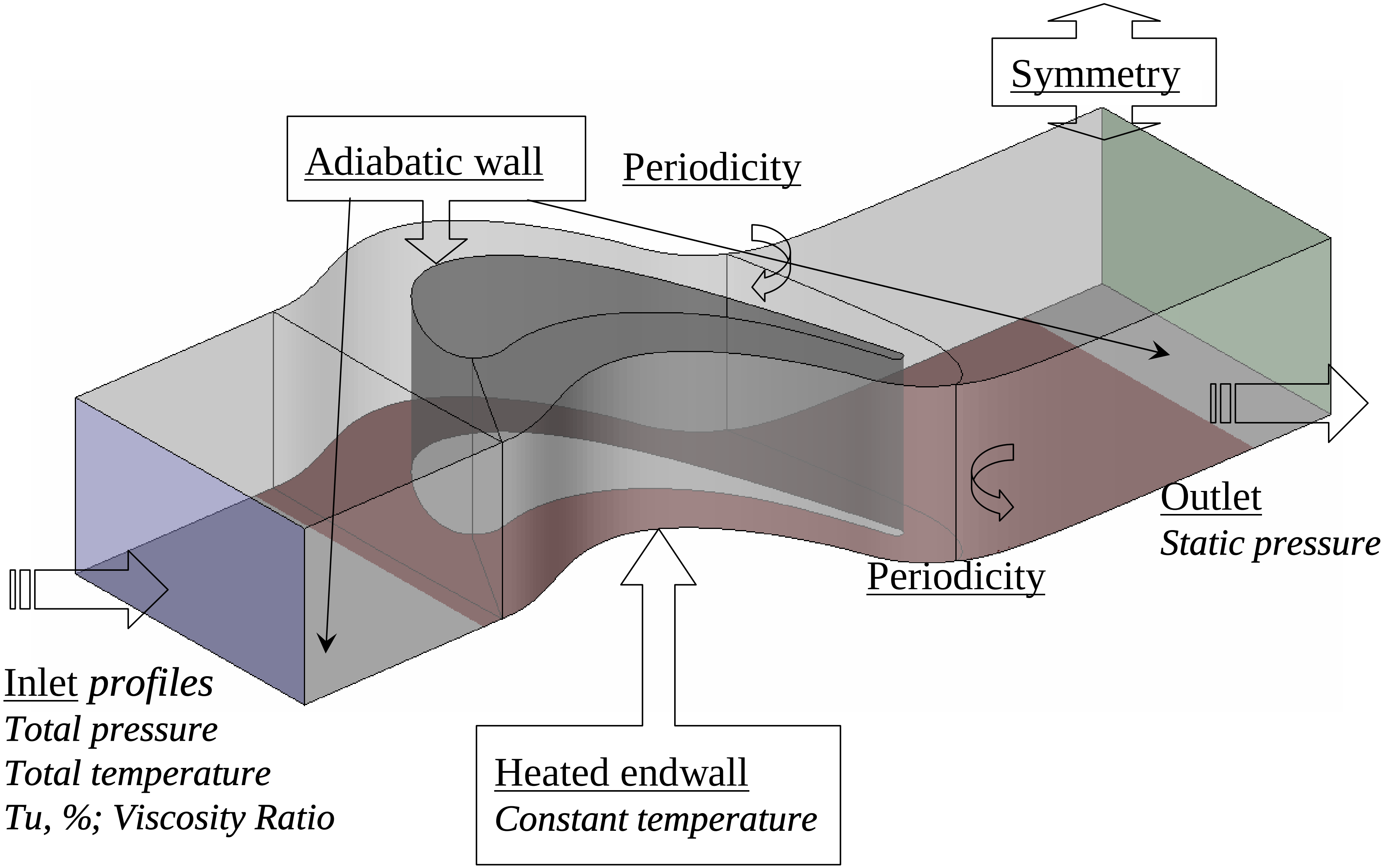
CFD code SINF (Supersonic-to-INcompressible Flows)

In-house 3D Navier-Stokes code (start of development: 1992)

- steady and unsteady flows
- absolute and rotating reference system
- sliding grids; options for rotor-stator interaction
- deforming grids (ALE); fluid-structure interaction options
- conjugate heat- and mass transfer
- RANS turbulence models (k, ν_t-SA, k-ε, k-ω, MSST, v2f)
- LES and RANS/LES (DES) in complex geometry domains

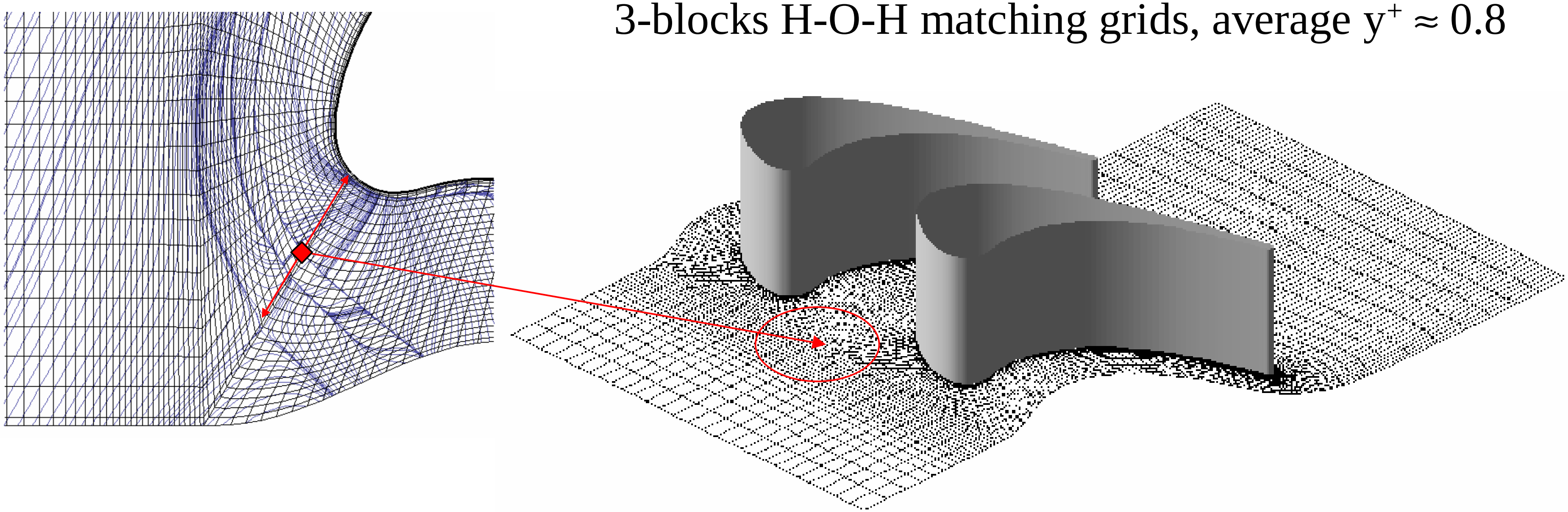
- body-fitted block-structured matching/non-matching grids
- second-order finite-volume spatial discretization
- second-order physical time stepping
- parallel computing (Domain Decomposition; MPI)

Computational domain and boundary conditions



Computational grids

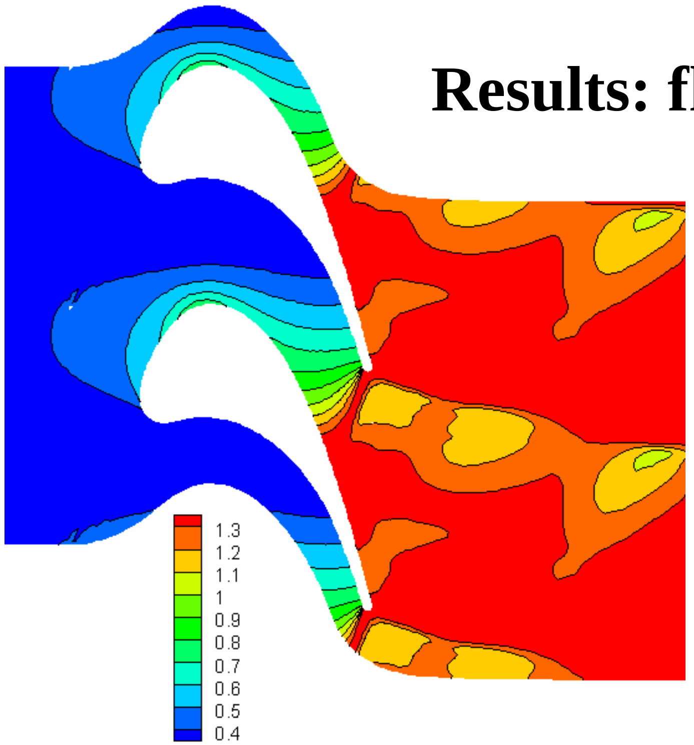
3-blocks H-O-H matching grids, average $y^+ \approx 0.8$



D* is the averaged cell size in the region of horseshoe vortex formation

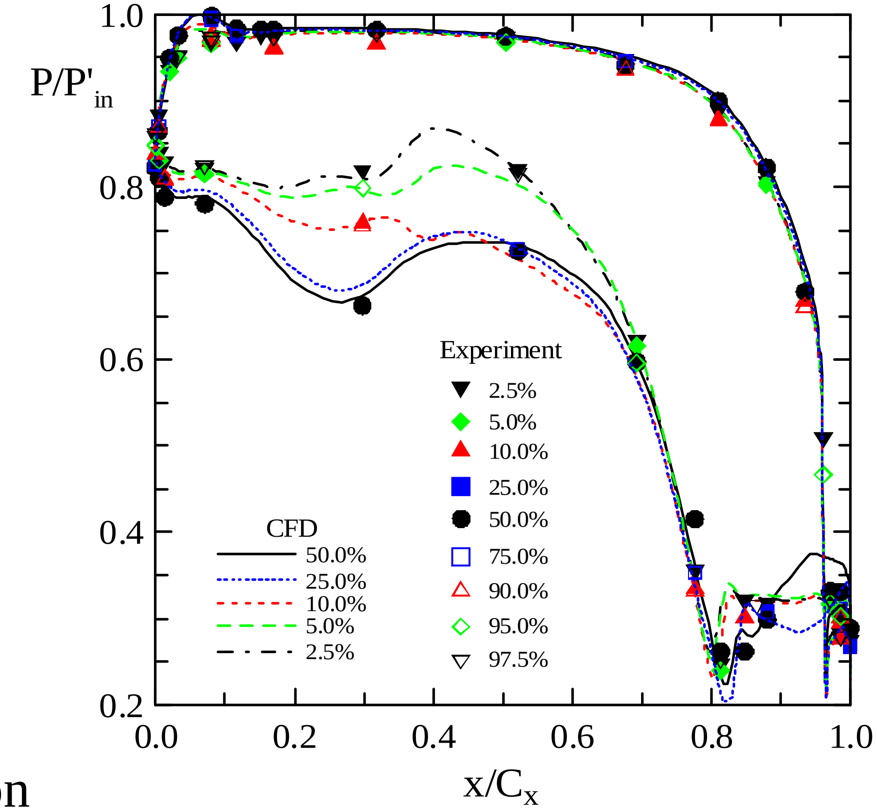
Grid	Number of cells	Δ^*/ C_x	Refinement aspects
A	360,000	0.027	Initial grid
B	730,000	0.022	Add nodes for all the blocks, far away from the blade
C	750,000	0.022	Equalize cell aspect ratio in the free-stream flow region
D	760,000	0.017	Shift gridlines to the blade
E	1,200,000	0.01	Add nodes for all blocks, especially in the LE region

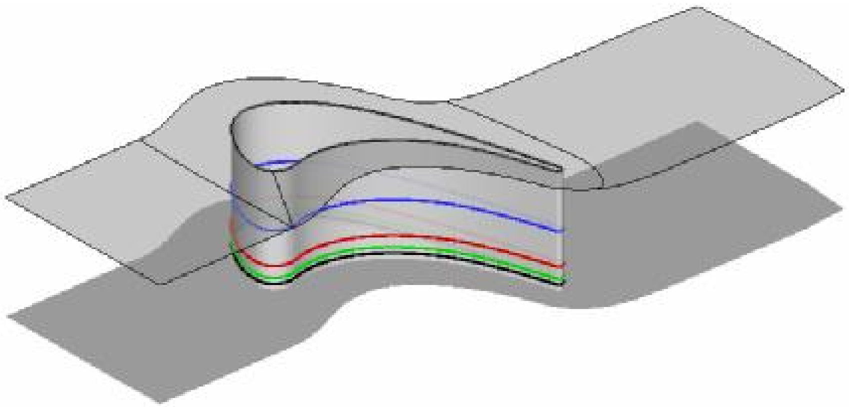
Results: flow field



Grid B, MSST model

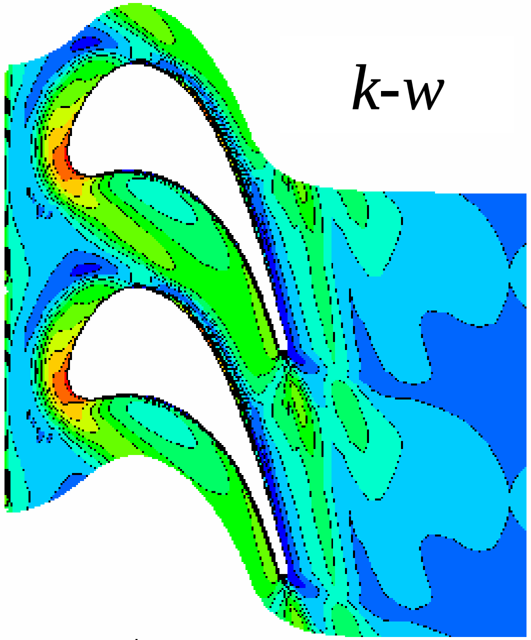
Computed mid-span Mach number distribution

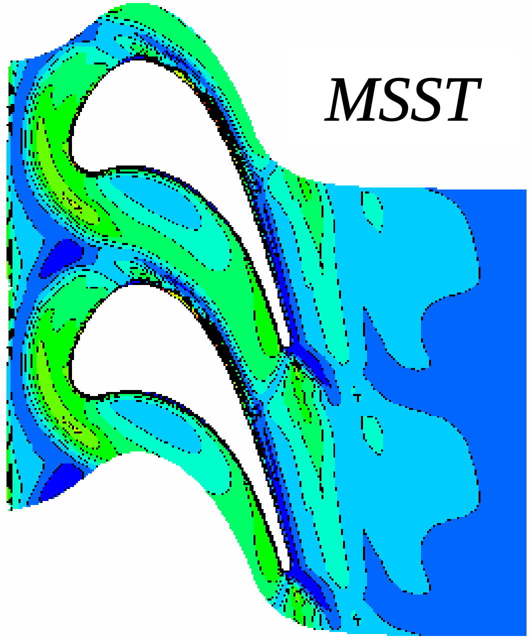




Comparison of computed and measured static pressure distributions over the blade surface for various span positions *(P'_{in} – inlet total pressure)*

Endwall heat transfer: influence of turbulence models

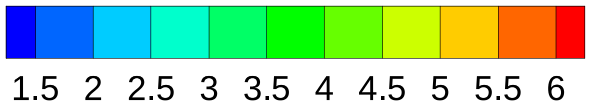


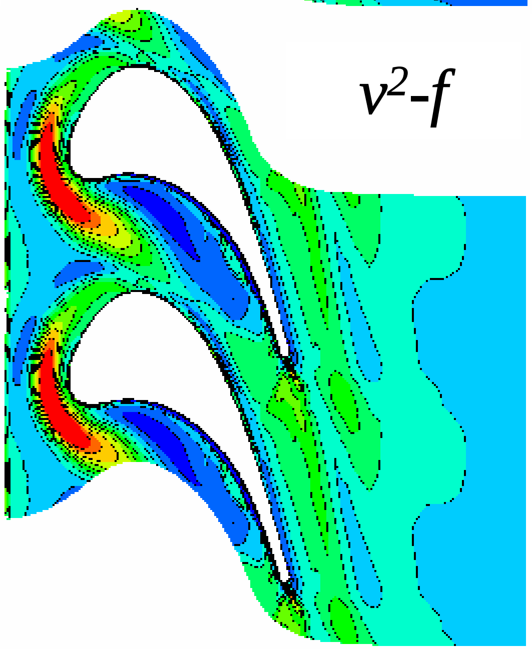


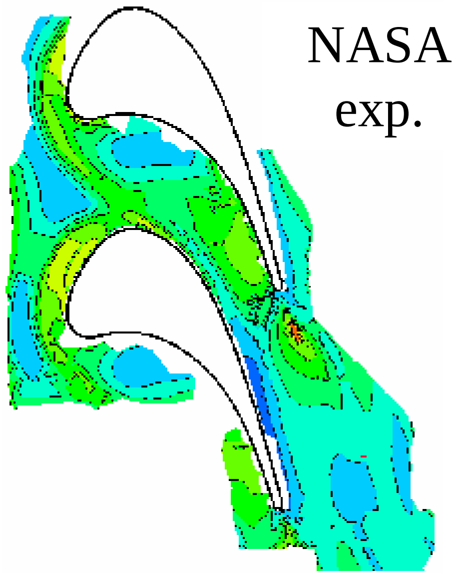
$$St = \frac{q_w}{\rho_{ref} U_{in} c_p \left(T_w - T_{aw}\right)}$$

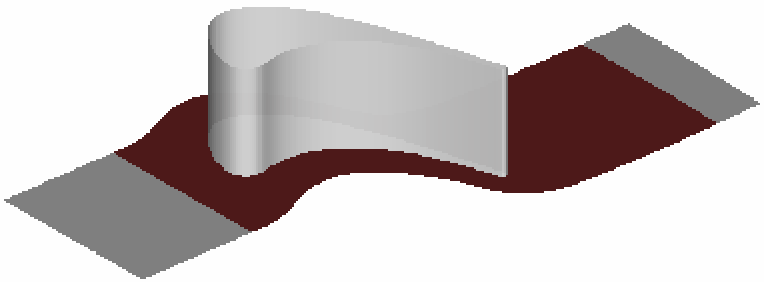
Stanton number $St \times 10^3$,

Grid B





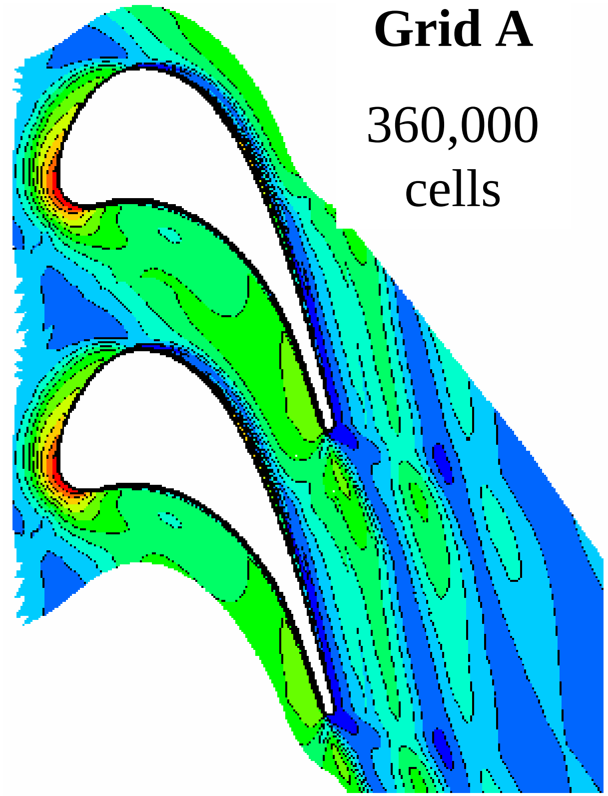




Endwall heat transfer: grid sensitivity of *k-w* model

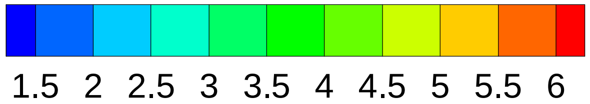
Grid A

360,000 cells



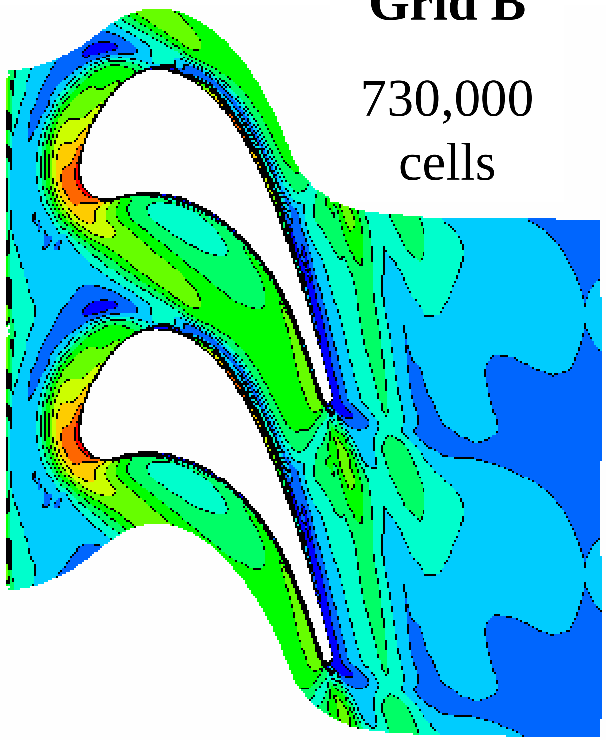
$$St = \frac{q_w}{\rho_{ref} U_{in} c_p (T_w - T_{aw})}$$

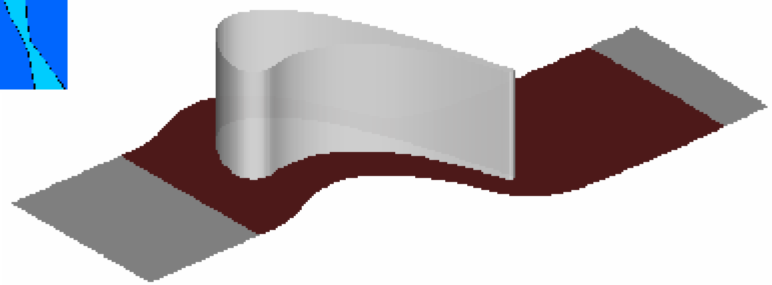
Stanton number $St \times 10^3$



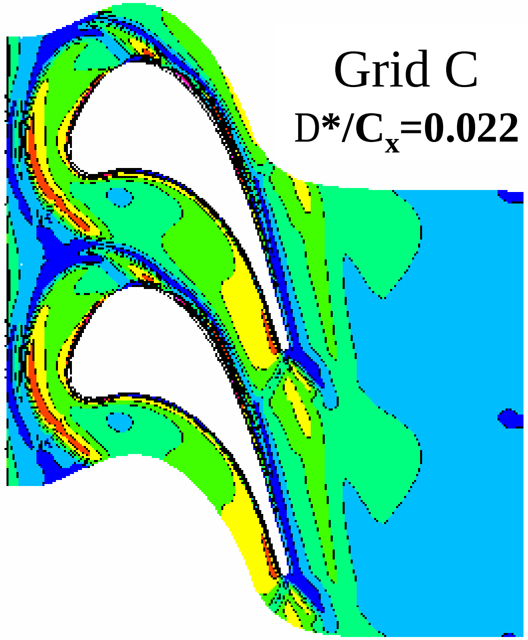
Grid B

730,000 cells

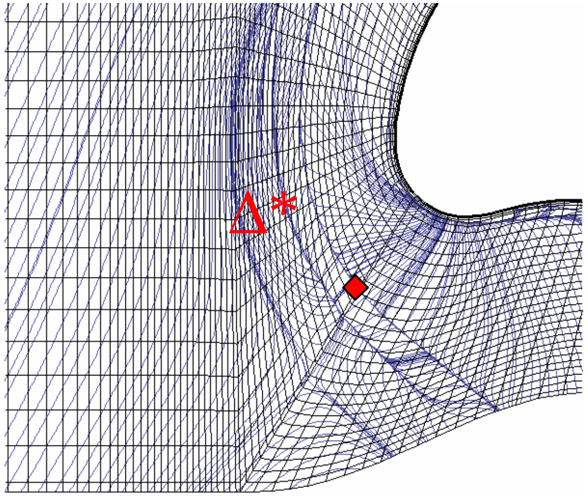


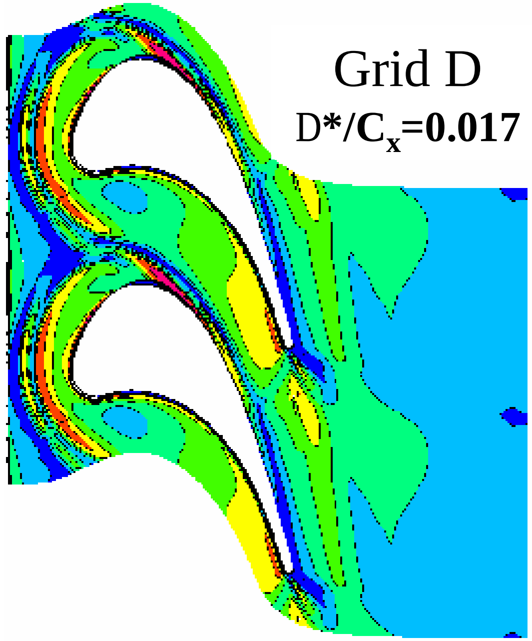


Endwall heat transfer: grid sensitivity of *MSST* model

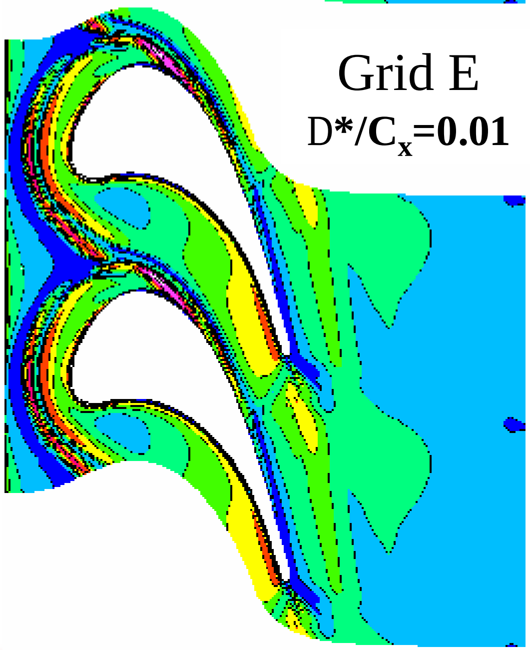


Grid C
D*/C_x=0.022



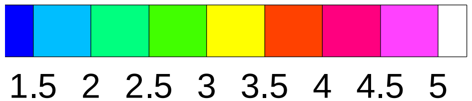


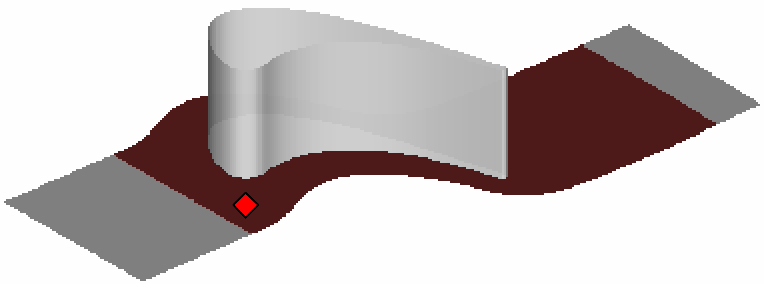
Grid D
D*/C_x=0.017

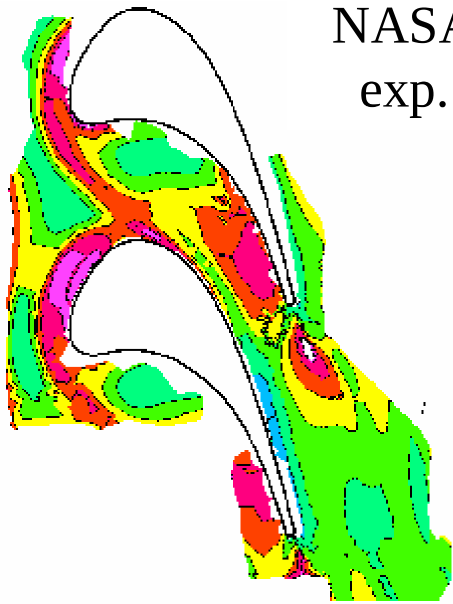


Grid E
D*/C_x=0.01

Stanton number St×10^3



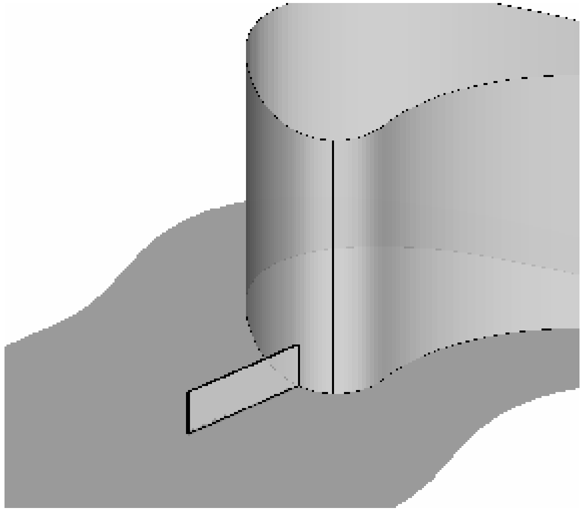


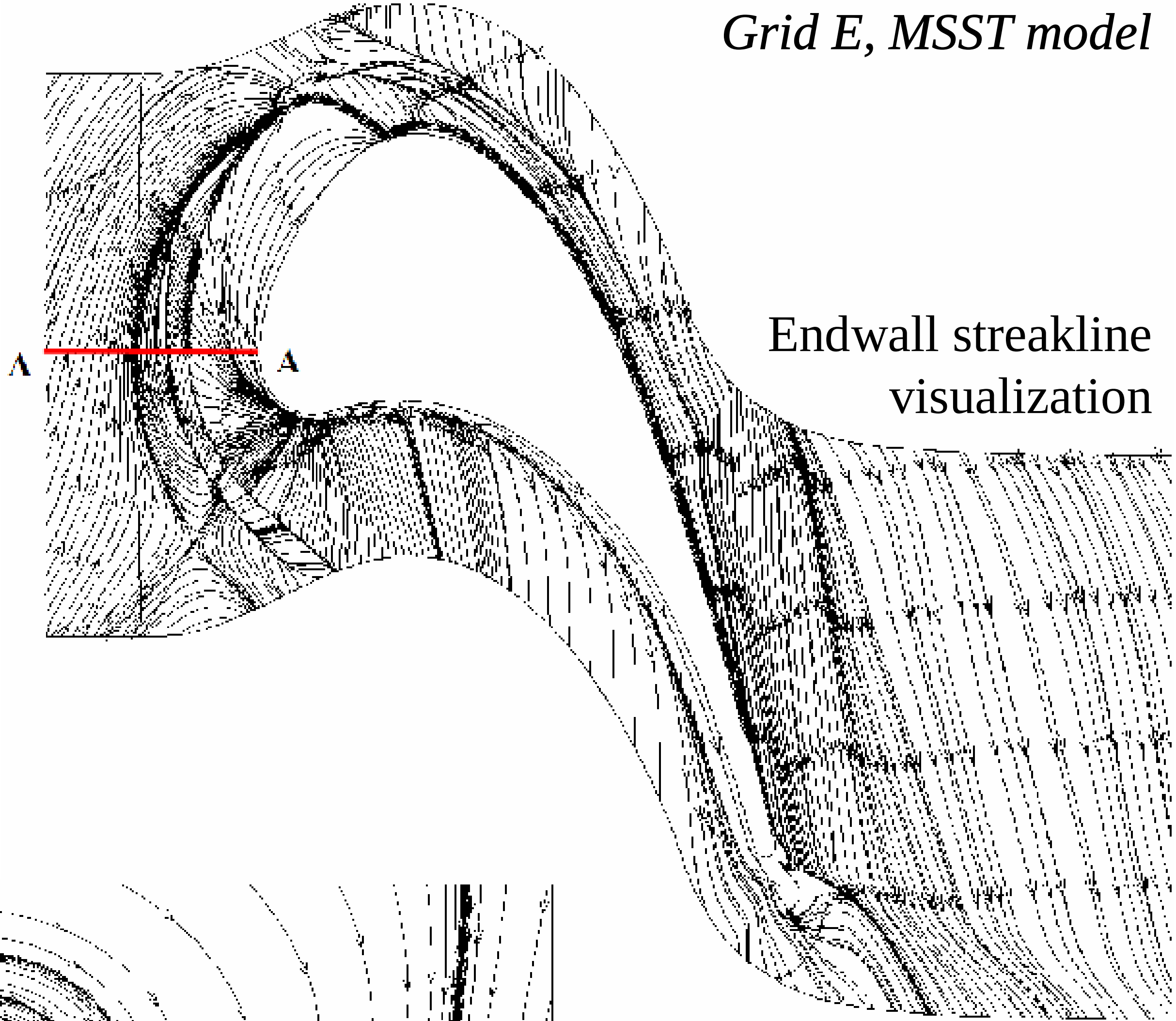


NASA
exp.

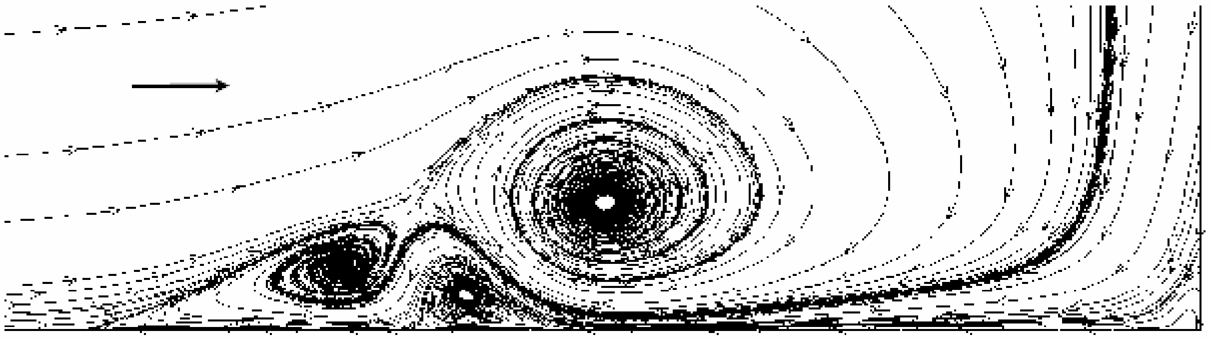
Vortex structure near blade leading edge

Grid E, MSST model





Endwall streakline visualization

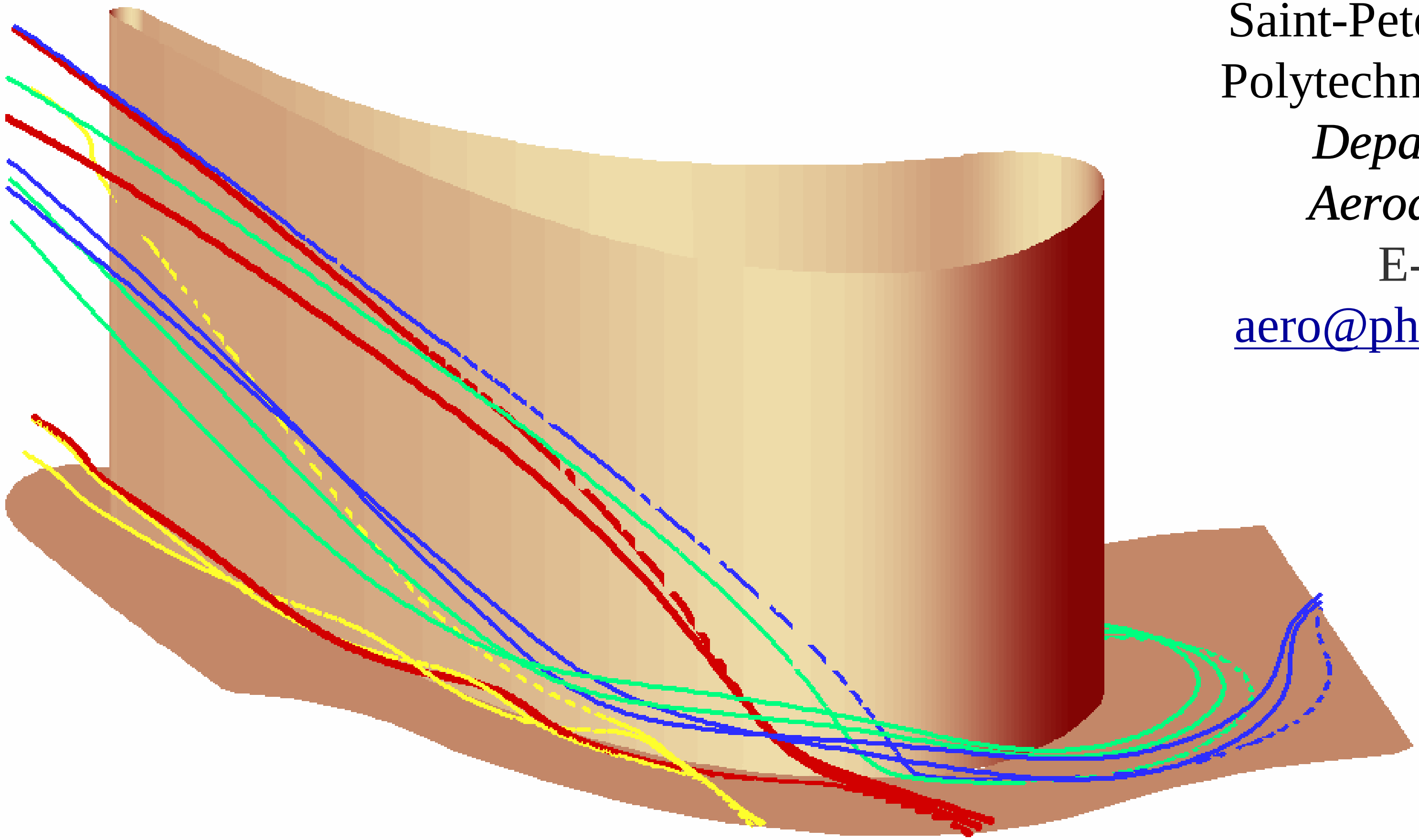


Streamline topologies in plane A-A

Conclusion

- With an in-house code SINF, effects of computational grid refinement have been investigated for the problem of 3D turbulent flow and endwall heat transfer. Three turbulence models were used at the computations. The main attention for the grid-sensitivity aspects was paid to the cases of the *k*-*w* and the MSST models.
- It has been established that the MSST model prediction results are considerably more sensitive to grid refinement as compared with the k-*w* model. MSST model results in prediction of a complicated flow topology as compared with the k-*w* model.
- Rather fine computational grids are needed to get grid-independent data on the endwall local heat transfer controlled by complex 3D structure of secondary flows. With CFD codes of second-order accuracy, one should use grids comprised of about or more than 2 millions cells (for each full blade passage) to get a definite conclusion on capabilities of one or another turbulence model for predictions of phenomena under consideration.

Thank you for your attention!



Saint-Petersburg State
Polytechnic University
Department of Aerodynamics
E-mail:
aero@phmf.spbstu.ru