On Reynolds-stress Modelling of Turbulence: Conventional vs. Eddy-resolving Closure

TECHNISCHE UNIVERSITÄT DARMSTADT

Suad JAKIRLIĆ & Robert MADUTA

s.jakirlic@sla.tu-darmstadt.de

Technische Universität Darmstadt, Germany

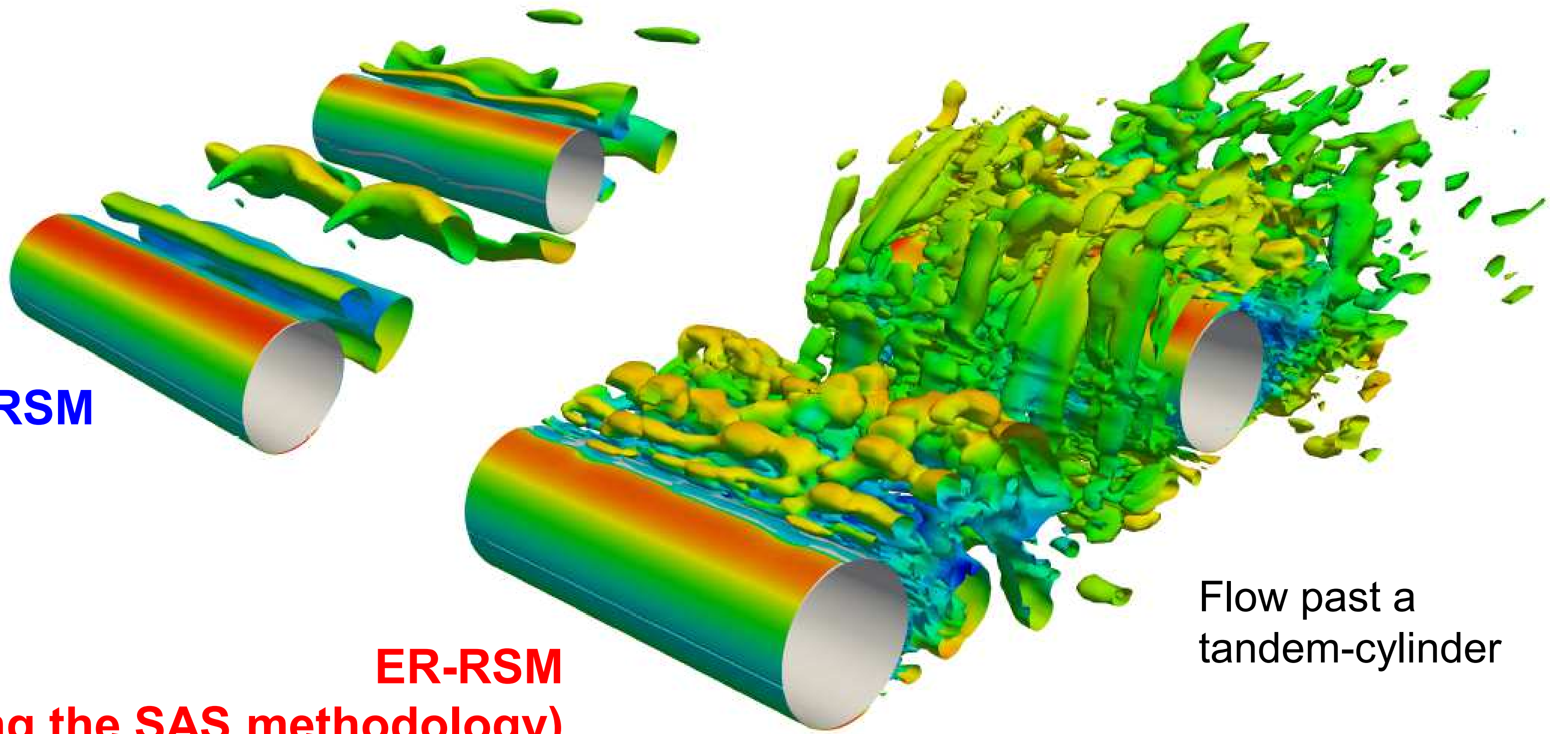
July 11-13, 2017
Ann Arbor, MI. USA

AEROSPACE ENGINEERING

UNIVERSITY of MICHIGAN ▪ COLLEGE of ENGINEERING

Objective

- **To formulate a (near-wall) RANS-based model on the second-moment closure level capable of capturing the turbulence fluctuations → towards an Eddy-Resolving RSM (ER RSM)**



RANS-RSM

ER-RSM
(using the SAS methodology)

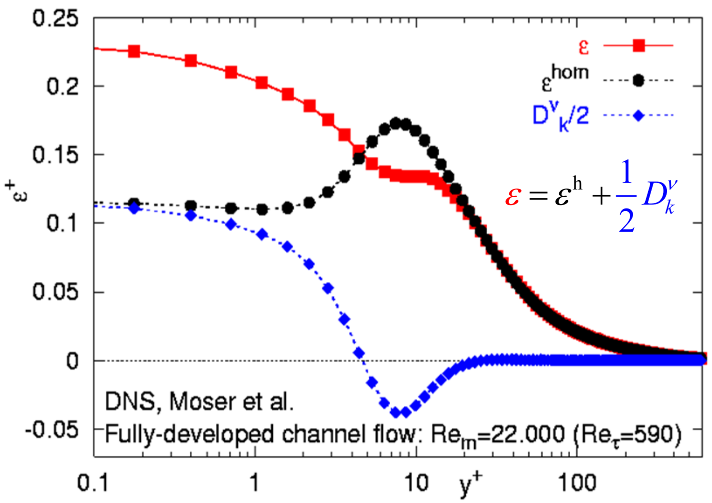
Flow past a
tandem-cylinder

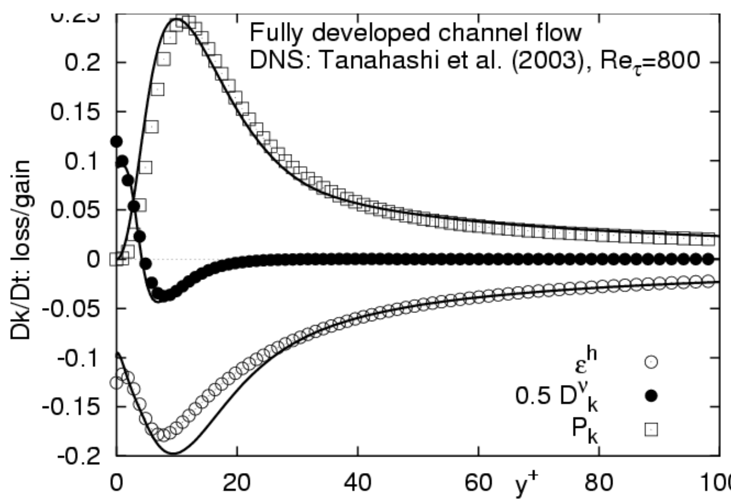
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, structure 1

- **Homogeneous dissipation (ε^h) as the scale supplying variable (JFM 459, 656)**

$$\frac{\partial\left(\overline{u_i u_j}\right)}{\partial t} + \frac{\partial\left(U_k \overline{u_i u_j}\right)}{\partial x_k} = \frac{\partial}{\partial x_k}\left[\left(\frac{1}{2}\nu\delta_{kl} + C_s \frac{k}{\varepsilon}\overline{u_k u_l}\right)\frac{\partial \overline{u_i u_j}}{\partial x_l}\right] + P_{ij} - \varepsilon_{ij}^h + \Phi_{ij} + \Phi_{ij}^w$$

$$\frac{D\varepsilon^h}{Dt} = \frac{\partial}{\partial x_k}\left[\left(\frac{1}{2}\nu\delta_{kl} + C_\varepsilon \overline{u_k u_l}\frac{k}{\varepsilon^h}\right)\frac{\partial \varepsilon^h}{\partial x_l}\right] + C_{\varepsilon,1}\frac{\varepsilon^h}{k}P_k - C_{\varepsilon,2}\frac{\tilde{\varepsilon}^h \varepsilon^h}{k} + P_{\varepsilon,3}$$



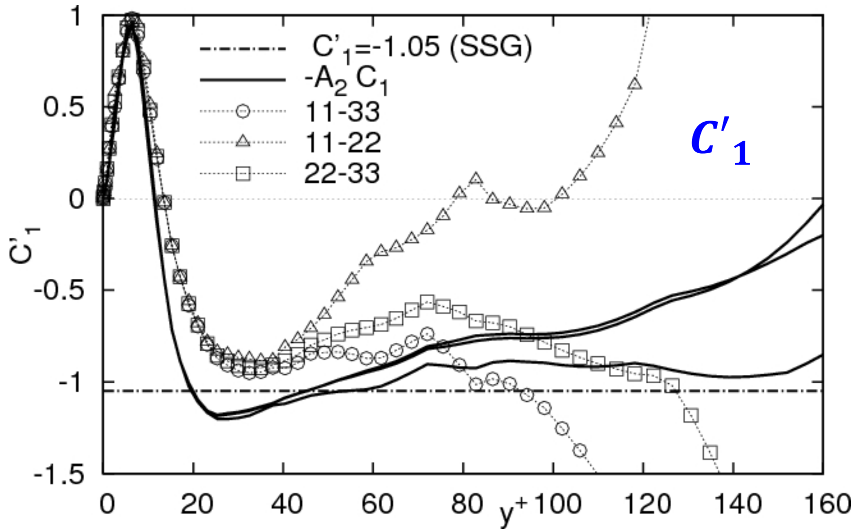


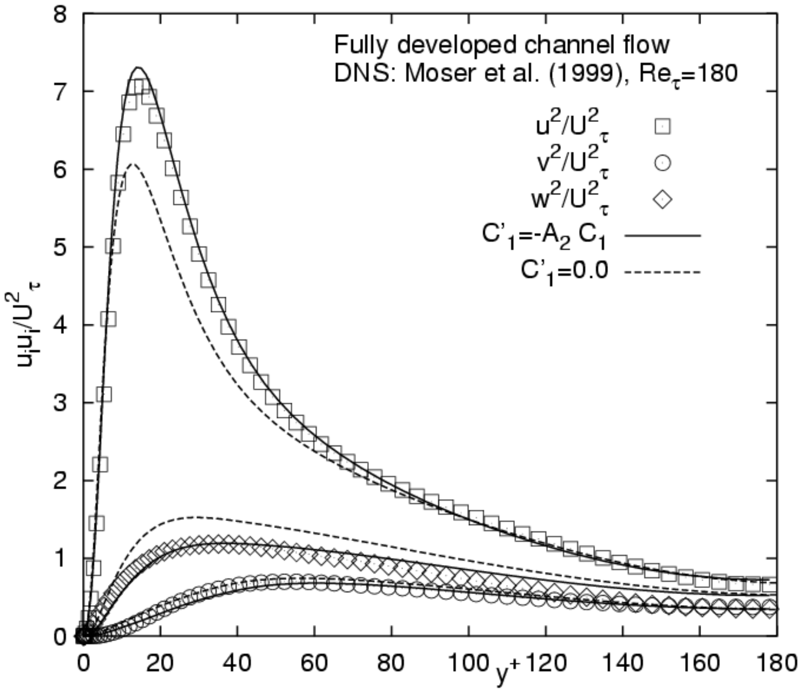
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, structure 2

- **Pressure-strain term model: slow (quadratic) + rapid (linear)**

$$\Phi_{ij,1} = -\varepsilon\left[C_1 a_{ij} + C_1'\left(a_{ik}a_{kj} - \frac{1}{3}A_2\delta_{ij}\right)\right] \qquad \Phi_{ij,2} = -C_2\left(P_{ij} - \frac{2}{3}\delta_{ij}P_k\right)$$

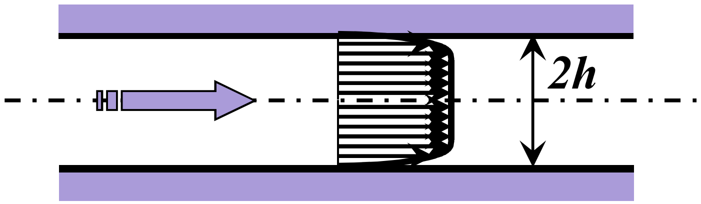
- **DNS-aided determination of the model coefficients (FDR'13)**

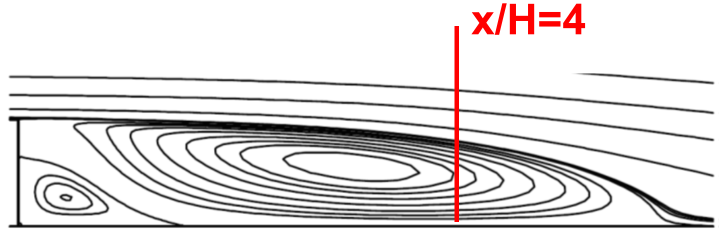


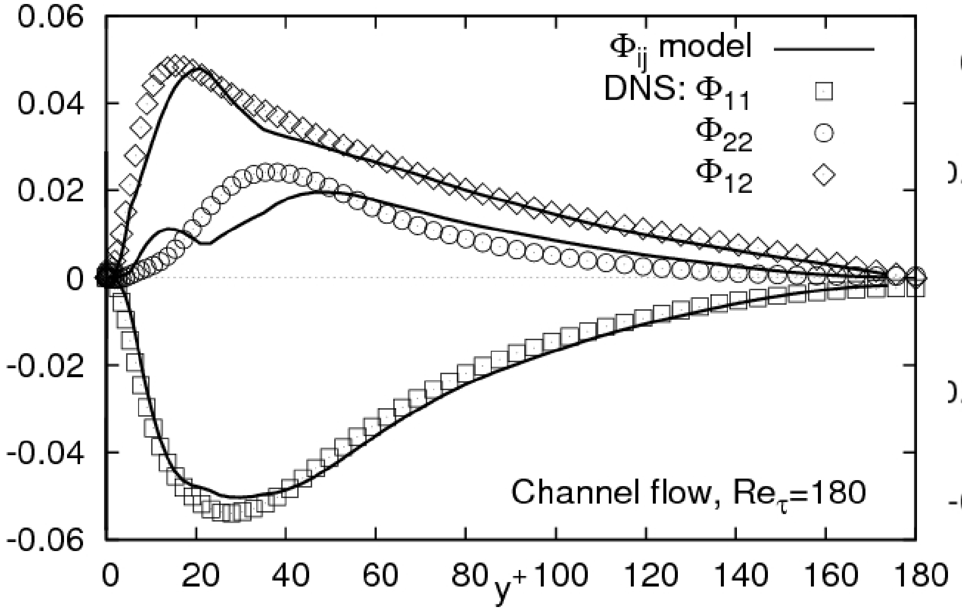


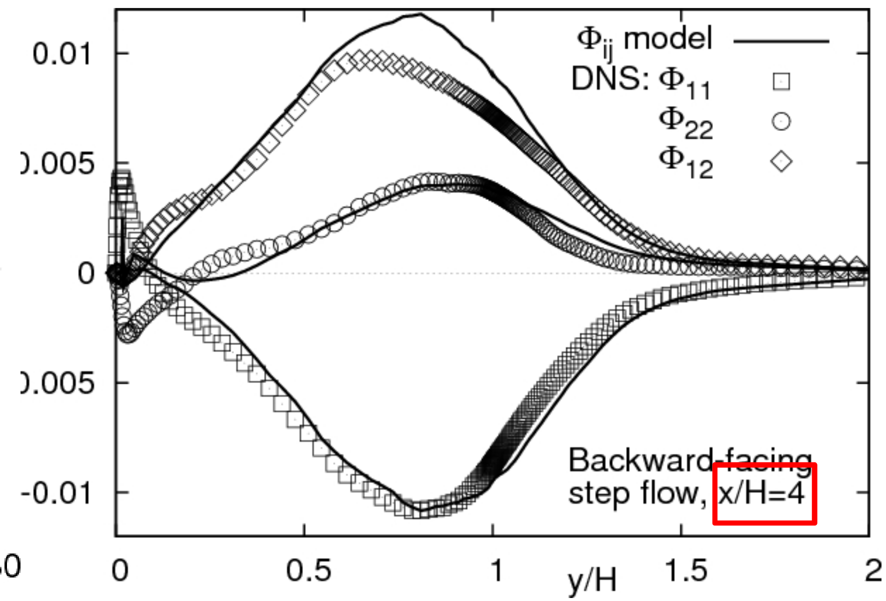
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, structure 3

- **Pressure-strain term model: slow (quadratic) + rapid (linear)**





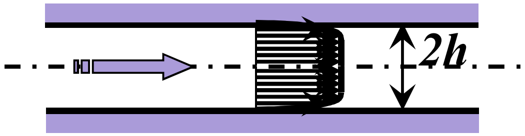


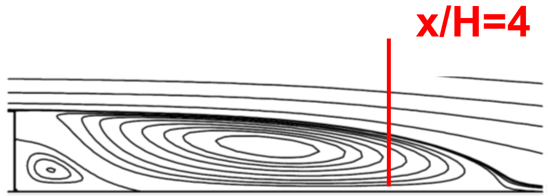


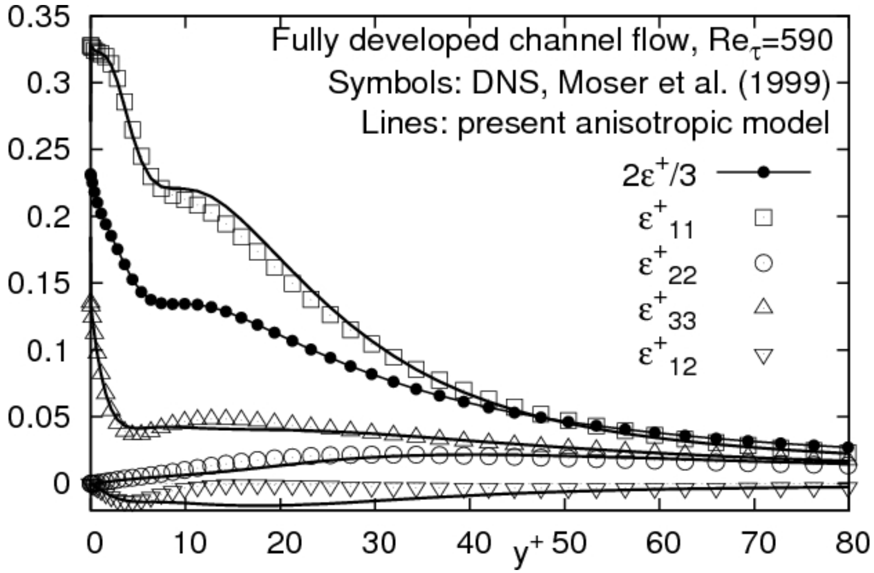
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, structure 4

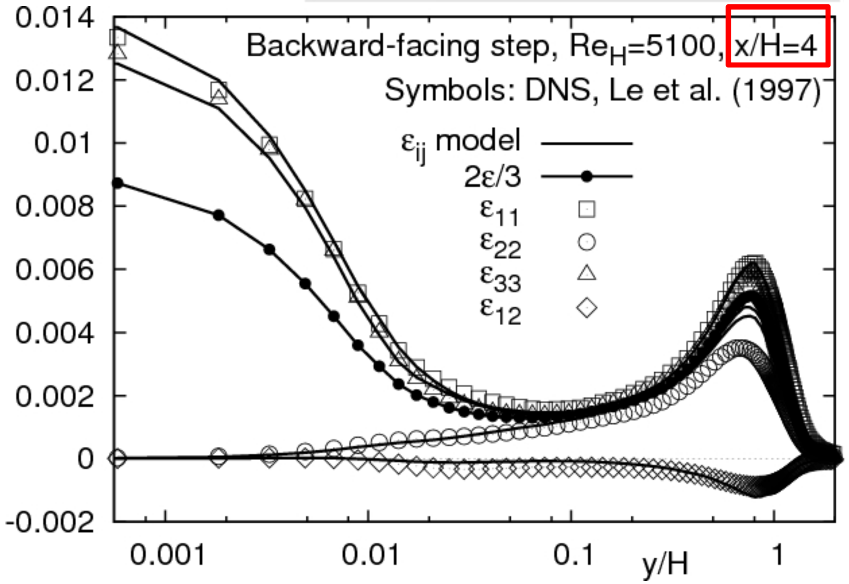
➢ Anisotropic dissipation correlation model

$$\varepsilon_{ij} = \underbrace{(1-f_s)\frac{2}{3}\delta_{ij}\varepsilon^h + f_s\varepsilon^h\frac{\overline{u_i u_j}}{k}}_{\varepsilon_{ij}^h} + \underbrace{\frac{1}{2}D_{ij}^{\nu}}_{\varepsilon_{ij}^{non-h}}$$





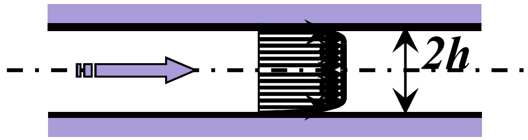


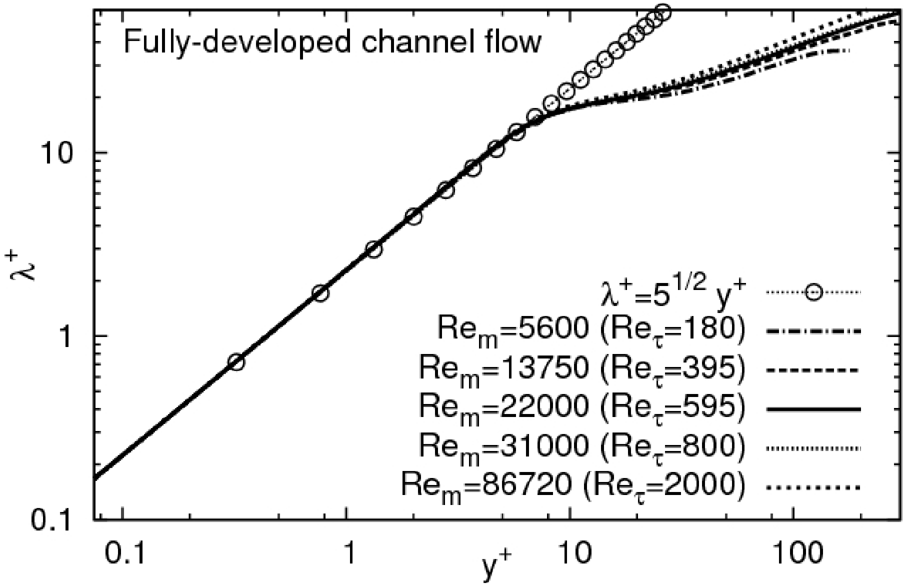


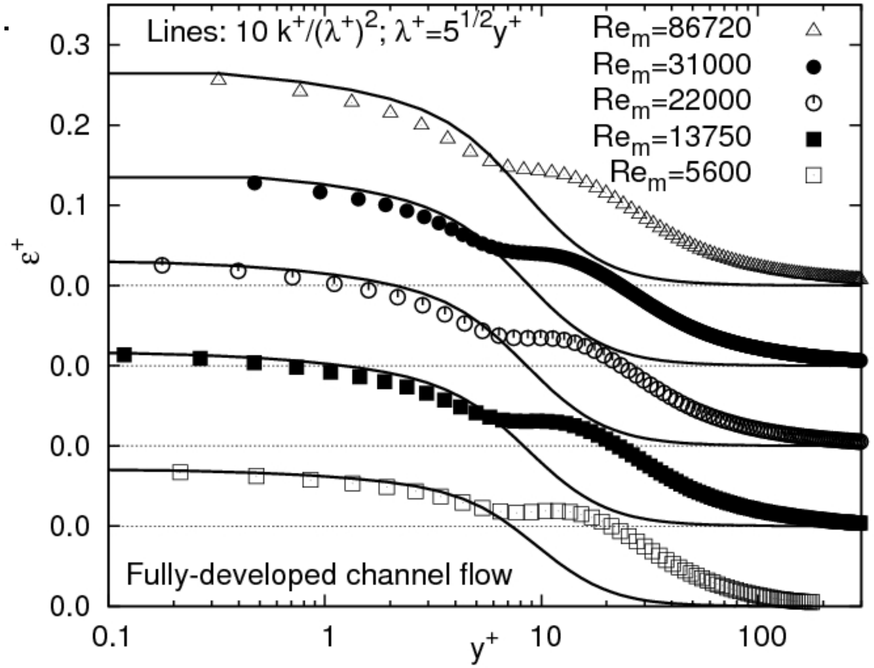
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, structure 4

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Wall boundary conditions based on the asymptotic behaviour of Taylor microscale (λ) and its exact relationship to ε^h, i.e. ε (JFM 656, FTaC'13)**







Symbols: DNS

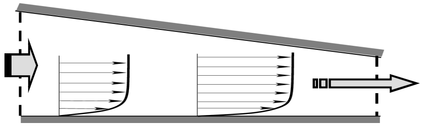
Lines: $\lambda = \sqrt{10\nu\, k/\varepsilon}$

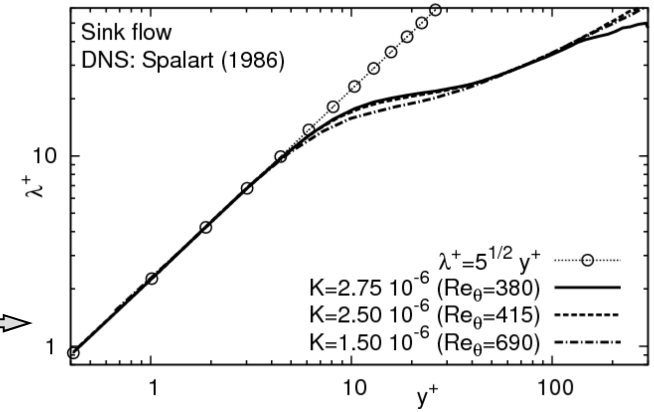
Symbols: $\lambda = \sqrt{5}\,y$

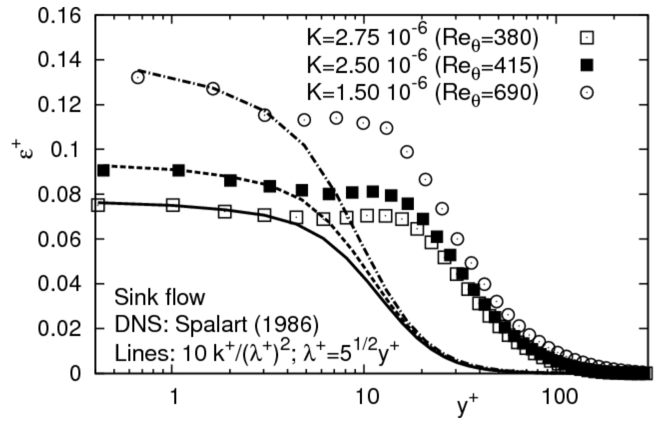
Lines: $\varepsilon = 10\nu \dfrac{k}{\lambda^2} = 5\nu \dfrac{k}{y^2}$

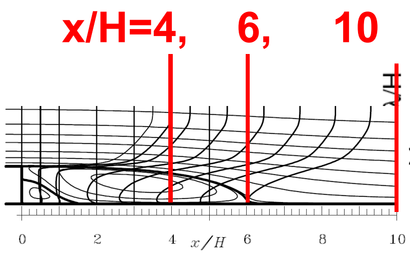
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, structure 5

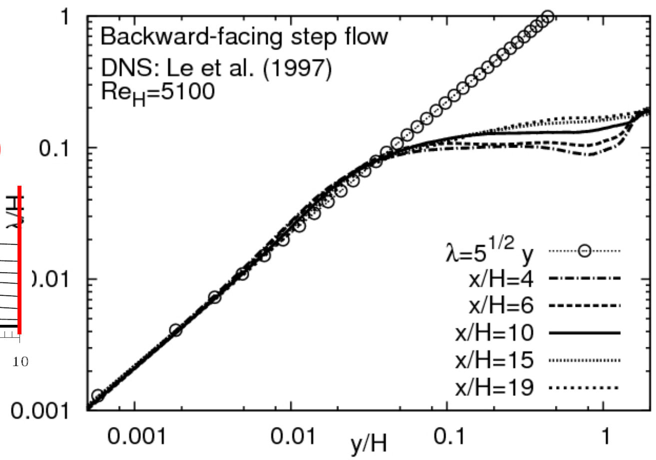
- **Wall boundary conditions based on the asymptotic behaviour of Taylor microscale (λ) and its exact relationship to ε^h , i.e. ε (JFM 656, FTaC'13)**

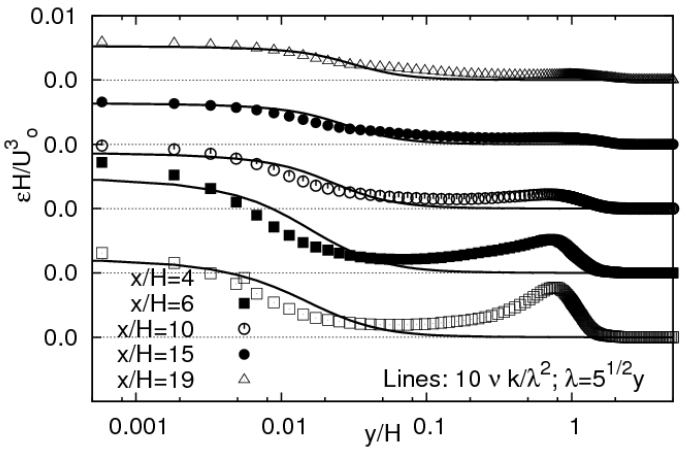






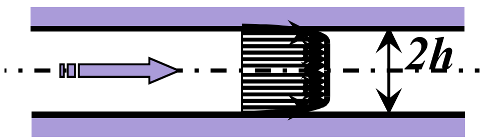


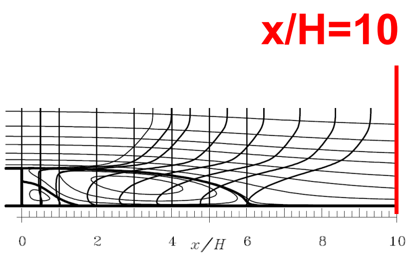


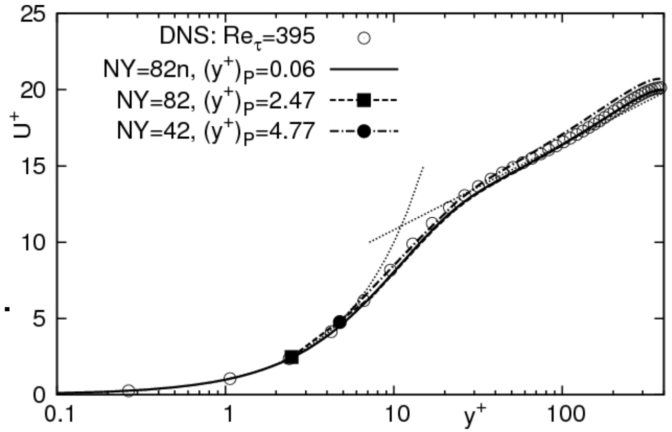


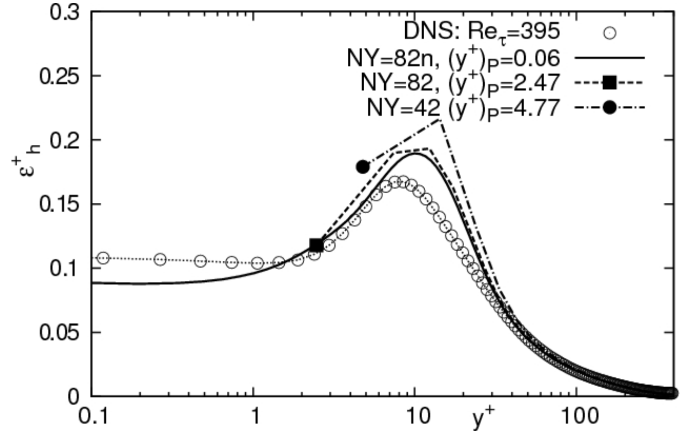
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, structure 6

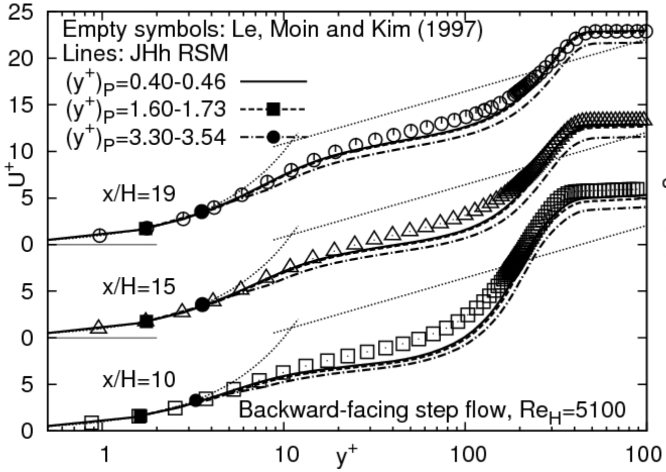
- **Wall boundary conditions based on the asymptotic behaviour of Taylor microscale (λ) and its exact relationship to ε^h, i.e. ε (JFM 656, FTaC'13)**

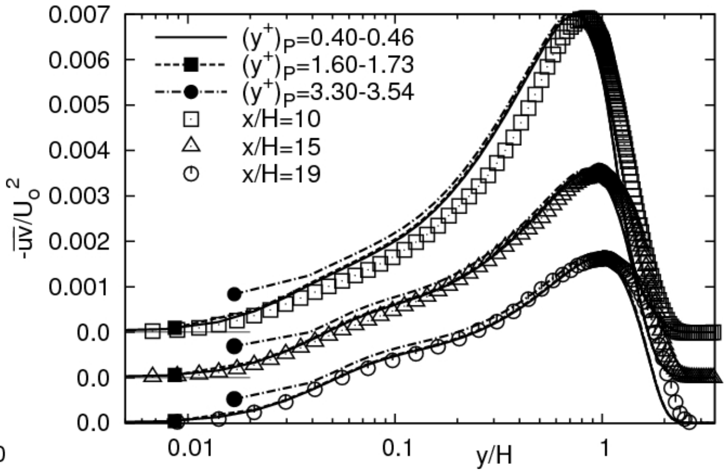






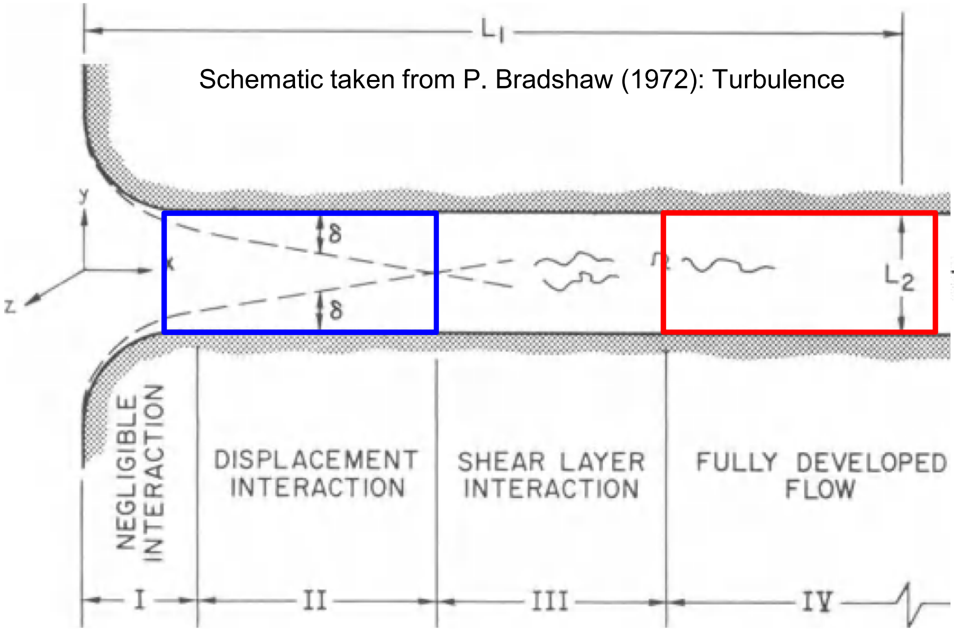


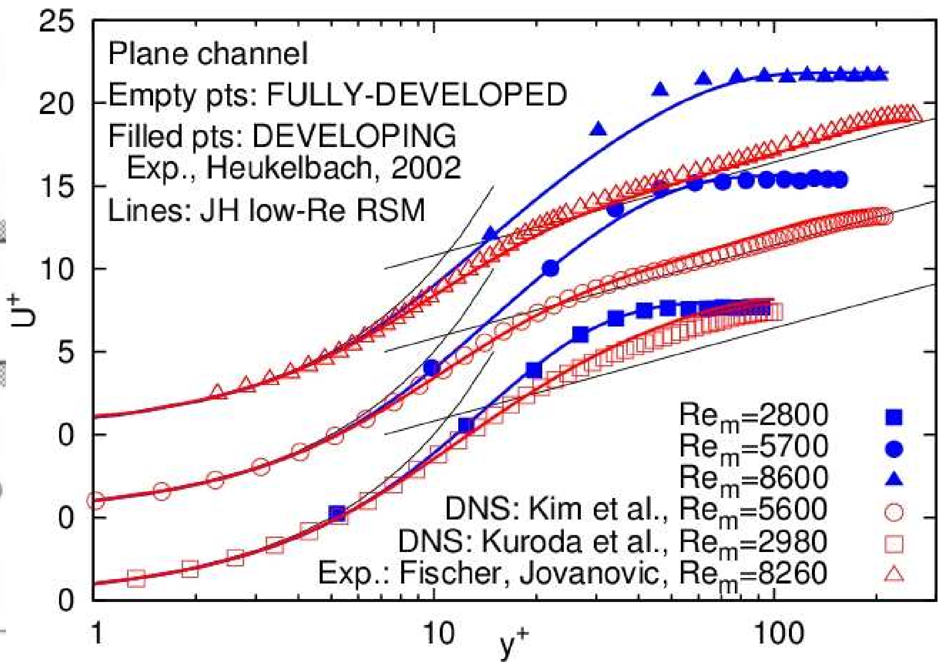




Background RSM: $\overline{u_i u_j} - \varepsilon^h$, performances 1

➢ Channel flow: developing vs. fully-developed





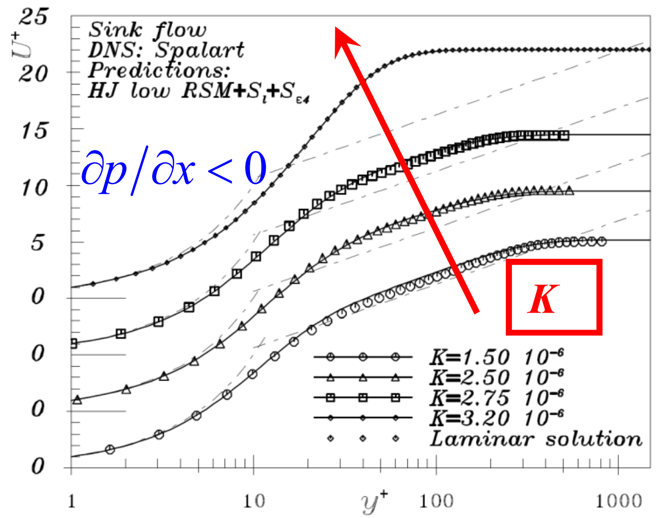
*Heukelbach, K., Jakirlić S., Nakić, R. and Tropea, C. (2002): Influence of turbulence on the stability of liquid sheets. *Int. Conf. on Liquid Atomization and Spray Systems - ILASS*, Zaragoza, Spain, September 9-11

Background RSM: $\overline{u_i u_j} - \varepsilon^h$, performances 2

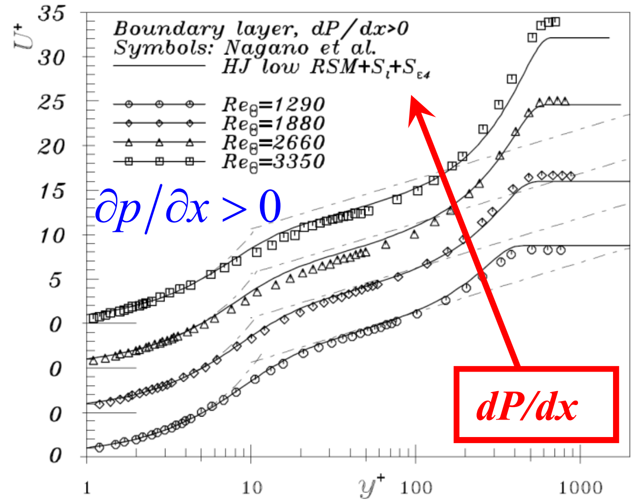
-boundary layers subjected to different PG

TECHNISCHE UNIVERSITÄT DARMSTADT

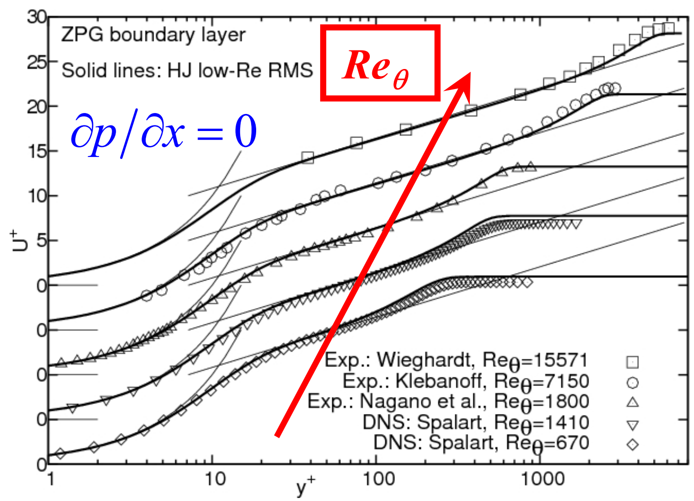
➤ **Favourable PG BL!**



➤ **Adverse PG BL!**



➤ **Zero PG BL!**



Background RSM: $\overline{u_i u_j} - \varepsilon^h$, performances 3

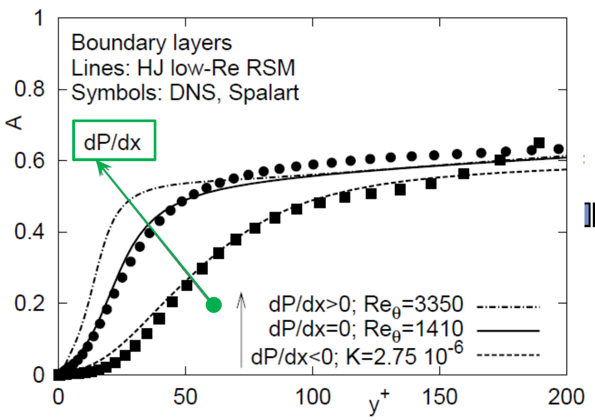
-boundary layers subjected to different PG

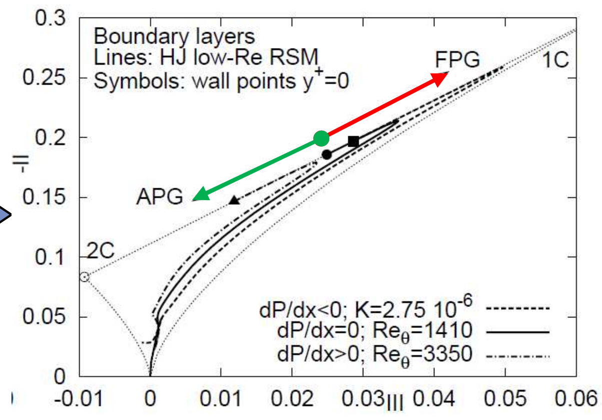
TECHNISCHE UNIVERSITÄT DARMSTADT

FPG: $dP/d\sigma<0$; $dU/d\sigma>0$

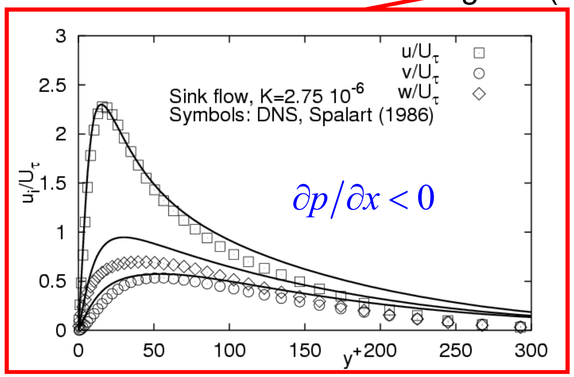
ZPG: $dP/d\sigma=0$; $dU/d\sigma=0$

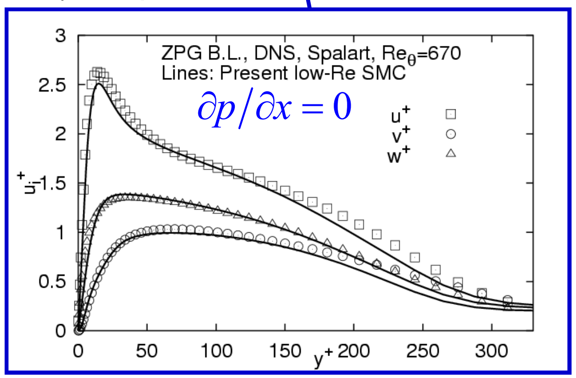
APG: $dP/d\sigma>0$; $dU/d\sigma<0$

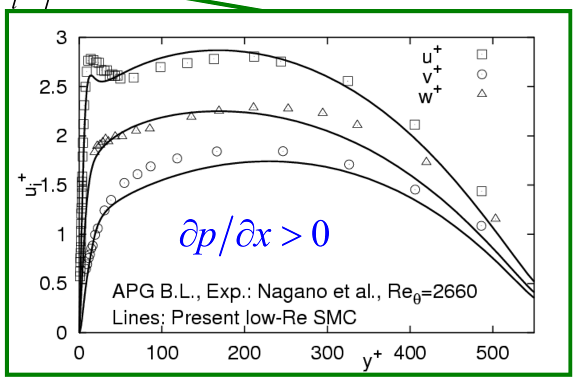




Diagonal (normal) components of the Re-stress tensor $\overline{u_i u_j}$



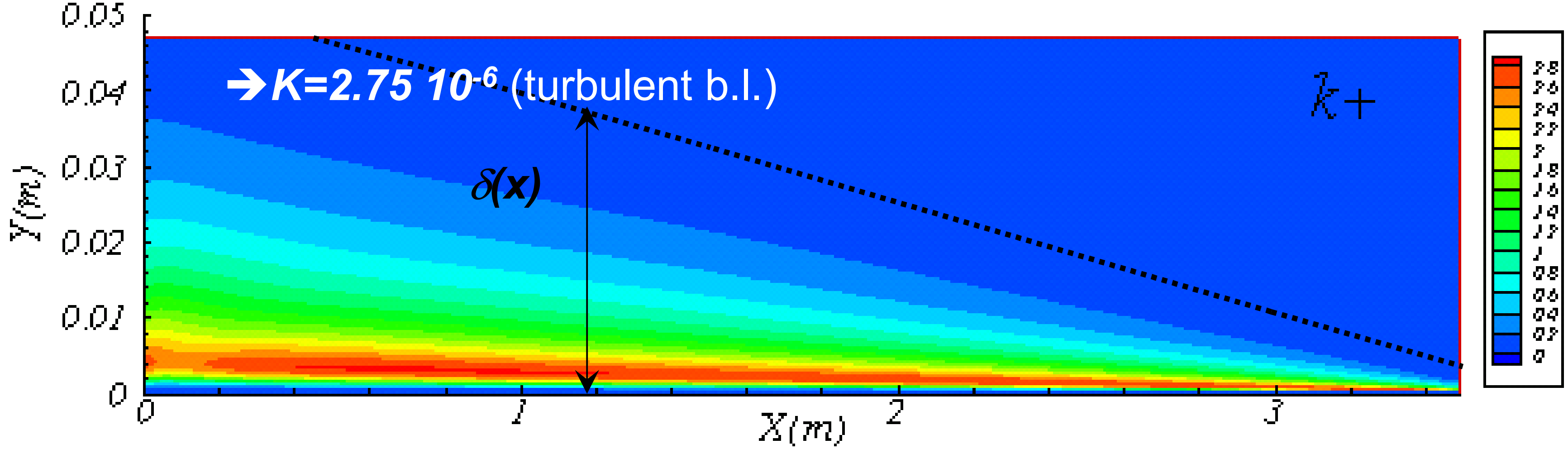


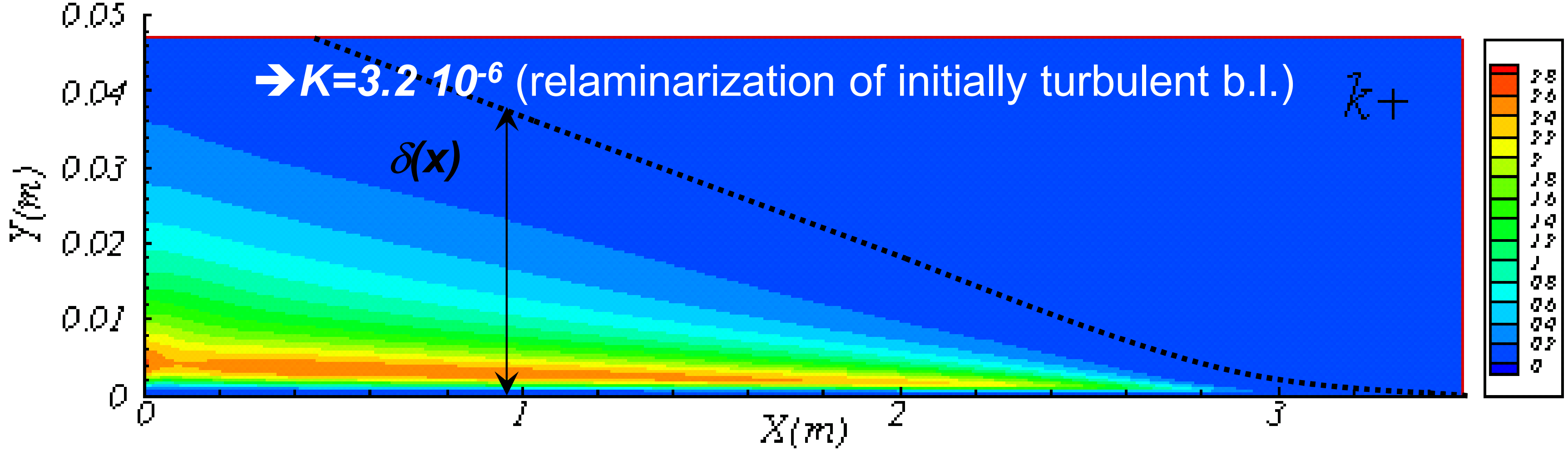


Anisotropy strengthening **Anisotropy weakening**

Background RSM: $\overline{u_i u_j} - \varepsilon^h$, performances 4

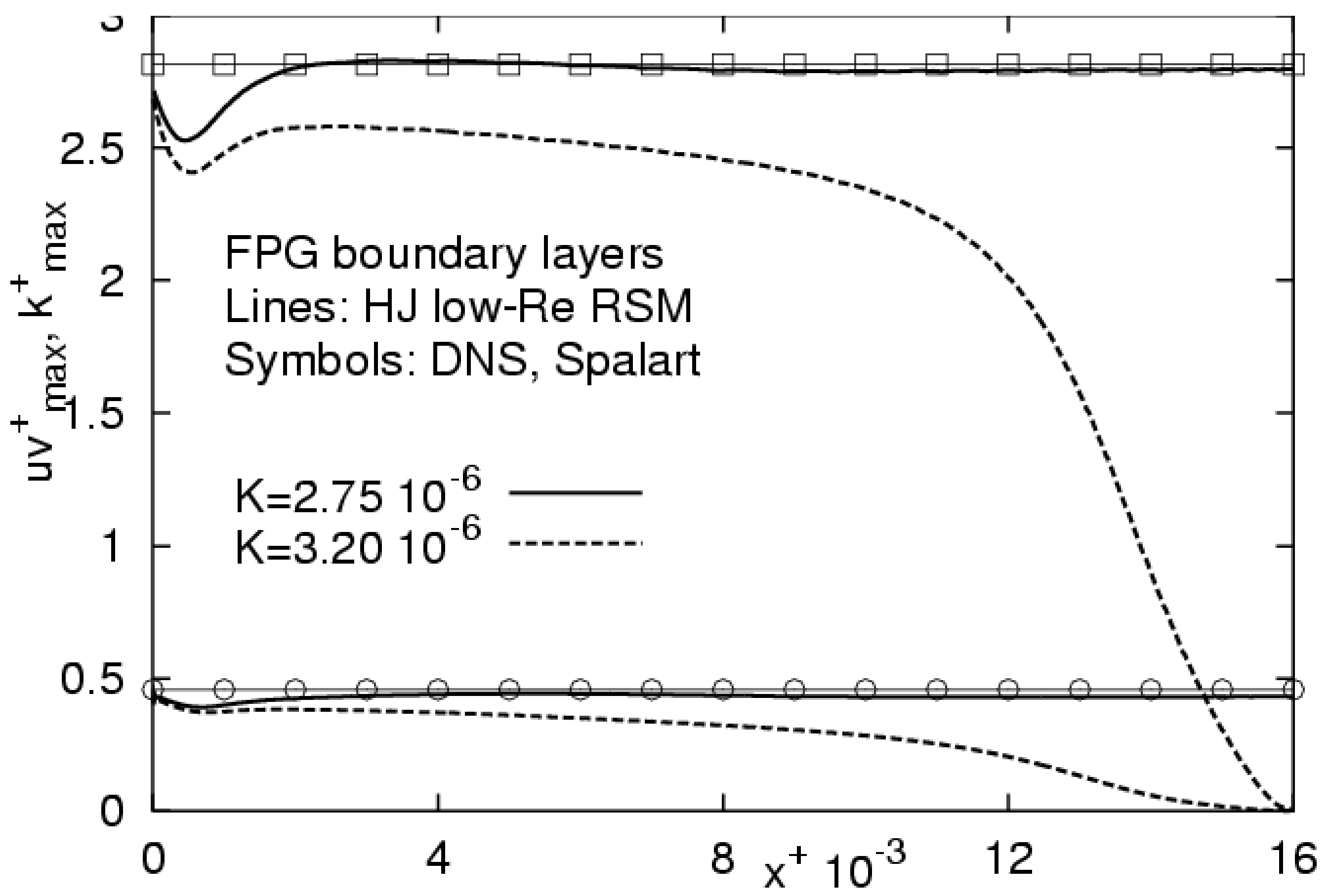
- *sink-flow b. l.: turbulence development/decay*





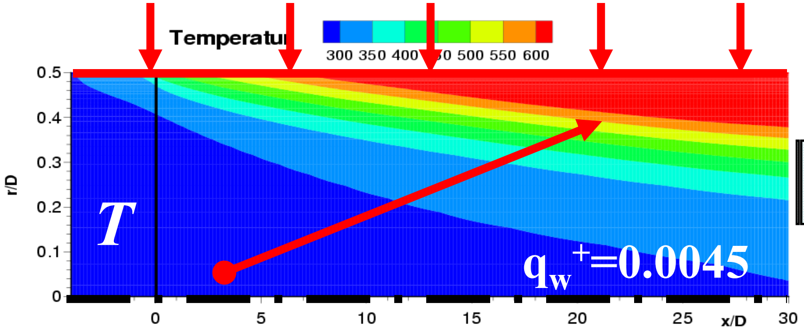
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, performances 5

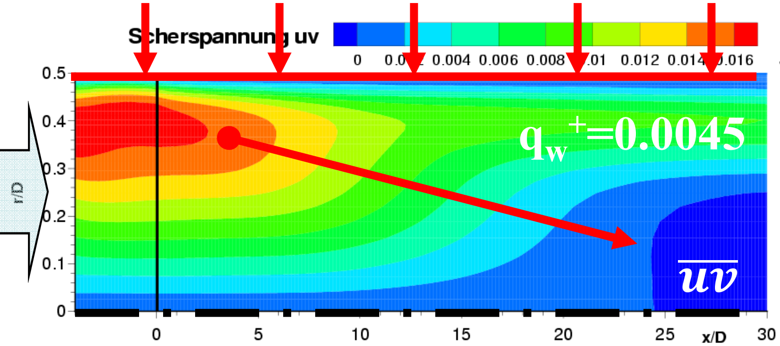
- sink-flow b. l.: turbulence development/decay

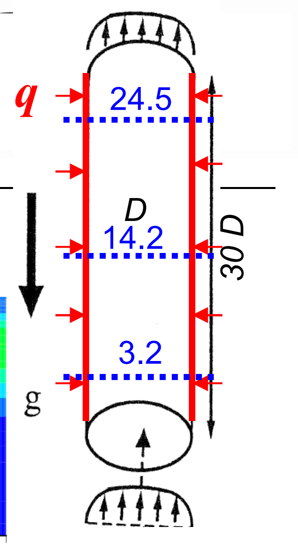


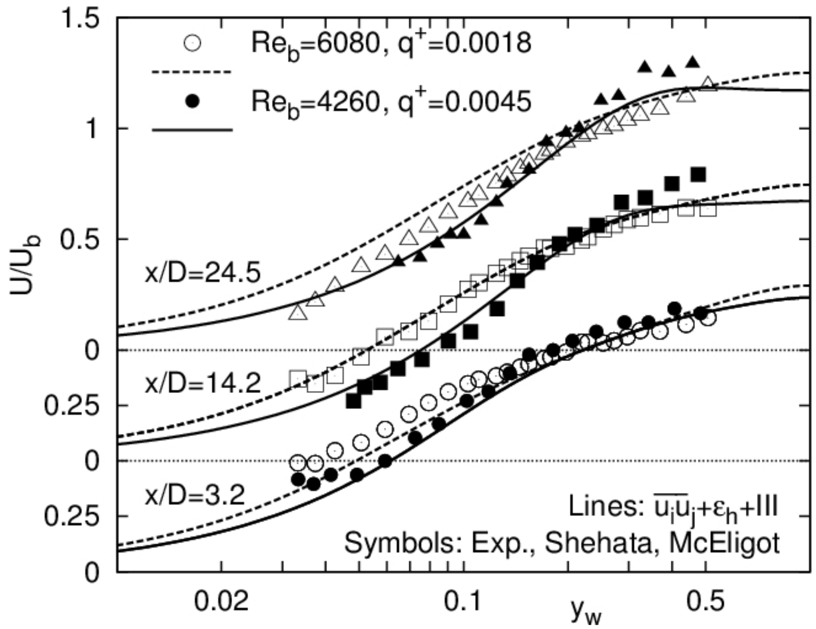
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, performances

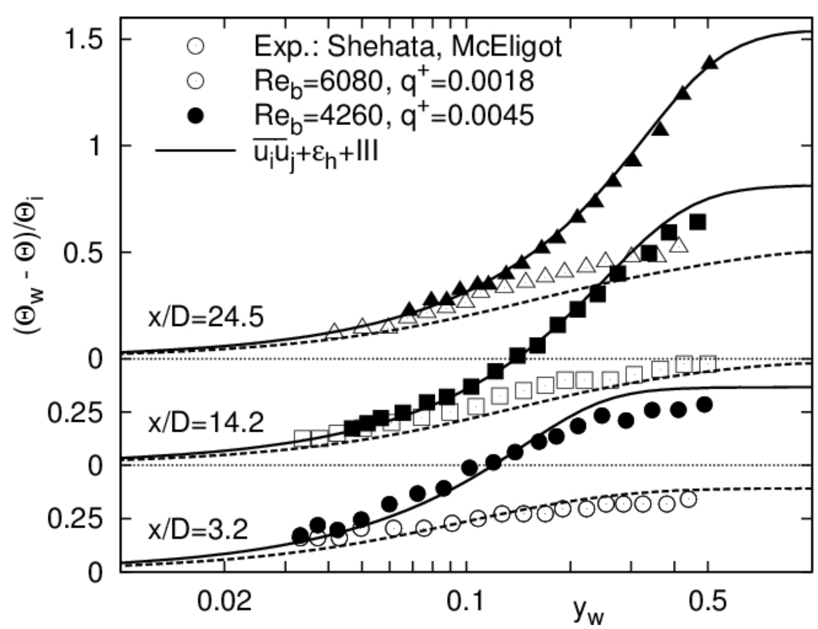
-strongly-heated gas flow in a finite-length pipe





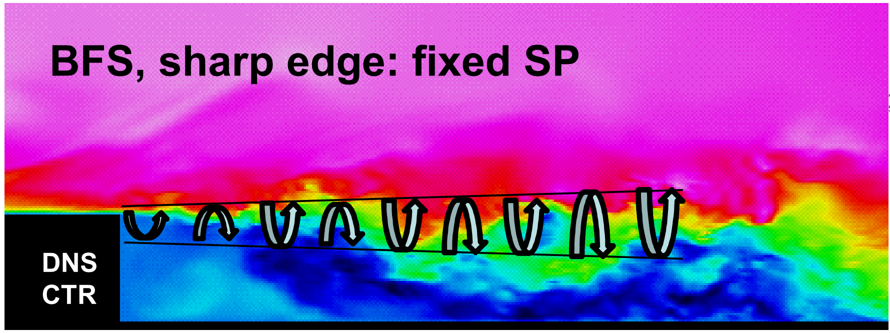


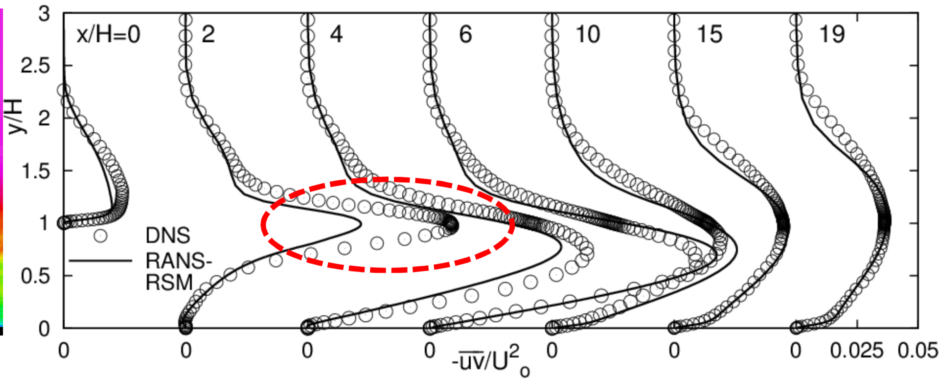


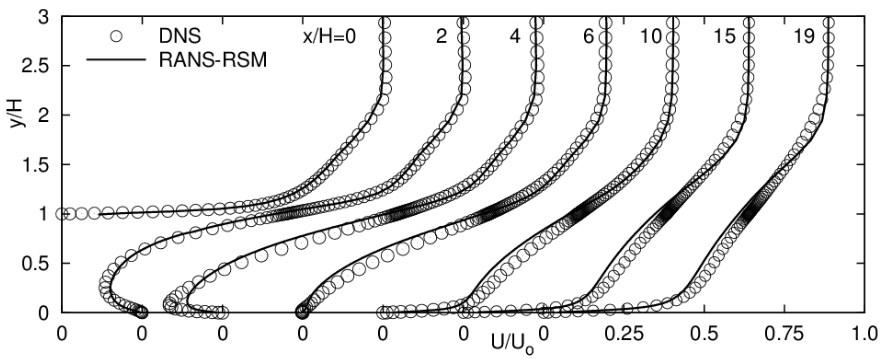


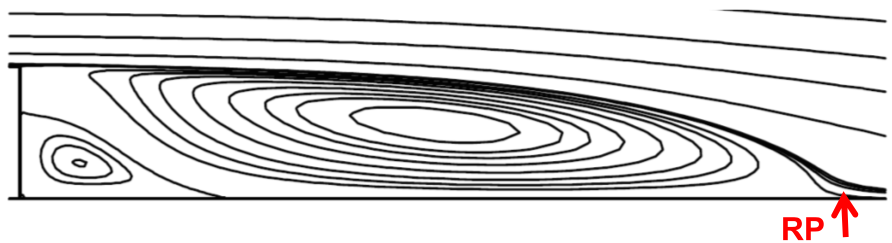
Background RSM: $\overline{u_i u_j} - \varepsilon^h$, performances:

- flow over a backward-facing step







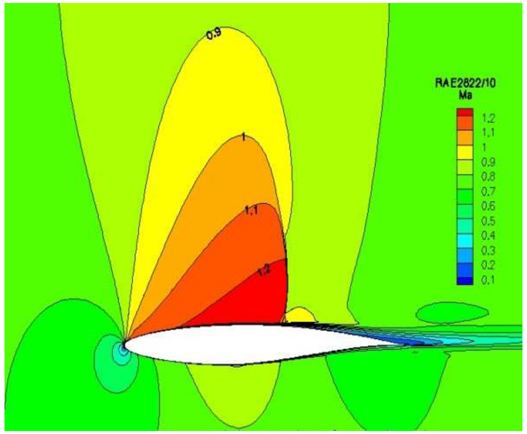


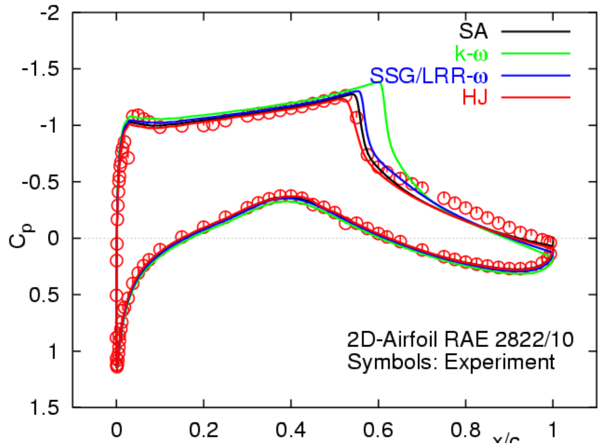
➢ Tested in a series of BFS configurations over a range of Re-numbers (up to 10^5)

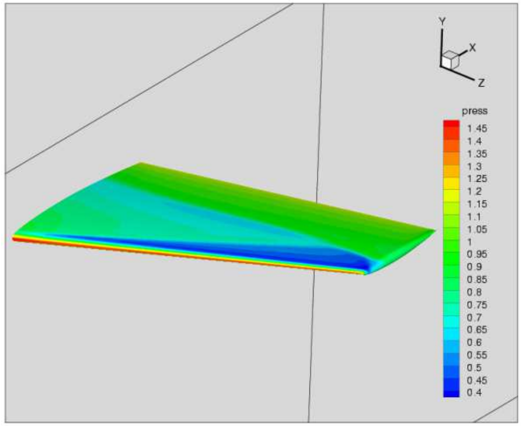
Background RSM: $\overline{u_i u_j} - \varepsilon$, performances:

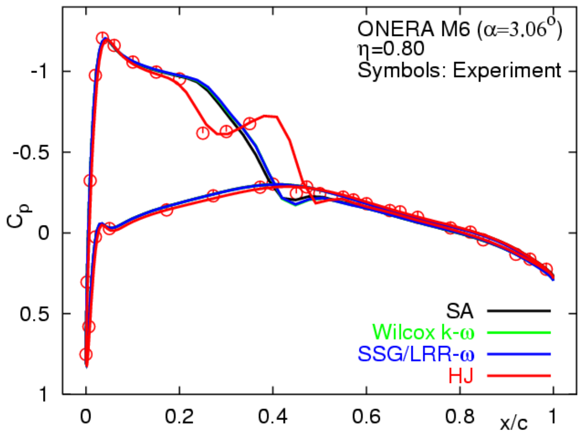
- *transonic flow configurations*

Jakirlić, S., Eisfeld, B., Jester-Zürker, R. and Kroll, N. (2007): *Int. J. Heat and Fluid Flow*, Vol. **28**(**4**)**:** 602-615

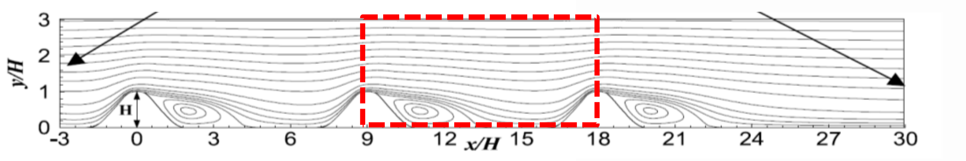


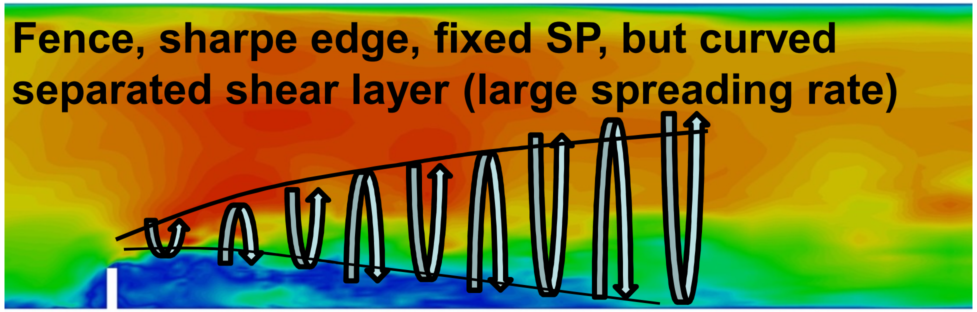


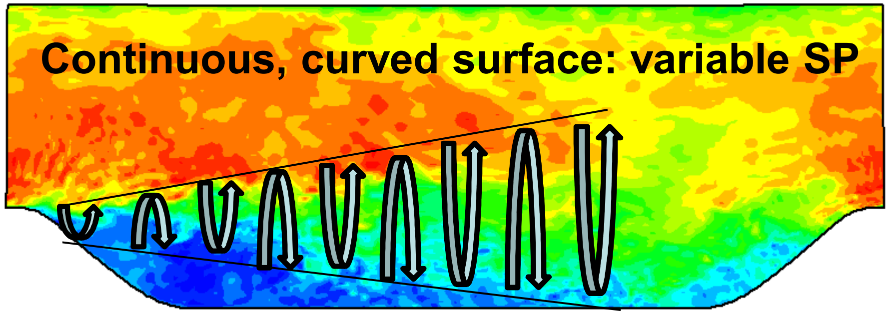


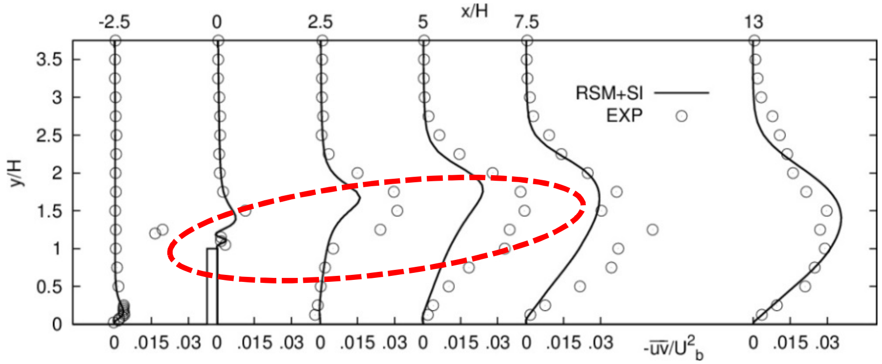


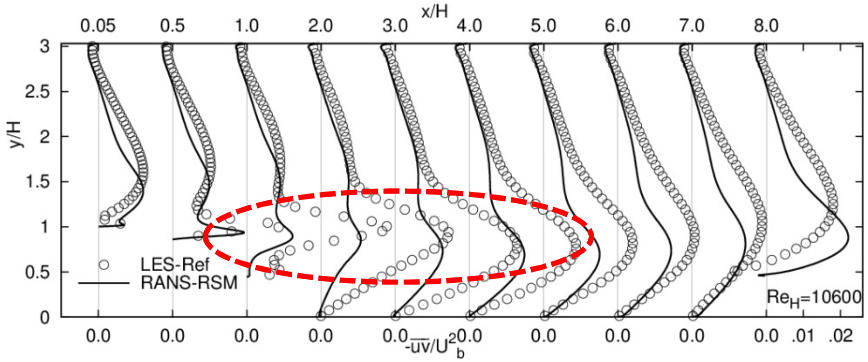
RSM, complex separated flows

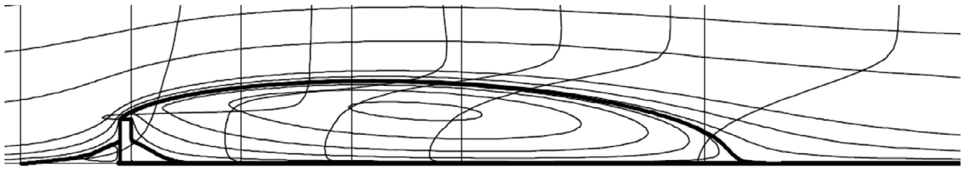




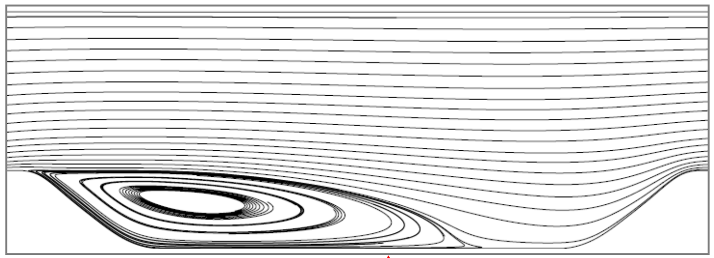








↑ RP



↑ RP

- **An Eddy-Resolving model has to be developed!**

Introduction: eddy-resolving models

TECHNISCHE UNIVERSITÄT DARMSTADT

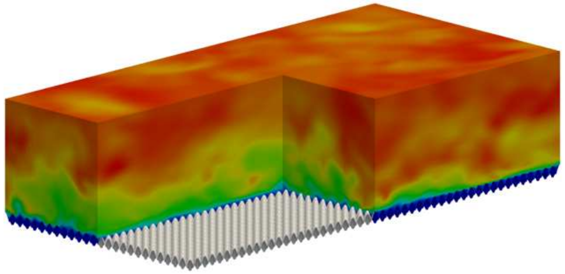
- **RANS** computational framework ⇒ **fully-modelled turbulence**
- **LES** framework ⇒ high portion of **resolved turbulence** ($\geq 80\%$)
- The basic of any **Hybrid RANS/LES** method is a **RANS-based model formulation describing the modelled fraction of turbulence**
- **This model is** appropriately **"sensitized" to account for turbulence unsteadiness** (fluctuating turbulence) **by introducing** either
  - **a grid-spacing-dependent filter parameter** (mostly in the length-scale determining equation – PANS/PITM or ν_t-equation/expression – DES-related schemes/VLES) or

This presentation

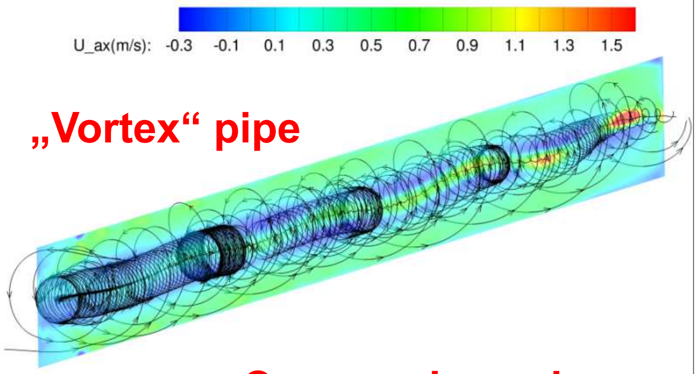
  - **the von Karman length scale** $L_{vK} = \kappa S/\left|\nabla^2 U\right|$ – nominally a grid-spacing-free model formulation (SAS-related models, Menter et al.)
- Accordingly, **the model equations** (formulated and validated within the Steady RANS framework, describing the fully-modeled turbulence), **adopt automatically** (by interplaying with the grid resolution) **to the highly-unsteady** (unresolved, residual) **sub-scale turbulence**

Computational illustrations, VLES/PANS

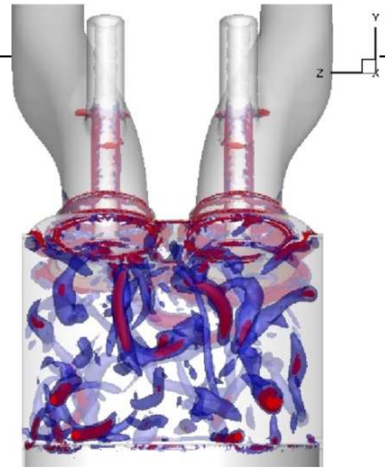
Channel (heat transfer, rough walls)



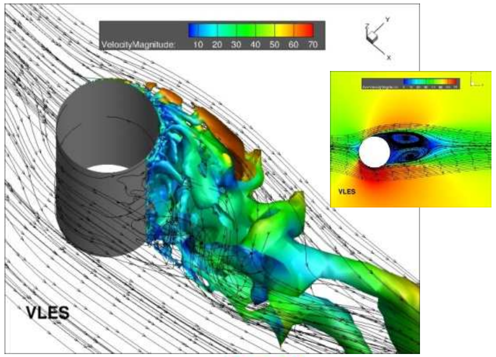
„Vortex“ pipe



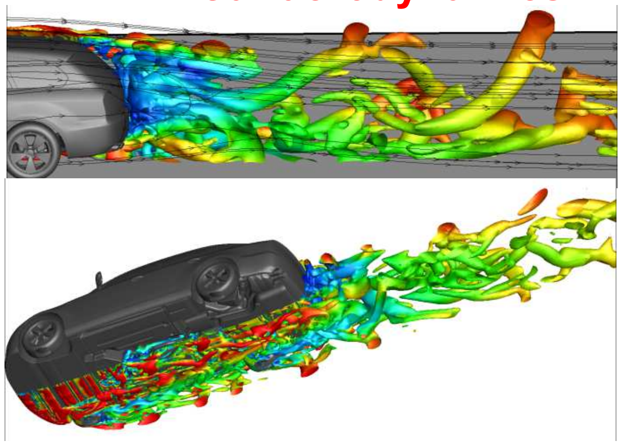
IC-engine configurations



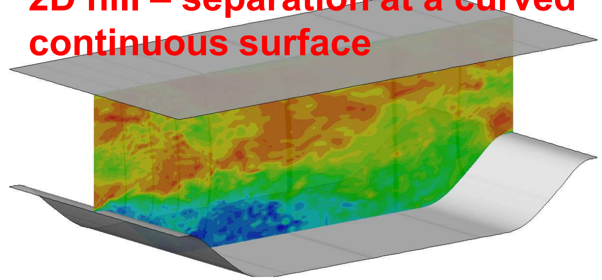
Flow past a rotating cylinder



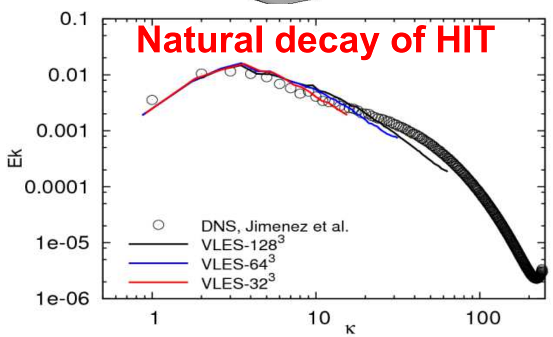
- **Car aerodynamics**



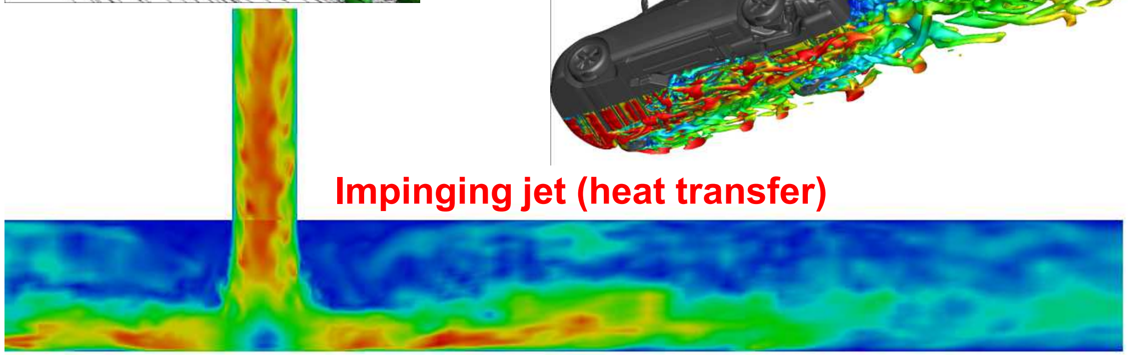
2D hill – separation at a curved continuous surface



Natural decay of HIT

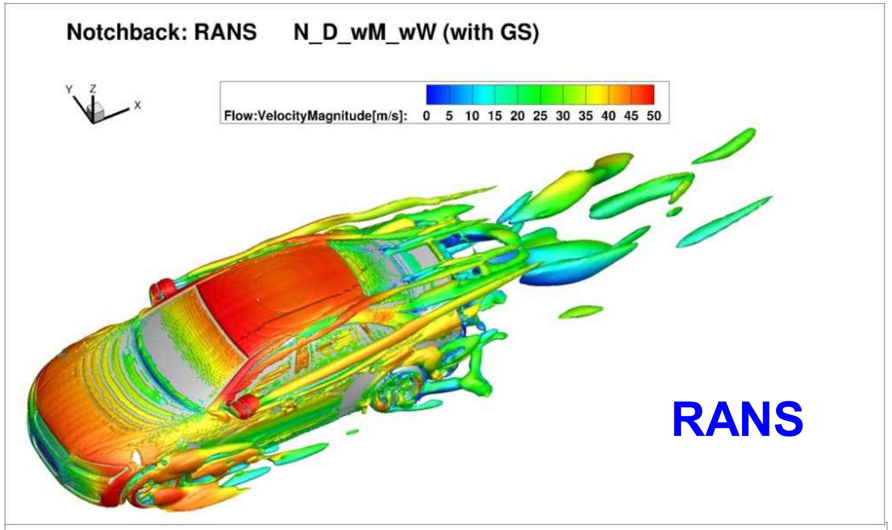


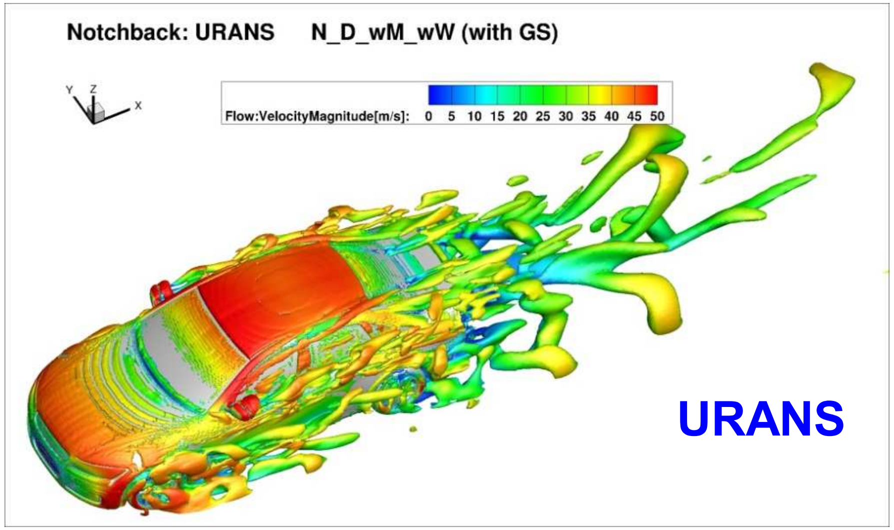
Impinging jet (heat transfer)

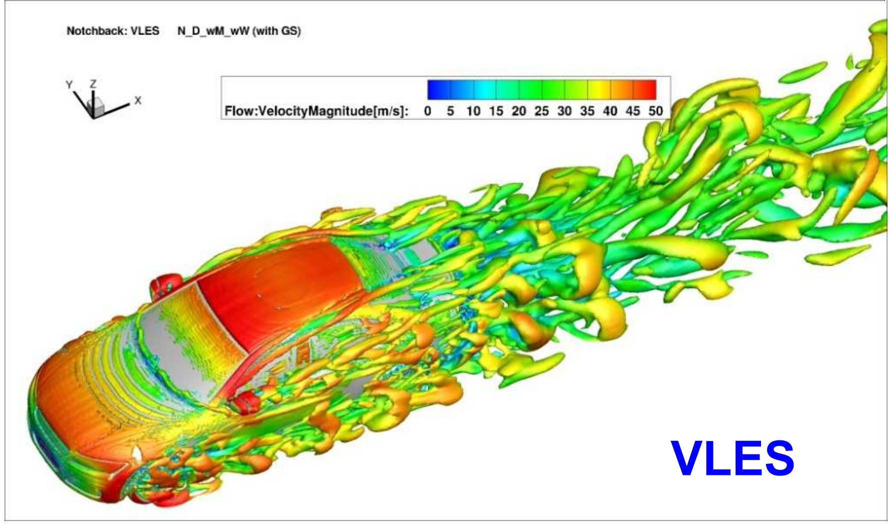


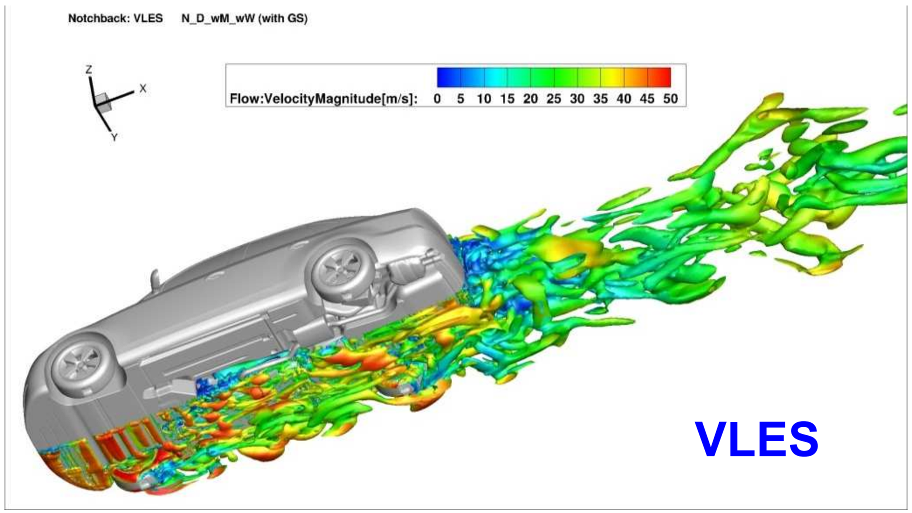
Vortex structure visualization: Q-criterion (6500 s^{-2})

illustration of the vortex structure refinement in terms of the systematically enhanced predictive capabilities of the applied models





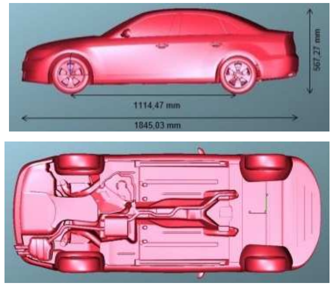




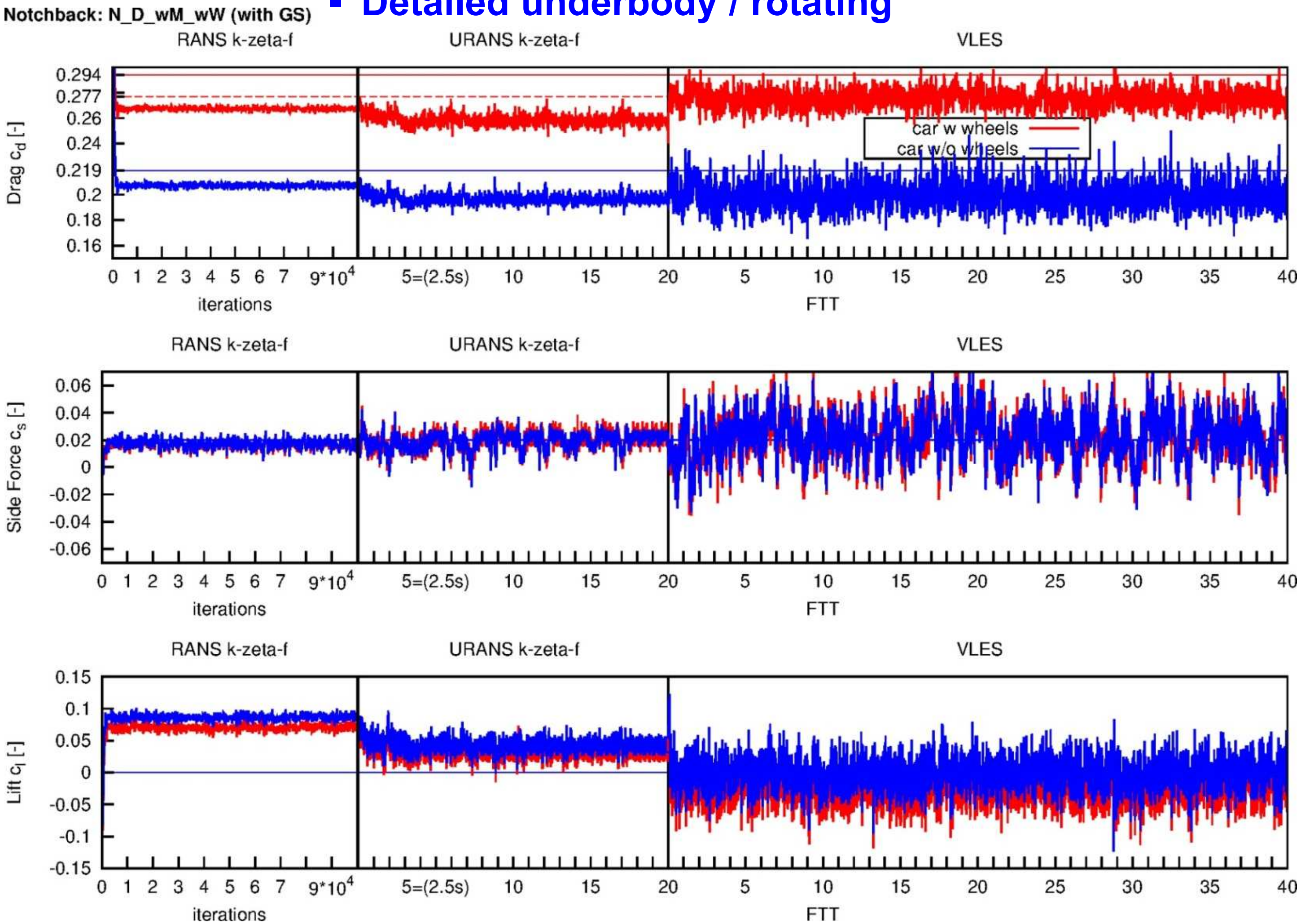
Drag, lift and side force coefficients,

$\boldsymbol{F_i = \iint \tau_{ji} n_j dA}$ **, with** $\boldsymbol{\tau_{ij} = -p(x,y,z)\delta_{ij} + 2\mu S_{ij}}$**:**

$$C_i = \frac{F_i}{0.5\rho U_\infty^2 A_i}$$



- **Detailed underbody / rotating**



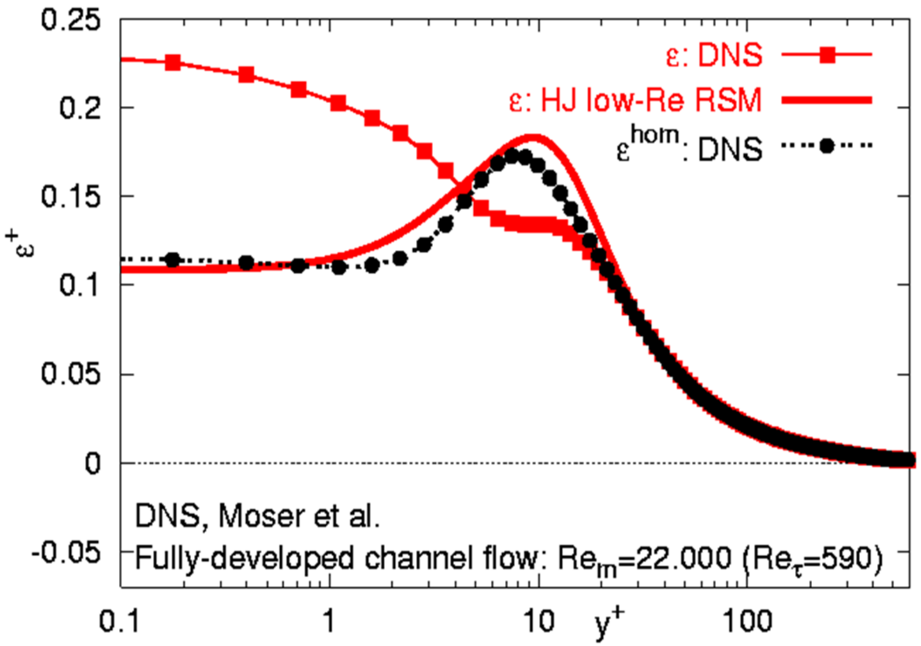
RANS (RSM): Total vs. homogeneous viscous dissipation rate - ε vs. ε_h

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Model ε^h-equation (Differential RSM), Jakirlic-Hanjalic (2002, JFM, Vol. 439)**

$$\frac{D\varepsilon^h}{Dt} = \underbrace{\overbrace{-\varepsilon^h_{ij}\frac{\partial U_i}{\partial x_j} - 1.0\overline{u_iu_j}\frac{\partial U_i}{\partial x_j}\frac{\varepsilon^h}{k}}^{-C_{\varepsilon,1}\overline{u_iu_j}\frac{\partial U_i}{\partial x_j}\frac{\varepsilon^h}{k};\,C_{\varepsilon,1}=1.44}}_{P^1_\varepsilon+P^2_\varepsilon} \underbrace{- 2\nu\left(\frac{\partial\overline{u_iu_k}}{\partial x_l}\frac{\partial^2 U_i}{\partial x_k\partial x_l} + C_{\varepsilon 3}\frac{k}{\varepsilon^h}\frac{\partial\overline{u_ku_l}}{\partial x_j}\frac{\partial U_i}{\partial x_k}\frac{\partial^2 U_i}{\partial x_j\partial x_l}\right)}_{P^3_\varepsilon}$$

$$\underbrace{-C_{\varepsilon,2}f_\varepsilon\frac{\tilde{\varepsilon}^h\varepsilon^h}{k}}_{P^4_\varepsilon - Y} + \underbrace{\frac{\partial}{\partial x_k}\left[\left(\frac{1}{2}\nu\delta_{kl} + C_\varepsilon\frac{k}{\varepsilon^h}\overline{u_ku_l}\right)\frac{\partial\varepsilon^h}{\partial x_l}\right]}_{D^\nu_\varepsilon + D^t_\varepsilon + D^p_\varepsilon}$$



Implication for modelling:

- **Only homogeneous dissipation is to be modelled**
- **Non-homogeneous part is exact – 0.5 $D_{\nu k}$ (no modelling necessary) / implicitly incorporated in the model**

RANS (RSM): Scale-supplying **equation: specific dissipation rate ω, i.e. ω_h**

TECHNISCHE UNIVERSITÄT DARMSTADT

- **ω^h-equation has been derived directly from the previous ε^h-equation:**

$$\frac{D}{Dt}\left(\omega^h = \frac{\varepsilon^h}{k}\right) \Rightarrow \frac{D\omega^h}{Dt} = \frac{1}{k}\frac{D\varepsilon^h}{Dt} - \frac{\varepsilon^h}{k^2}\frac{Dk}{Dt}$$

with k and ε^h equations (GGDH model for diffusion in $D\varepsilon^h/Dt$ was replaced by the SGDH model – in terms of ν_t - type):

$$\frac{Dk}{Dt} = \frac{\partial}{\partial x_k}\left[\left(\frac{1}{2}\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_k}\right] + P_k - \varepsilon^h$$

$$\frac{D\varepsilon^h}{Dt} = \frac{\partial}{\partial x_k}\left[\left(\frac{1}{2}\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon^h}{\partial x_k}\right] + C_{\varepsilon 1}\frac{\varepsilon^h}{k}P_k - C_{\varepsilon 2}\frac{\varepsilon^h \varepsilon^h}{k} + P_{\varepsilon,3}$$

Resulting equation for ω-homogeneous

$$\frac{D\omega^h}{Dt} = \frac{\partial}{\partial x_k}\left[\left(\frac{1}{2}\nu + \frac{\nu_t}{\sigma_\omega}\right)\frac{\partial \omega^h}{\partial x_k}\right] + \left(C_{\varepsilon 1} - 1\right)\frac{\omega^h}{k}P_k - \left(C_{\varepsilon 2} - 1\right)\omega^h \omega^h$$

$$+ \frac{2}{k}\left(\frac{1}{2}\nu + \frac{\nu_t}{\sigma_\omega}\right)\frac{\partial \omega^h}{\partial x_k}\frac{\partial k}{\partial x_k} + \frac{1}{k}P_{\varepsilon,3}$$

SRANS (IS-RSM) Scale-supplying equation: SAS-featured ω_h-equation, 1

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Additional term, adopted from Menter & Egorov's k-ω SST SAS model, has been introduced into the ω_h–equation to make the model "instability sensitive"**

$$\frac{D\omega_{h,SAS}}{Dt} = \frac{D\omega_h}{Dt} + \underbrace{C_{RSM,1} \max\left(P_{SAS}^*, 0\right)}_{P_{SAS}}$$

$$P_{SAS}^* = 2.3713\kappa S^2 \left(\frac{L}{L_{vk}}\right)^{1/2} - 3C_{RSM,2} k \max\left(\frac{\left(\nabla\omega_h\right)^2}{\omega_h^2}, \frac{\left(\nabla k\right)^2}{k^2}\right) \quad C_{RSM,1} = 0.004, \quad C_{RSM,2} = 8$$

with L being the turbulent length scale, S an invariant of the mean strain tensor S_{ij} and L_{vk} – the von Karman length scale

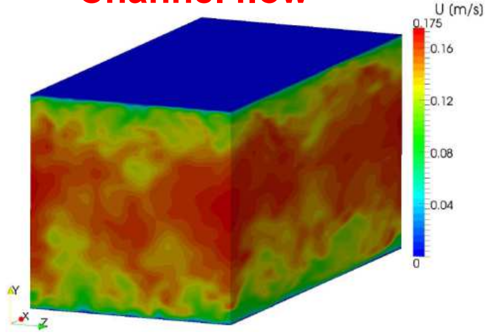
$$L = k^{1/2} / \omega^h \quad L_{vK} = \kappa S / \left|\nabla^2 U\right| \quad \nabla^2 U \left(\equiv U''\right) = \sqrt{\frac{\partial^2 U_i}{\partial x_j^2} \frac{\partial^2 U_i}{\partial x_j^2}} \quad S\left(\equiv U'\right) = \sqrt{2 S_{ij} S_{ij}}$$

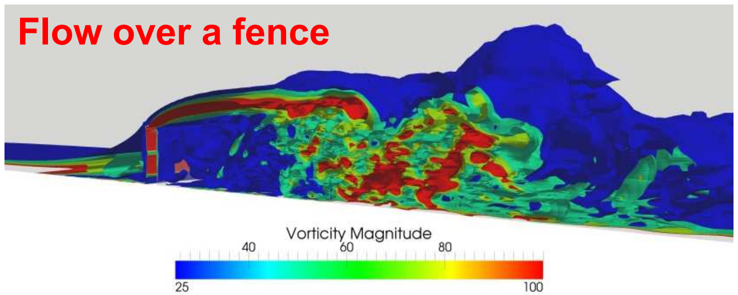
- **The model doesn't comprise explicitly a grid-dependent parameter: ⇒ towards a grid-spacing-free model formulation**

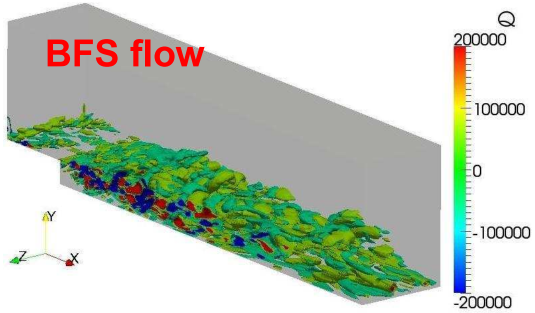
Computational illustrations: IS-RSM

TECHNISCHE UNIVERSITÄT DARMSTADT

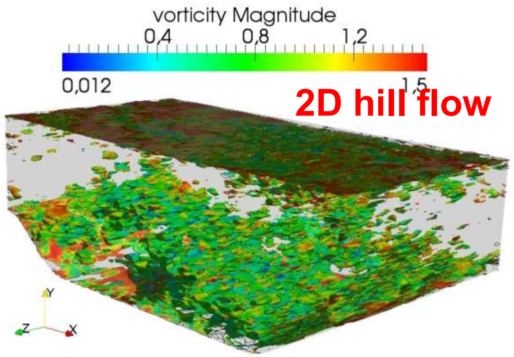
Channel flow

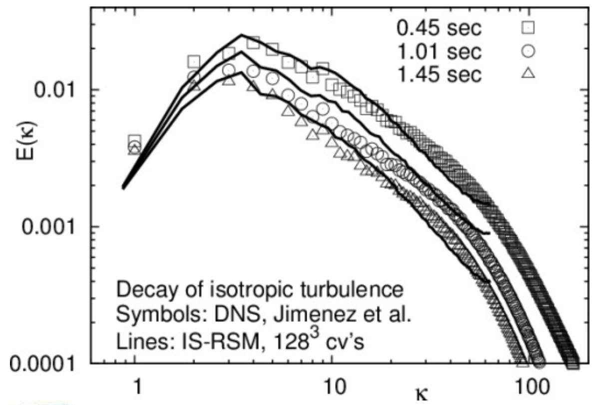


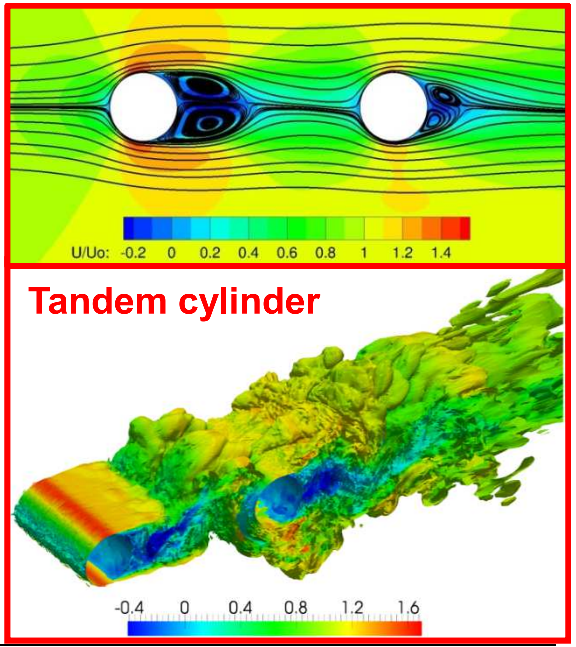


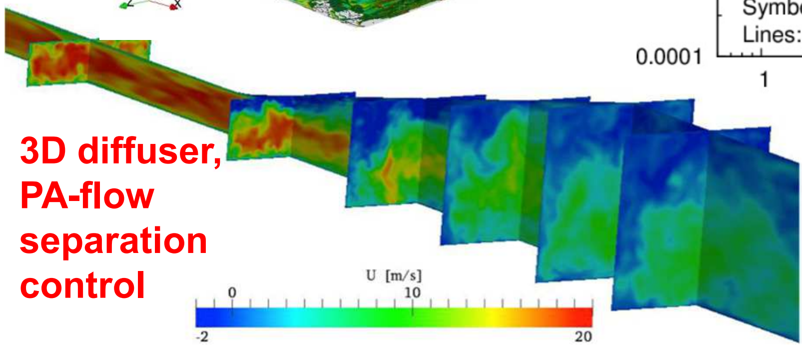


Natural decay of HIT

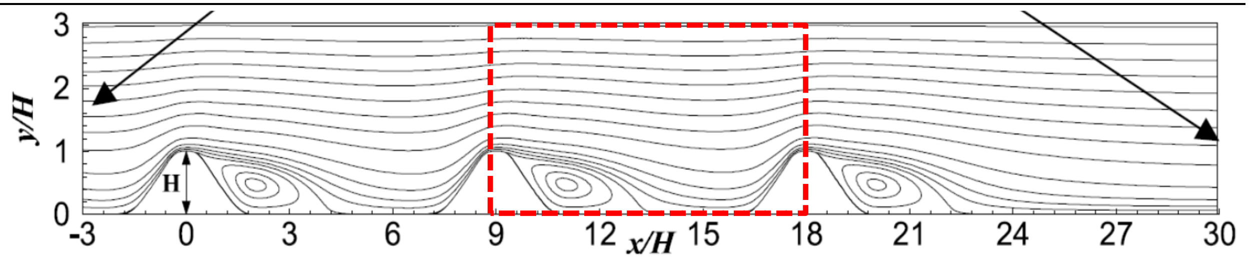






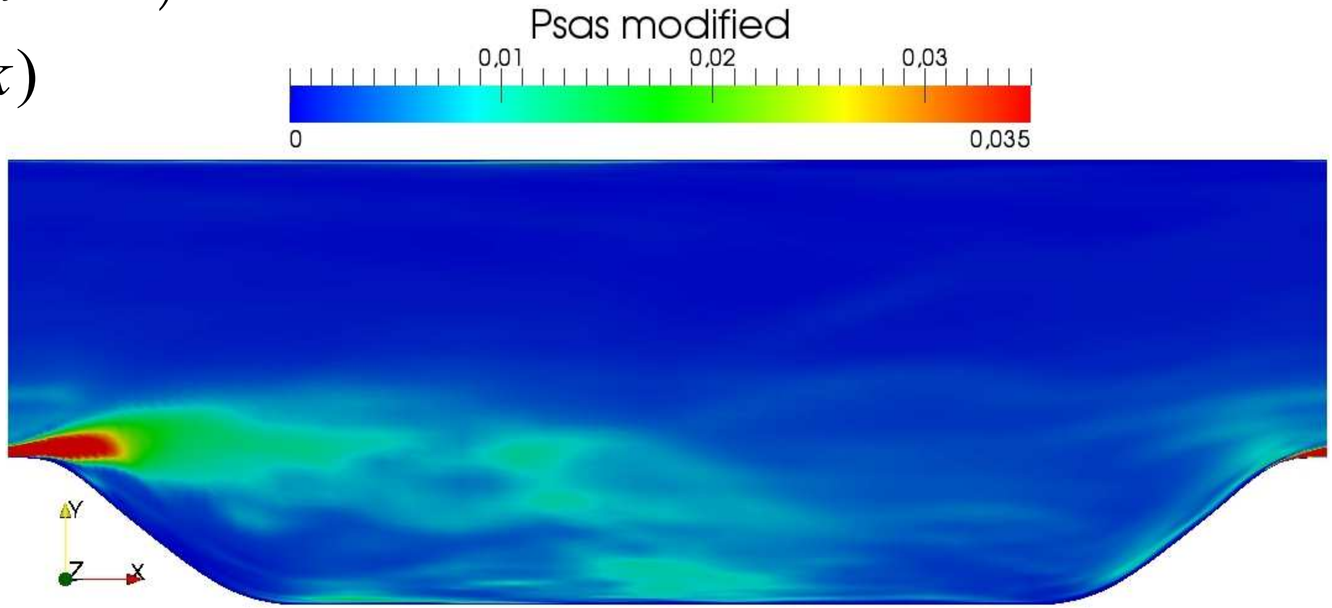


Scale-supplying equation: SAS-featured ω_h-equation, 2



$$P_{SAS}\left(\overline{u_i u_j} - \omega_h\right)$$

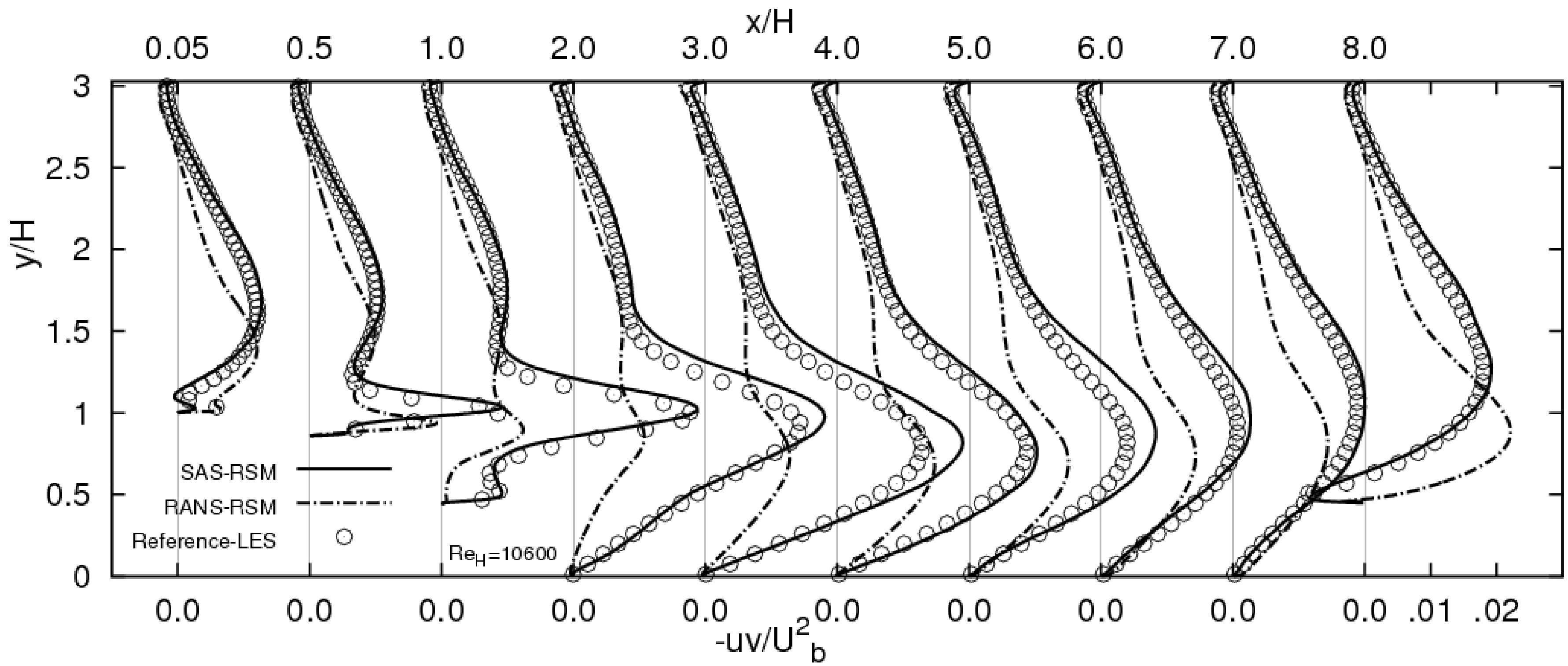
$$(\omega = \varepsilon / k)$$



Selected results of 2D-hill simulation with the proposed DRSM-SAS (ω_h-eq.), Re_H=10600, 3

TECHNISCHE UNIVERSITÄT DARMSTADT

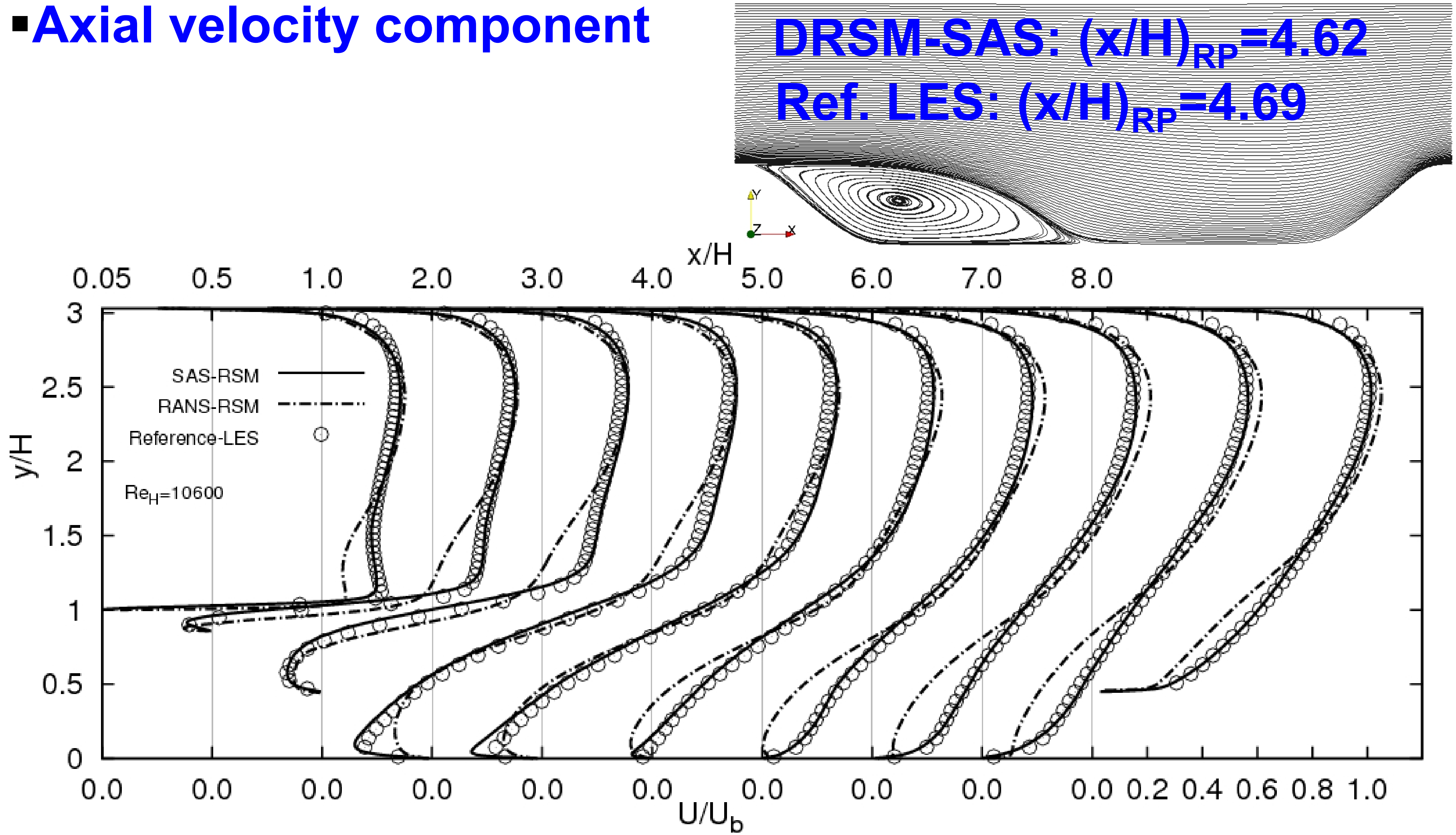
▪Shear stress component



Selected results of 2D-hill simulation with the proposed DRSM-SAS (ω_h-eq.), Re_H=10600, 4

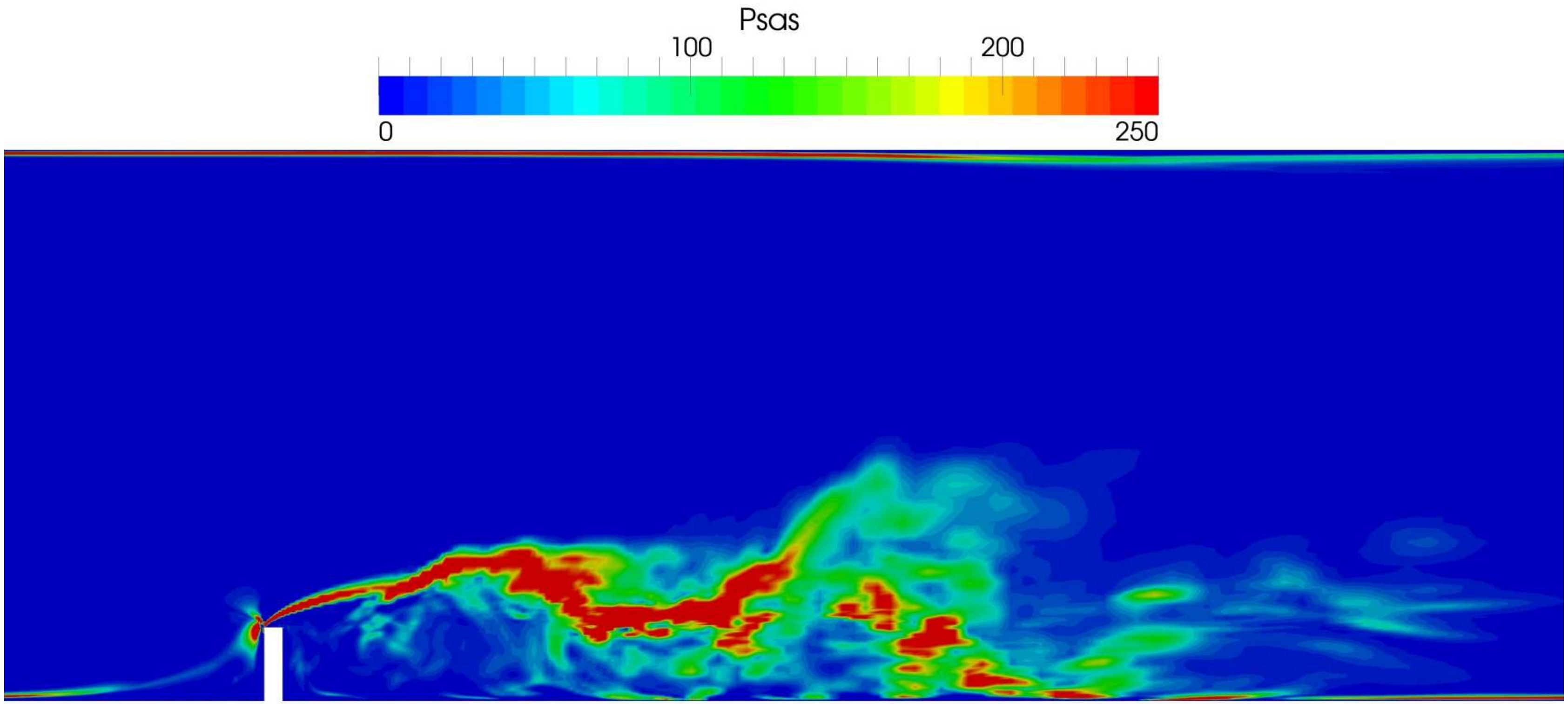
- **Axial velocity component**

DRSM-SAS: $(x/H)_{RP}$=4.62
Ref. LES: $(x/H)_{RP}$=4.69



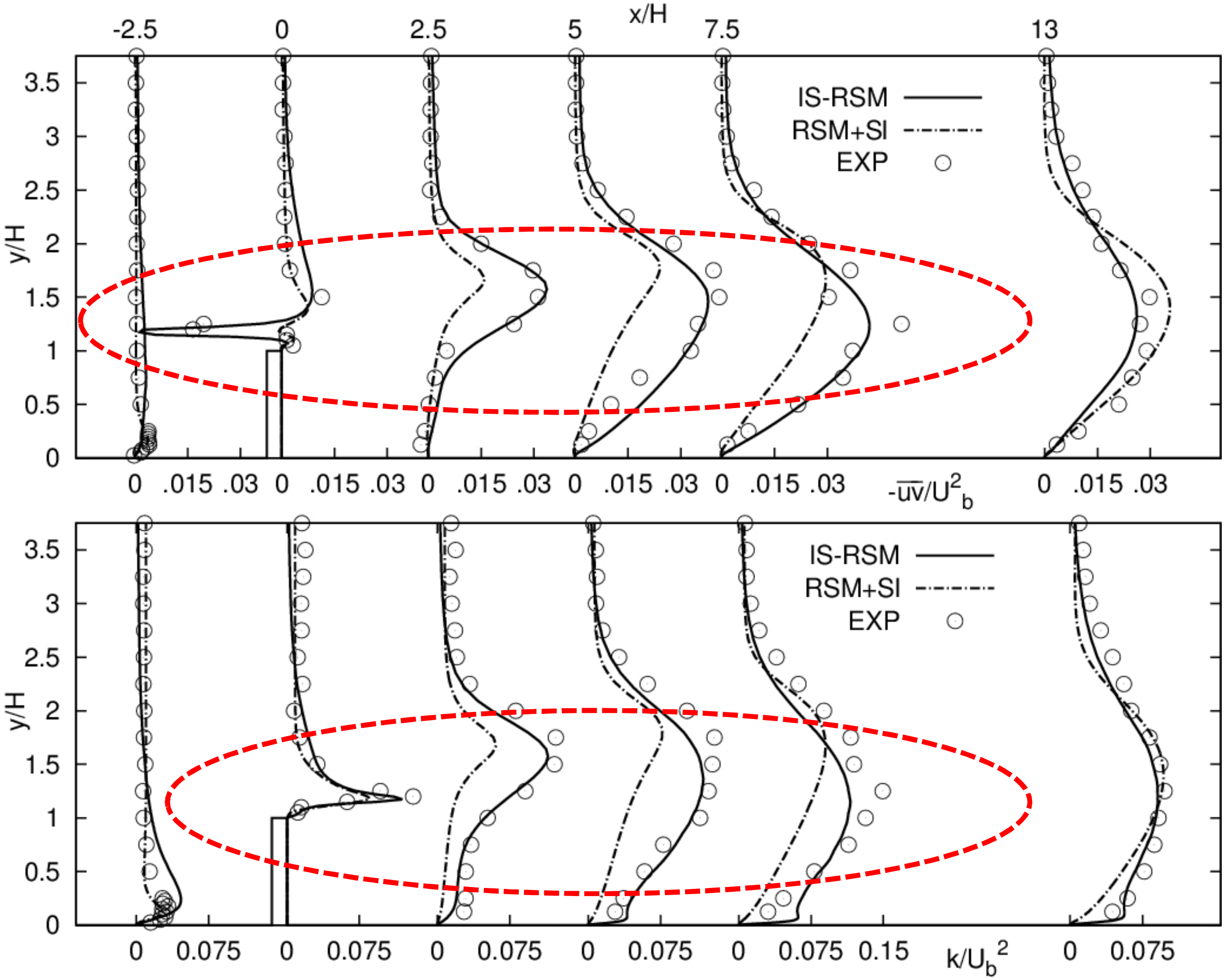
Flow over a 2D fence, IS-RSM: P_{SAS}-term

TECHNISCHE UNIVERSITÄT DARMSTADT



Flow over a 2D fence, RSM vs. IS-RSM : Reynolds shear stress and t.k.e.

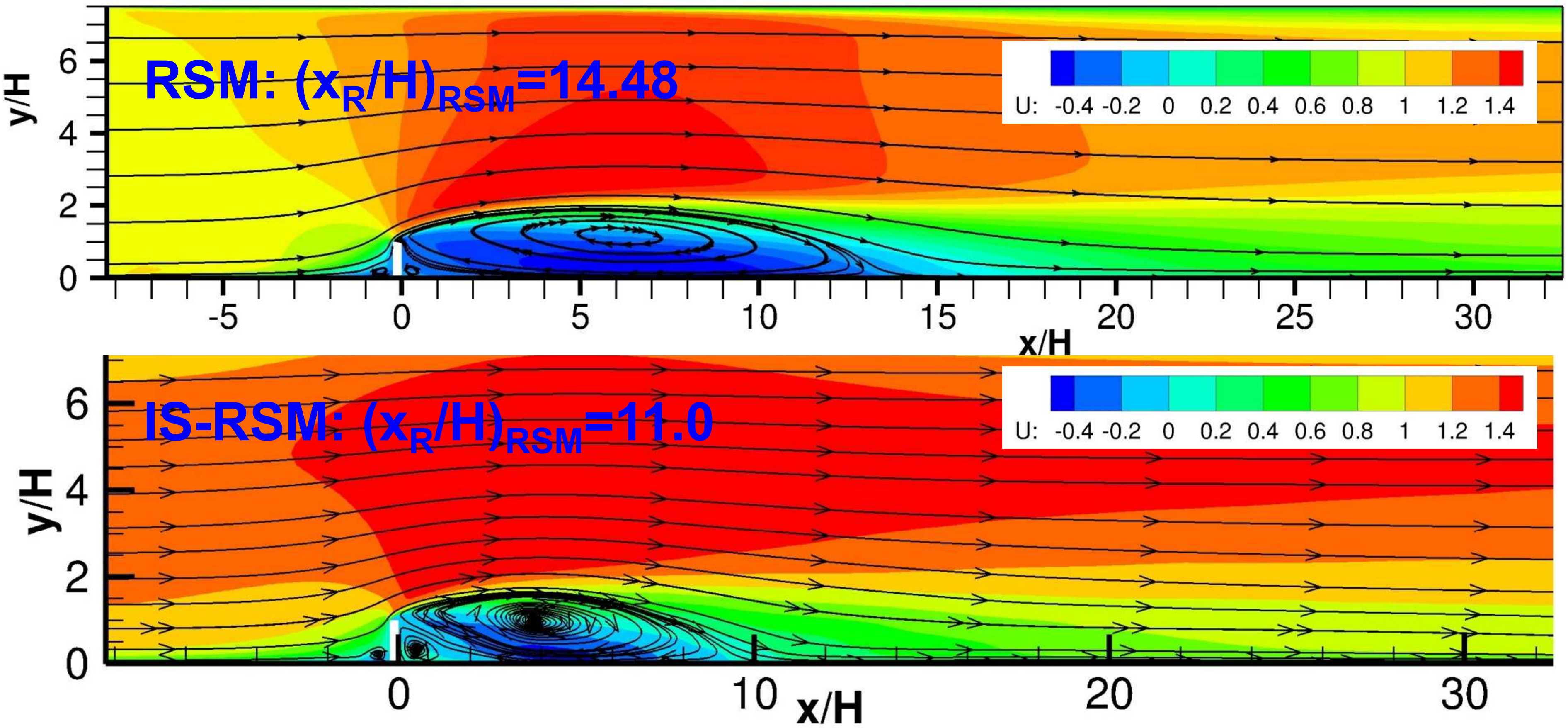
TECHNISCHE UNIVERSITÄT DARMSTADT



Flow over a 2D fence, RSM vs. IS-RSM: mean streamlines

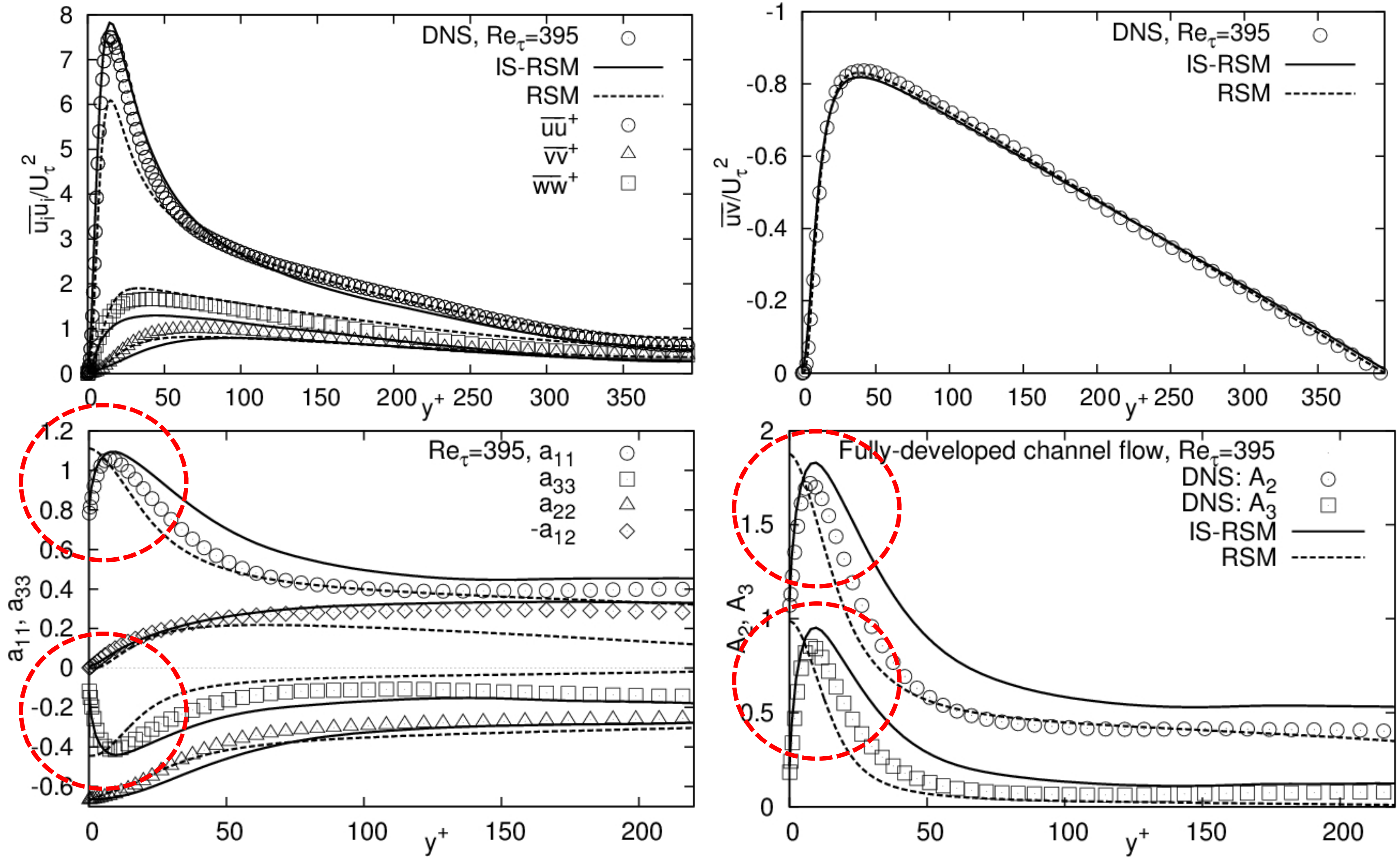
TECHNISCHE UNIVERSITÄT DARMSTADT

$(x_R/H)_{EXP}=11.7$

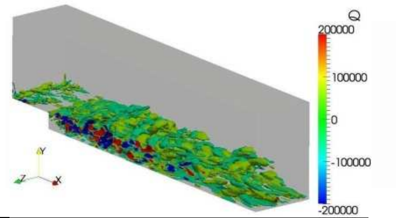


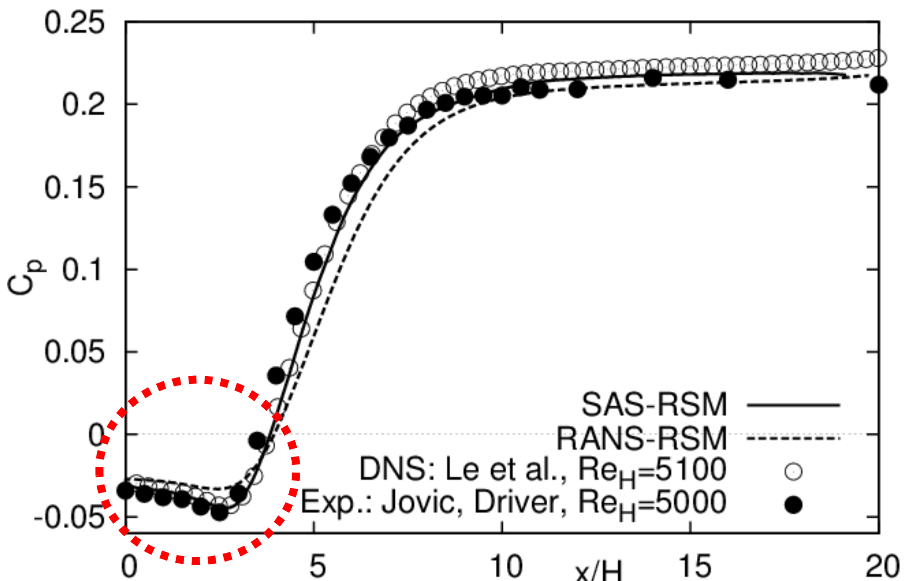
Fully-developed turbulent channel flow at Ret=395 computed by RSM-SAS (ω_h-eq.):

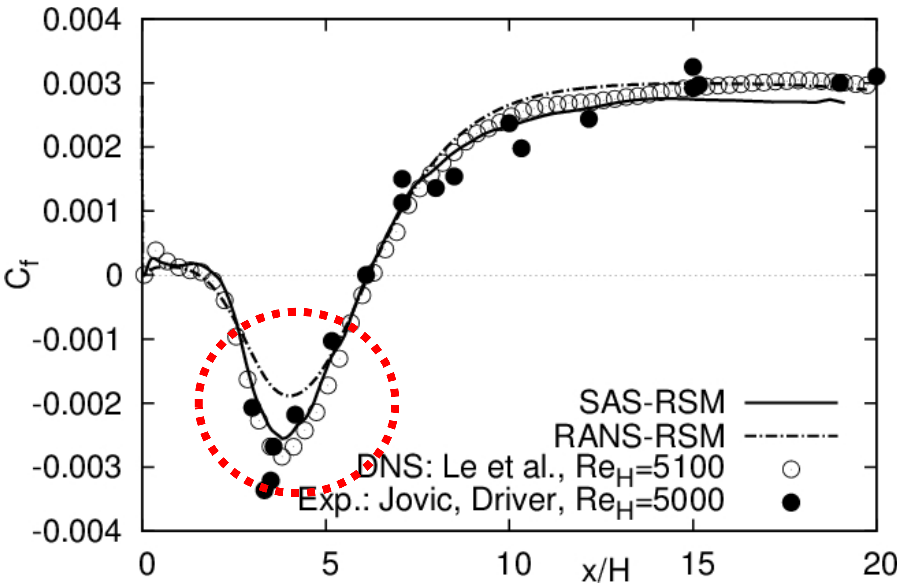
Reynolds stress field / anisotropy



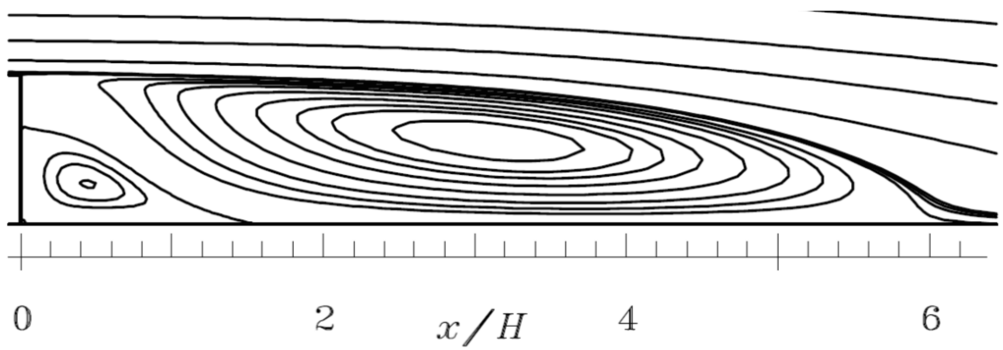
Results of back-step simulation with the proposed RSM-RANS and SAS-RSM (ω_h-eq.), Re_H=5100





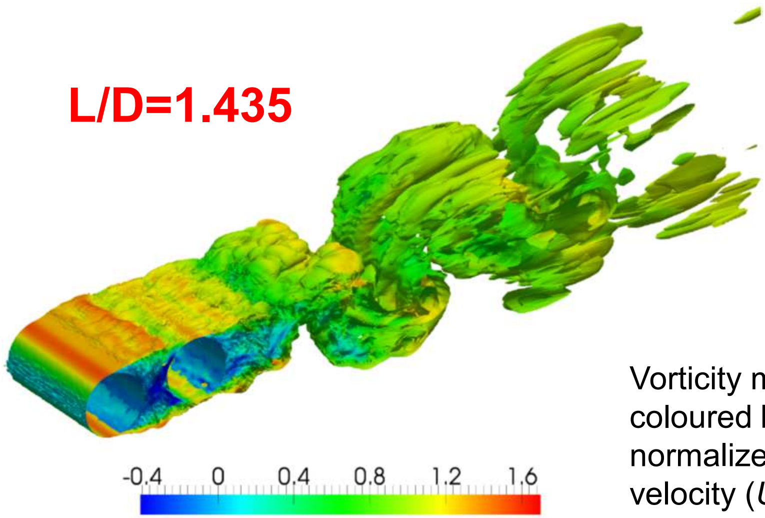


- As a result of the unsteadiness capturing the **SAS-RSM captures correctly high negative peak and shape of Cp and Cf developments at such a low Reynolds number**

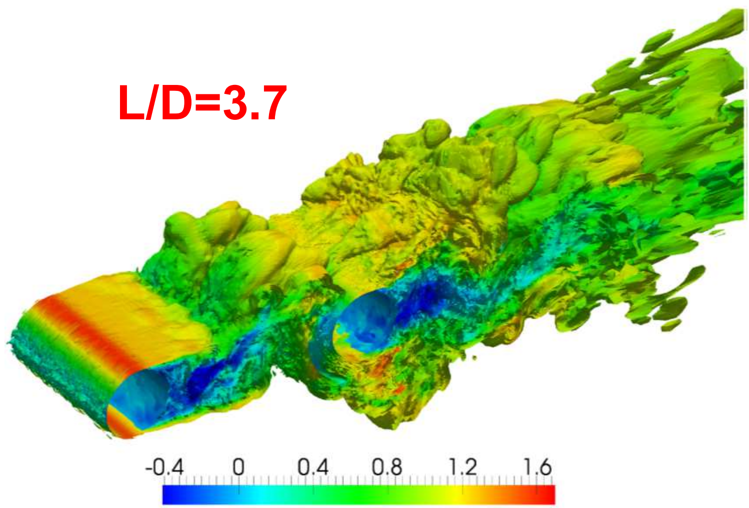


Tandem Cylinder Configuration (Re_D=166000), description, 3

- **The influence of difference in the distance between cylinders is reflected in strong structural changes.**
- **In the case of the longer distance the flow between the cylinders is bistable and switches between continuous shedding and intermittent shedding.**
- **In the short distance case the flow in the wake behind the downstream cylinder exhibits a continuous shedding behaviour. Here, the cylinders are close to each other resembling one long obstacle.**

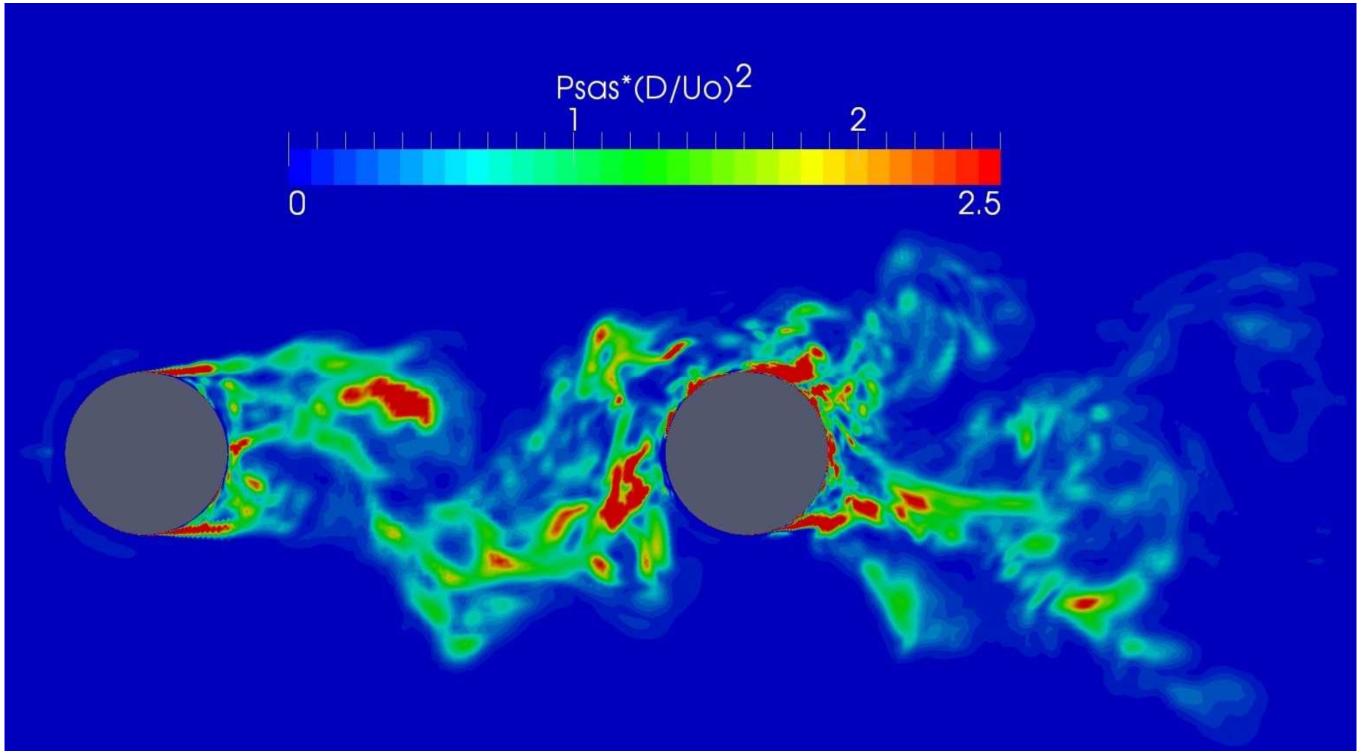


Vorticity magnitude coloured by the normalized axial velocity (*Ux/Uinlet*)



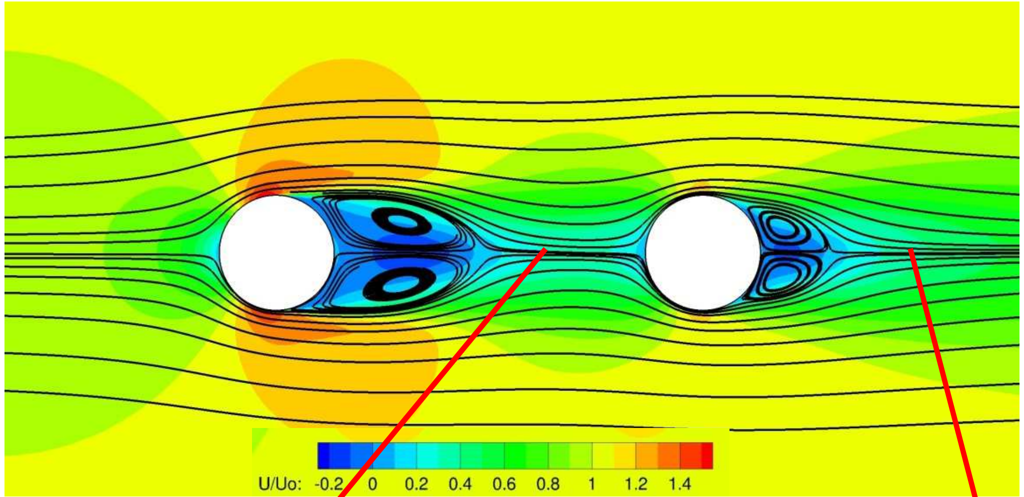
Scale-supplying equation:
SAS-featured ω_h-equation, P_{SAS} -Term

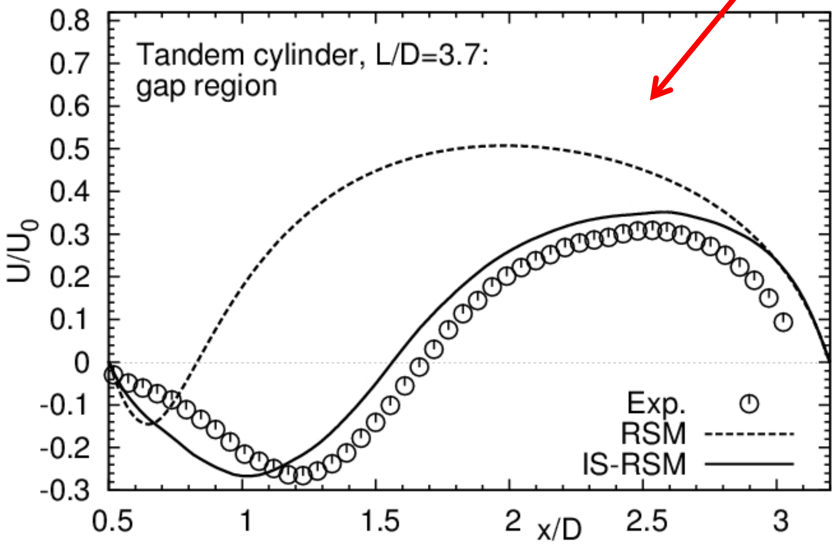
$$P_{SAS}\left(\overline{u_i u_j} - \omega_h\right), \omega_h = \varepsilon_h / k$$

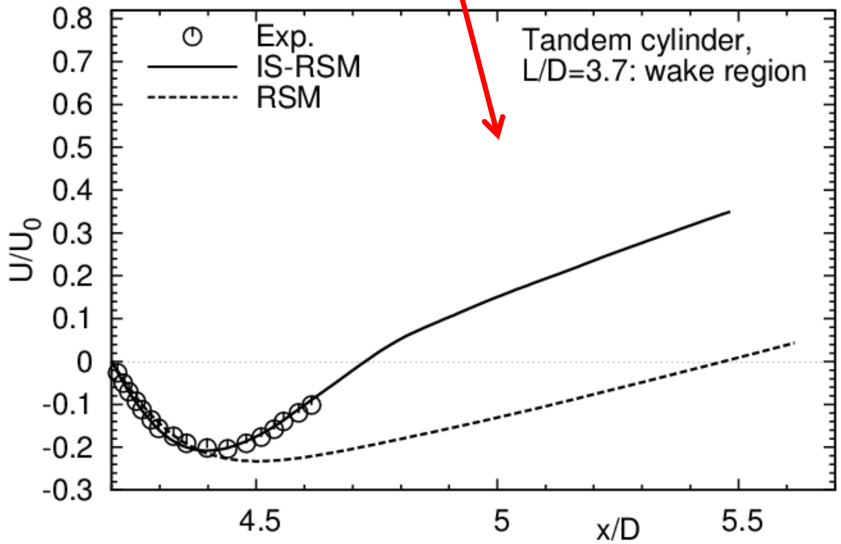


Results of Tandem Cylinder L/D=3.7 (SAS-RSM, RANS-RSM) (ω_h-eq.), Re_D=166000, Mean velocity

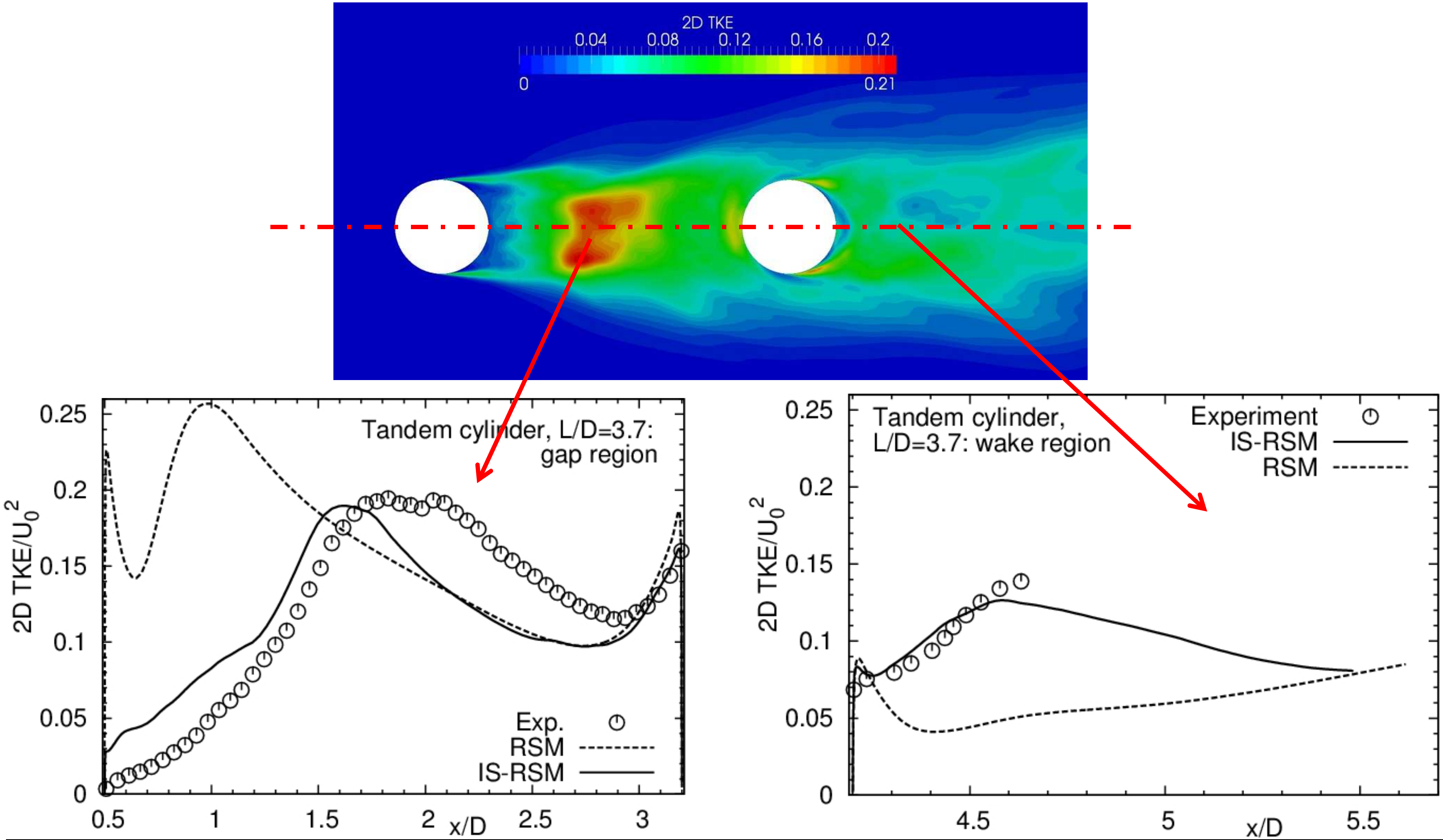
TECHNISCHE UNIVERSITÄT DARMSTADT



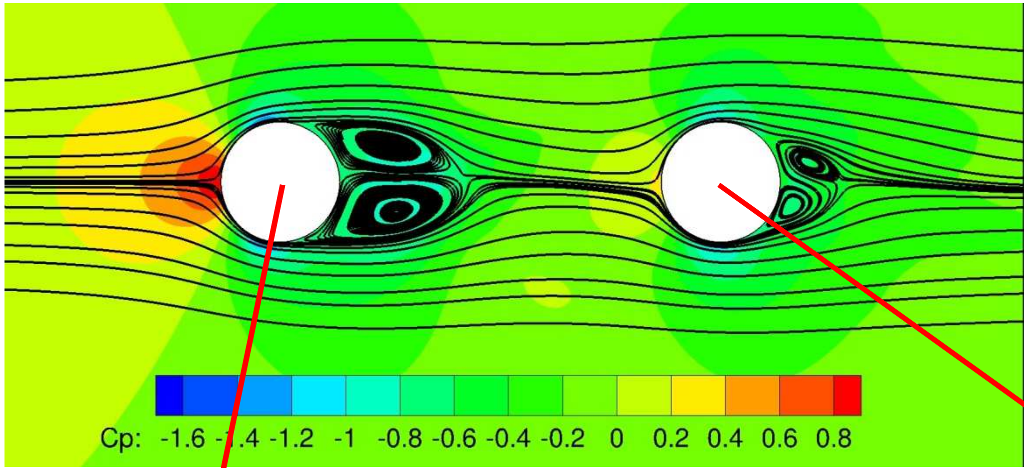


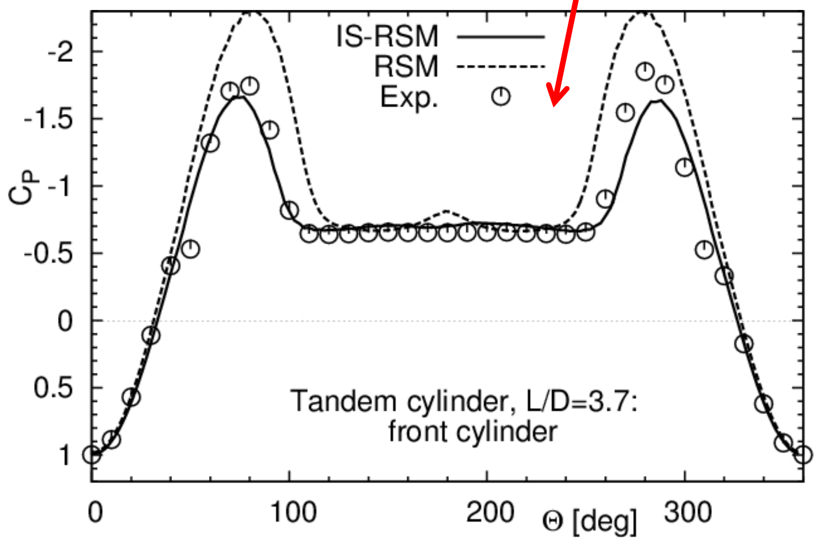


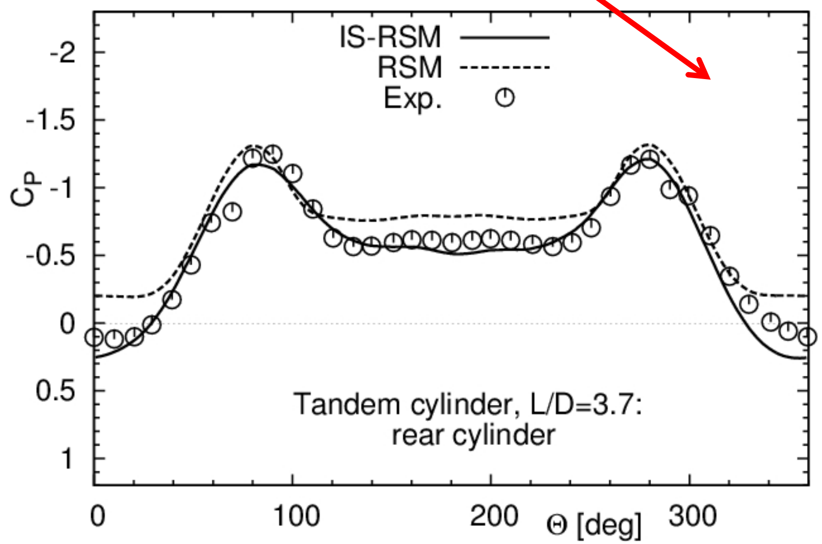
Results of Tandem Cylinder L/D=3.7 (SAS-RSM, RANS-RSM) (ω_h-eq.), Re_D=166000, t.k.e.



Results of Tandem Cylinder L/D=3.7 (SAS-RSM, RANS-RSM) (ω_h-eq.), Re_D=166000, pressure distribution

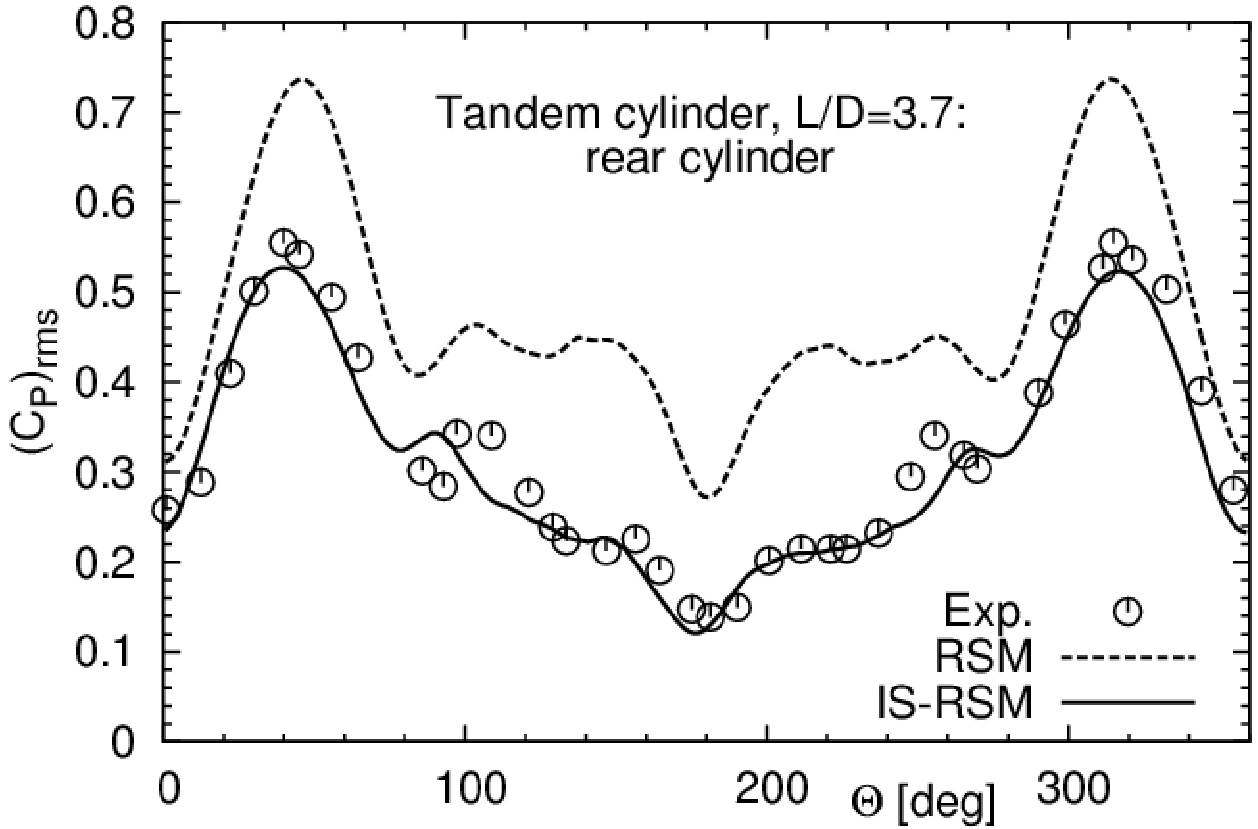






Results of Tandem Cylinder L/D=3.7 (SAS-RSM, RANS-RSM) (ω_h-eq.), Re_D=166000, rms of fluctuating pressure

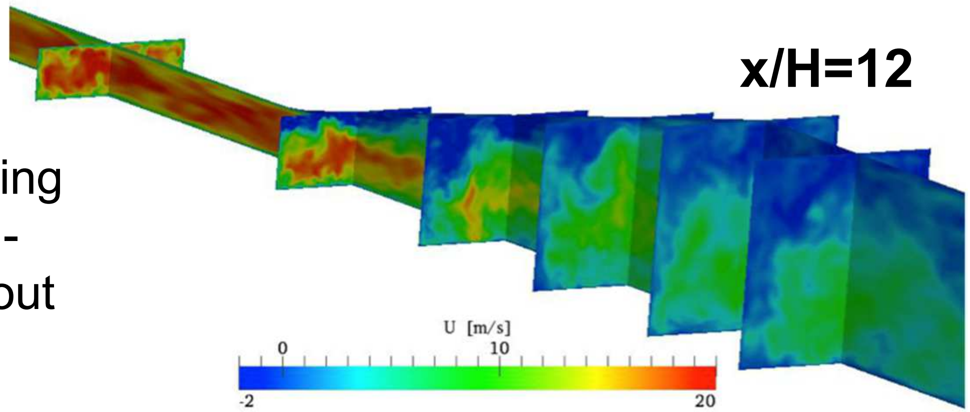
TECHNISCHE UNIVERSITÄT DARMSTADT

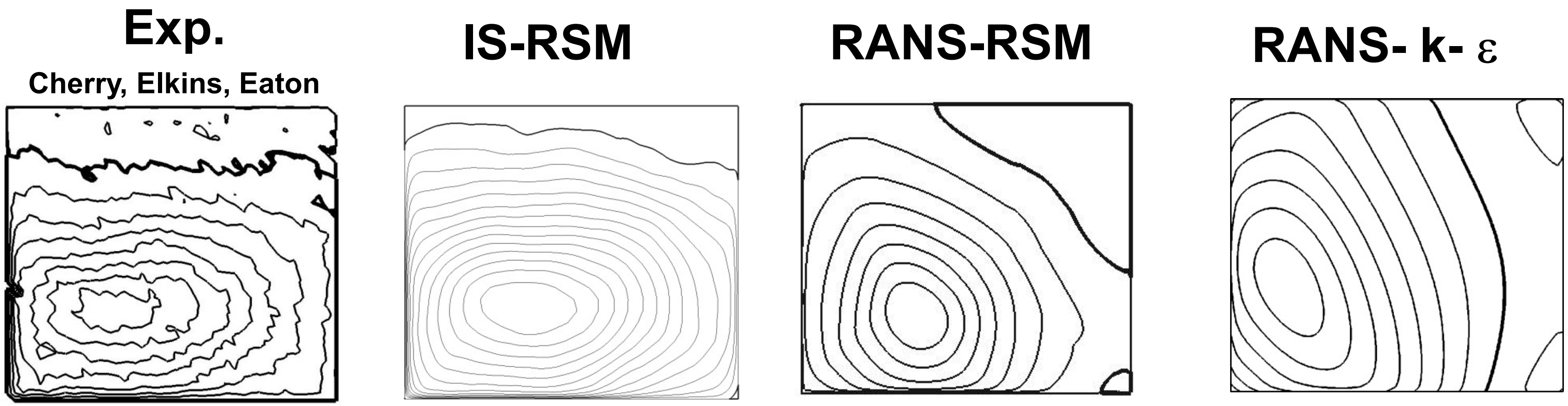


Baseline configuration:
Instantaneous velocity field

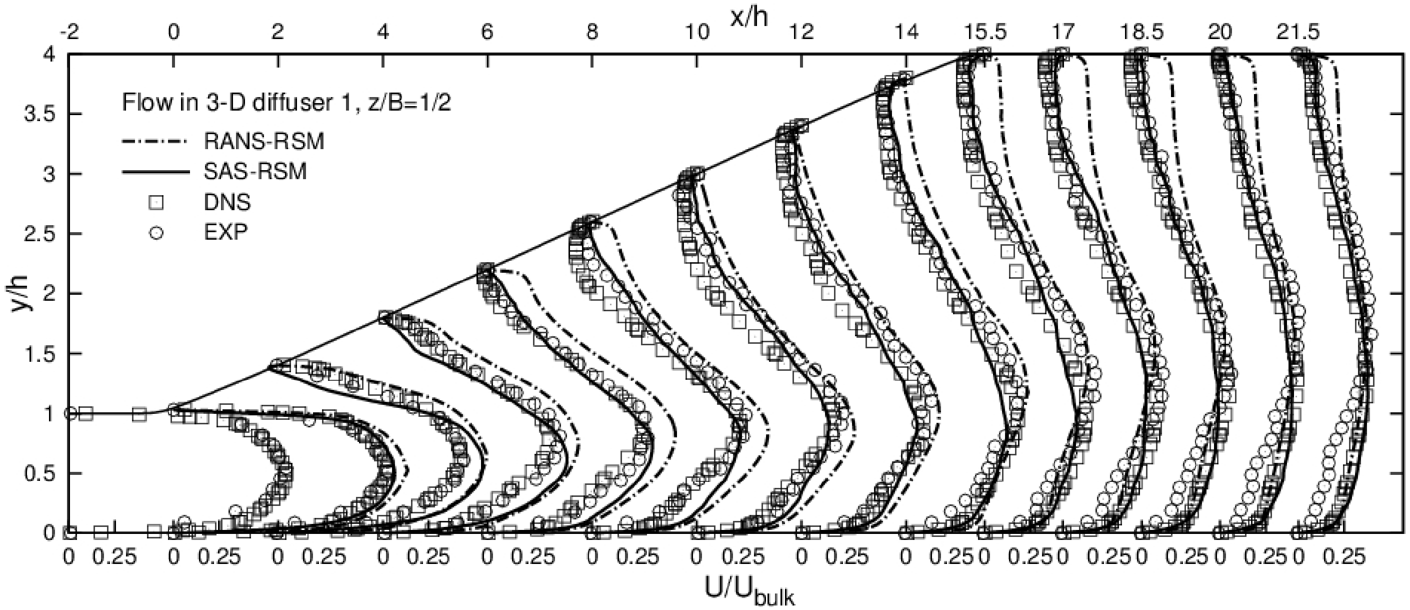
Instantaneous velocity field:

- Highly unsteady turbulent flow field captured by the IS-RSM
  - Inflow: inflow duct simulated – recycling method (Baba Ahmadi, Tabor; 2009) - simultaneously with the diffuser without imposing any initial fluctuations





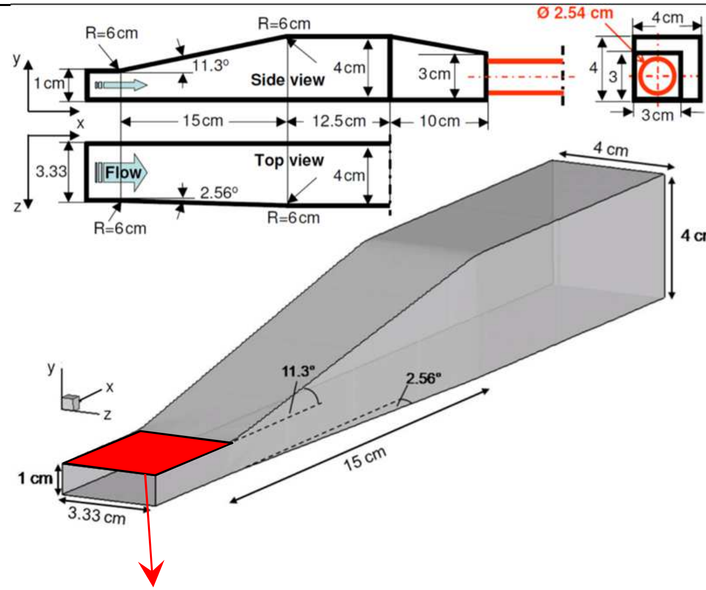
Baseline configuration:
Time-averaged velocity field



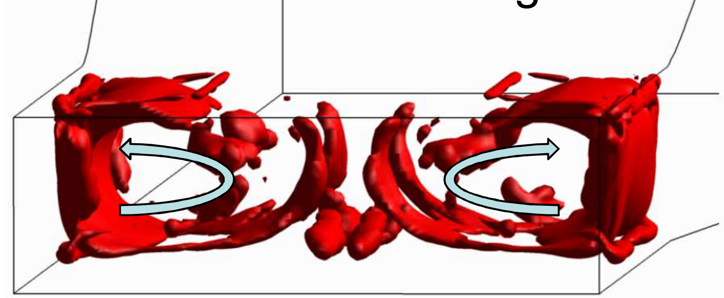
- **Good agreement between SAS-RSM and Exp. (flow behaviour with separation at upper wall has been properly captured); RANS-RSM shows large corner separation on upper-right corner**
- **Substantially better quantitative agreement between SAS-RSM and Exp. (large overestimation of velocity at z/B=0.5 obtained by RANS-RSM due to attached flow at upper wall)**

3D Diffuser: Discharge-Based Flow-Control:

- Asymetric 3D diffuser Re = 10000
  - Database 2 (present), Baseline + Actuated configs.:
    - Exp.: Grundmann *et al.* (2011): *Exp. Fluids* 50 (1):217-231
      - Time averaged velocity profiles (Pitot probe)
      - Pressure distribution (pressure taps)
- Streamwise-oriented arrangement of a Plasma-Actuator:
  - force directed towards the corners
  - increased momentum transport in the wall normal direction



➢ spanwise forcing (a pair of streamwise vortices is generated):



Q-criterion; quiescent air

Baseline vs. actuated configurations
flow reversal – separation zone: IS-RSM + PA

- Pulsed mode 40% DC

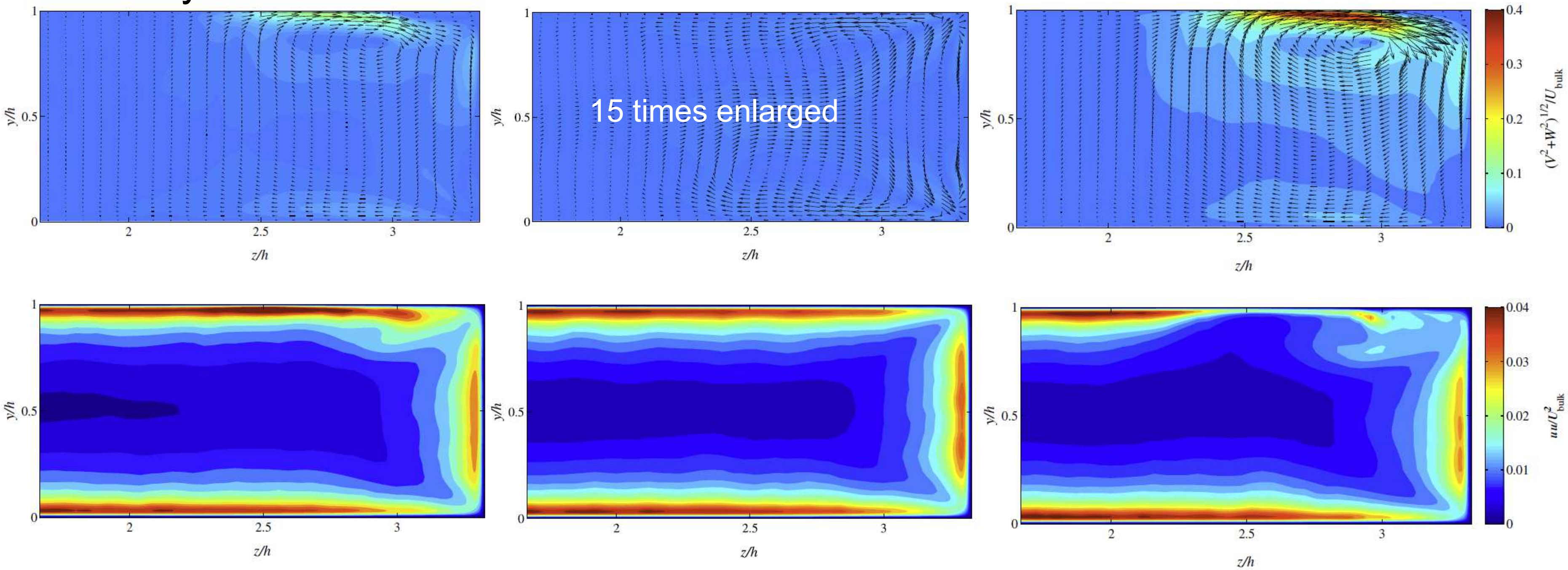
⇒ Enhancement of the momentum transfer towards corners (25%), correlated with turbulence activity intensification

- Baseline Case

⇒ Re-stress anisotropy induced secondary motion (2 % of the bulk flow intensity)

- Continuous mode 100% DC

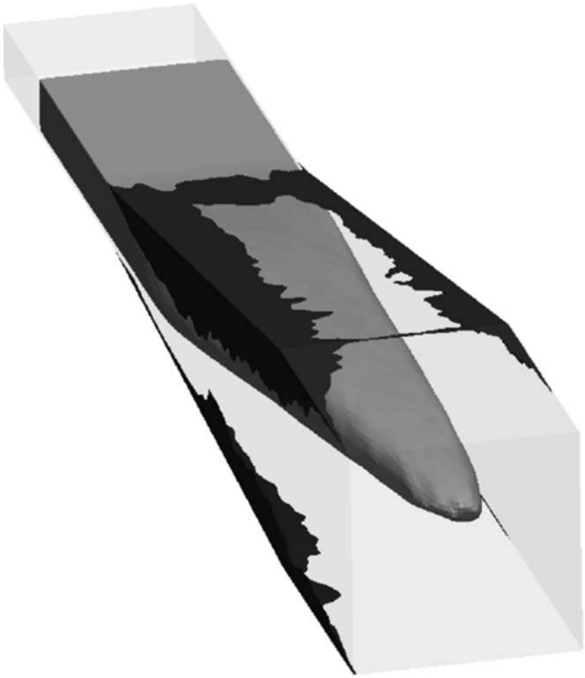
⇒ Strong continuous acceleration (40% of the bulk flow intensity) and turbulence activity weakening

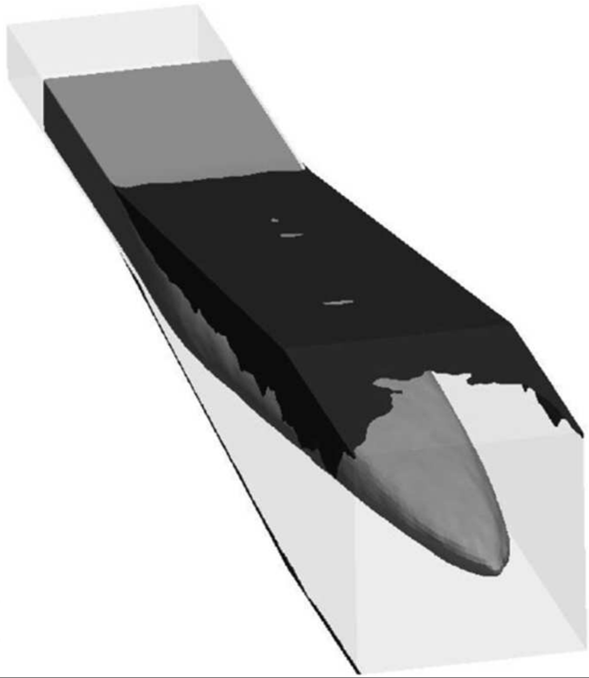


Baseline vs. actuated configurations
flow reversal – separation zone: IS-RSM + PA

Iso surfaces of axial velocity component:

- Pulsed mode 40% DC
  - ⇒ Size reduction of the recirculation bubble
- Baseline Case
  - ⇒ recirculation bubble occupies the entire upper wall
- Continuous mode 100% DC
  - ⇒ recirculation bubble occupies the entire deflected side





Baseline vs. actuated configurations
Surface (bottom wall) pressure distribution

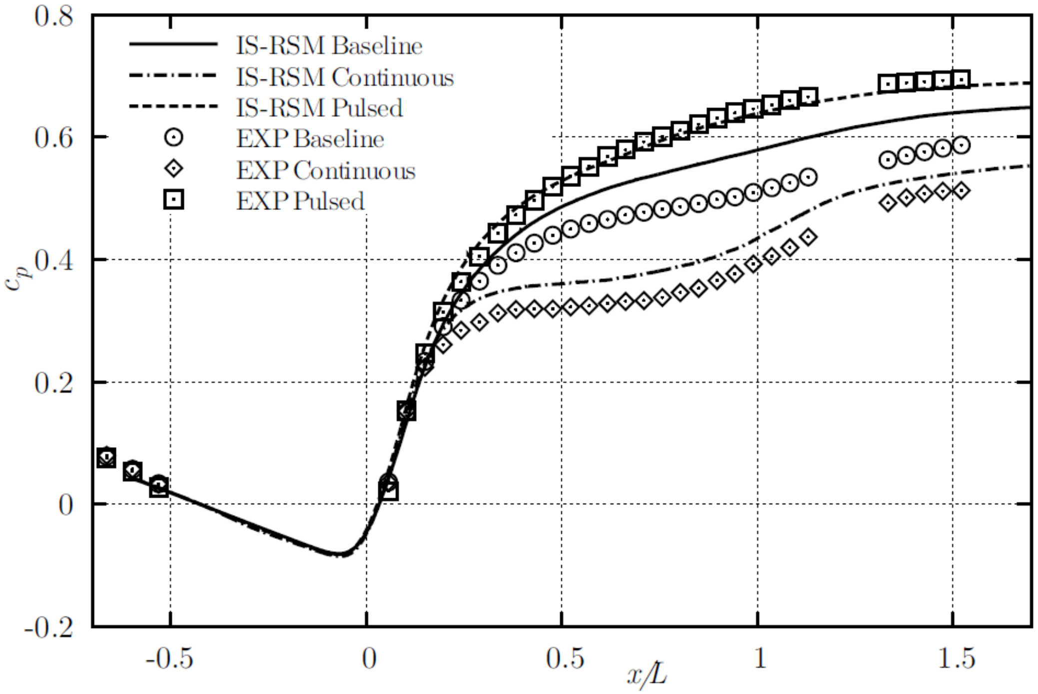
TECHNISCHE UNIVERSITÄT DARMSTADT

Pressure recovery coefficient along bottom wall:

- Actuated Configuration
  - Pulsed mode DC = 40%

    ⇒ increase pressure recovery
  - Continuous mode DC = 100%

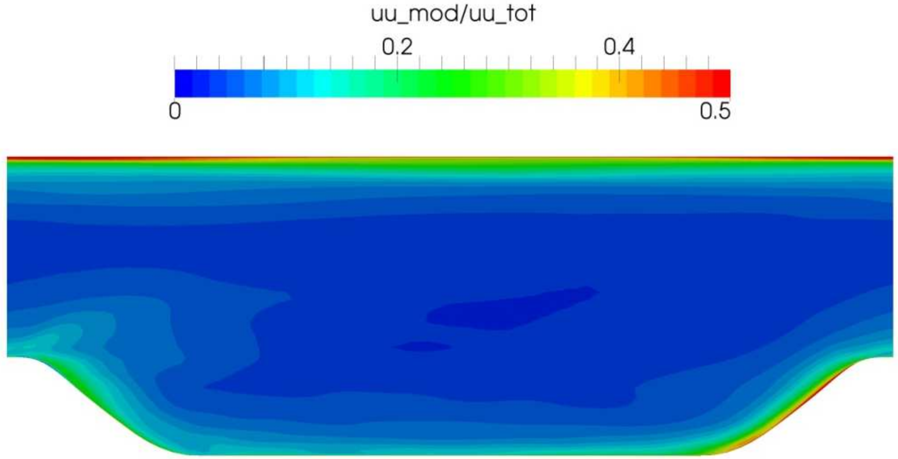
    ⇒ decrease pressure recovery
- **Both captured correctly by applying the IS-RSM Model**



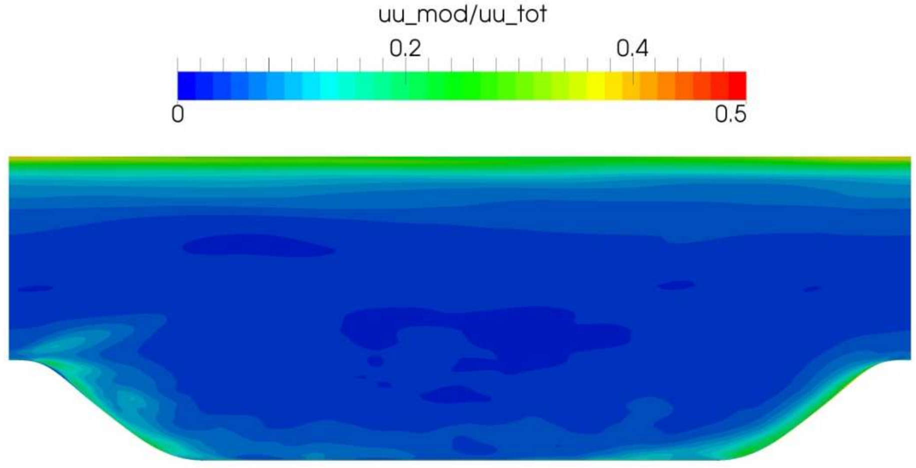
2D Hill, Re_H=10600, $\left(\overline{u^2}\right)_{modelled} / \left(\overline{u^2}\right)_{total}$:

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Coarse grid:**
  80 x100 x 30 = 240.000 cv

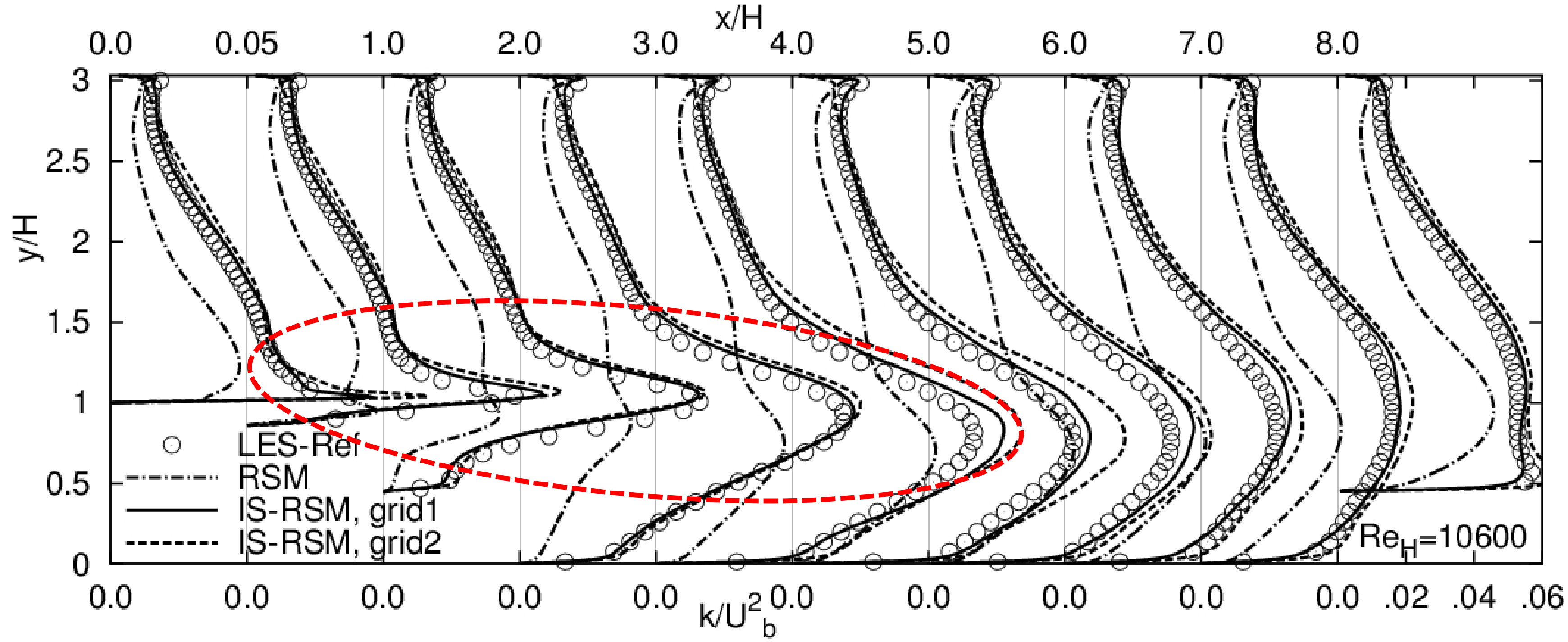


- **Fine grid:**
  160 x160 x 60 = 1.536.000 cv



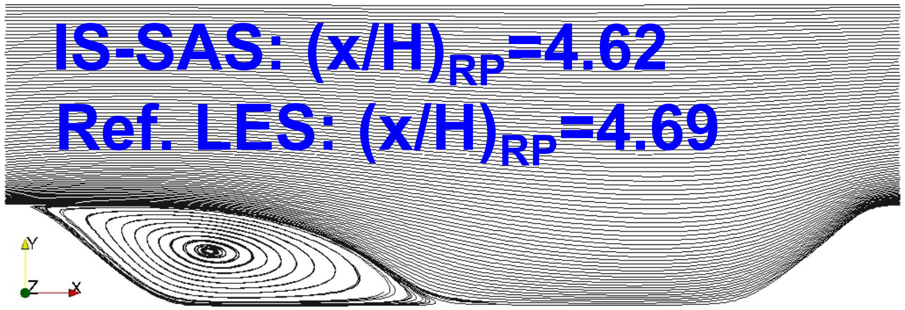
2D Hill, Re_H=10600, t.k.e. field:

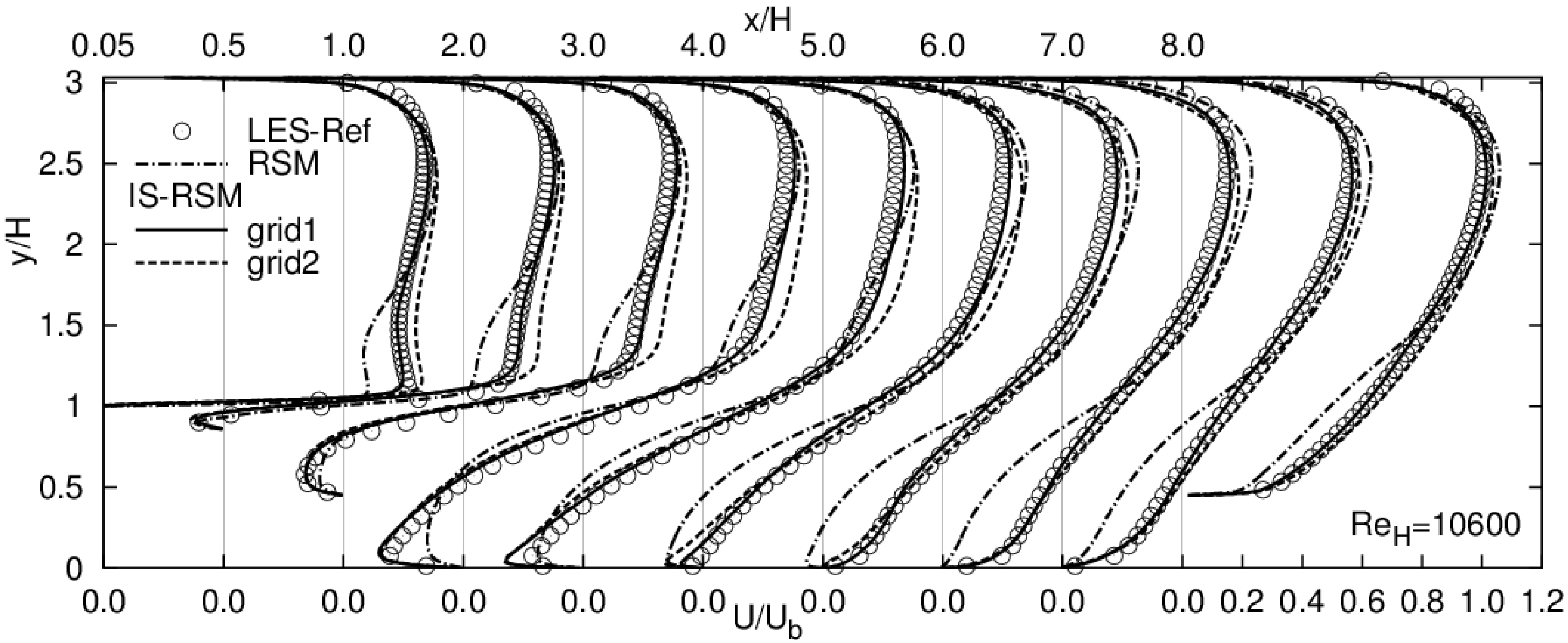
- **Coarse grid: 80 x100 x 30 = 240.000 cv**
- **Fine grid: 160 x160 x 60 = 1.536.000 cv**



2D Hill, Re_H=10600, Velocity field:

- **Coarse grid:**
  80 x100 x 30 = 240.000 cv
- **Fine grid:**
  160 x160 x 60 = 1.536.000 cv





SAS Term revisited, 1

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Origin of the SAS-term (Menter & Egorov, 2003-2010) is the exact kL-equation, with L representing the integral lengths scale:**

$$\frac{\mathrm{D}(kL)}{\mathrm{D}t} \Rightarrow \int_{-\infty}^{\infty} \frac{\partial U\left(\vec{x}+r_y\right)}{\partial y} R_{12} dr_y \rightarrow$$

$$\frac{\partial U\left(\vec{x}\right)}{\partial y} \int_{-\infty}^{\infty} R_{12} dr_y + \boxed{\frac{\partial^2 U\left(\vec{x}\right)}{\partial y^2} \int_{-\infty}^{\infty} R_{12} r_y dr_y} + \frac{1}{2} \frac{\partial^3 U\left(\vec{x}\right)}{\partial y^3} \int_{-\infty}^{\infty} R_{12} r_y^2 dr_y + \cdots$$

By adopting $R_{12} \propto \nu_t\, \partial U / \partial y$ **and** $\nu_t \propto L k^{1/2}$ with $L \propto k^{1/2}/\omega$

$$\rightarrow \quad \frac{\mathrm{D}(kL)}{\mathrm{D}t} \Rightarrow \frac{\partial^2 U\left(\vec{x}\right)}{\partial y^2} \int_{-\infty}^{\infty} R_{12} r_y dr_y \rightarrow R_{12} \frac{\partial^2 U\left(\vec{x}\right)}{\partial y^2} L^2 \propto \boxed{\left(k^{1/2} L^2\right) \kappa S^2 \left(\frac{L}{L_{vK}}\right)^n}$$

SAS Term revisited, 2

TECHNISCHE UNIVERSITÄT DARMSTADT

$$\frac{D\omega_{h,SAS}}{Dt} = \frac{D\omega_h}{Dt} + \underbrace{C_{RSM,1} \max\left(P^*_{SAS}, 0\right)}_{P_{SAS}} \qquad \nabla^2 U \left(\equiv U''\right) = \sqrt{\frac{\partial^2 U_i}{\partial x_j^2} \frac{\partial^2 U_i}{\partial x_j^2}}$$

$$P^*_{SAS} = \sqrt{k}\left|\nabla^2 U\right| - 3C_{RSM,2} k \max\left(\frac{\left(\nabla\omega_h\right)^2}{\omega_h^2}, \frac{\left(\nabla k\right)^2}{k^2}\right) \qquad \begin{aligned} C_{RSM,1} &= 0.087, \\ C_{RSM,2} &= 1.375 \end{aligned}$$

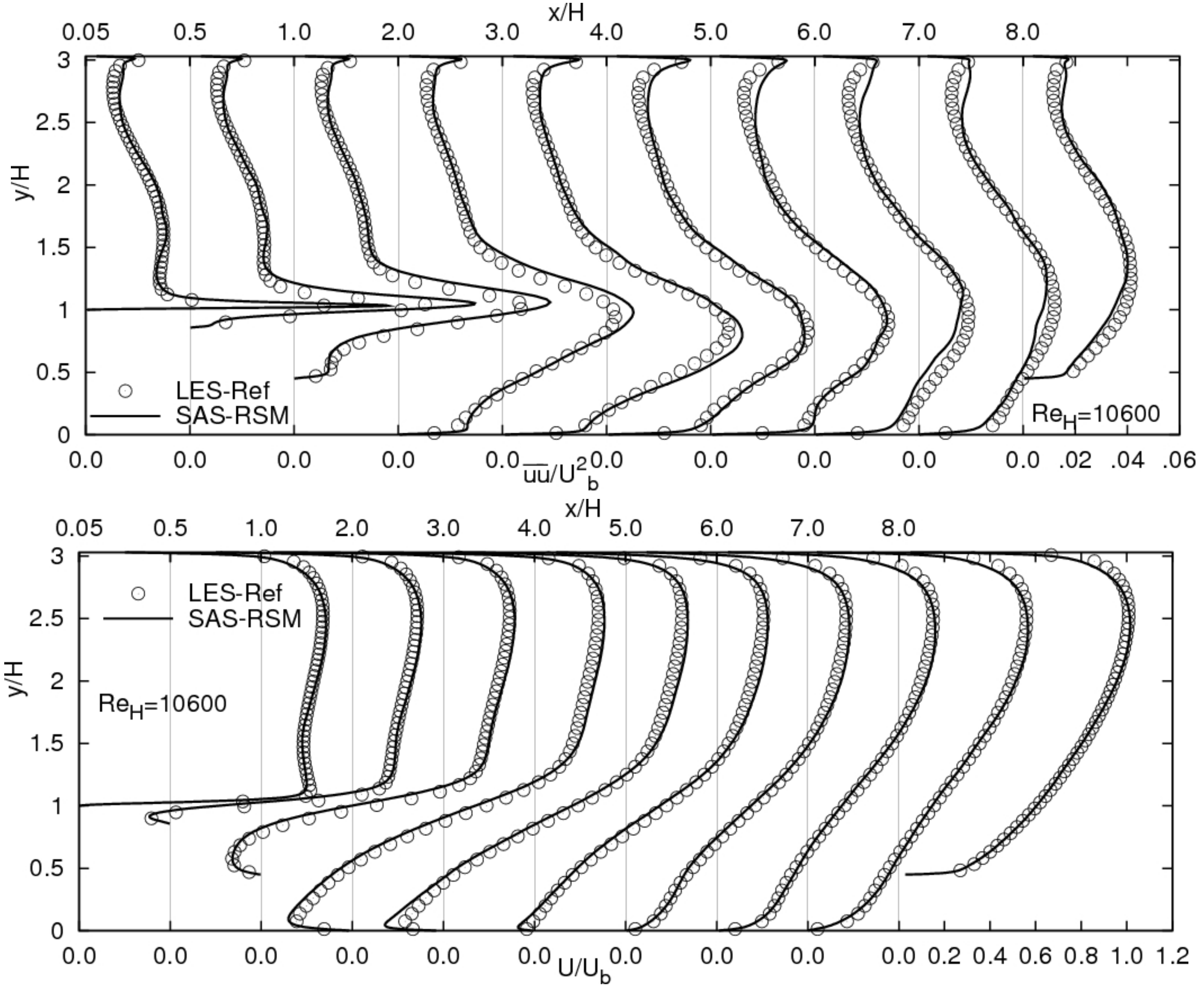
- **In addition, the model is made numerically more robust by blending the Reynolds-stress tensor entering the equation of motion:**

$$\overline{u_i u_j} = 0.7 * \underbrace{\overline{u_i u_j}_{\text{RSM}}}_{\text{explicit treatment}} + 0.3 * \underbrace{\overline{u_i u_j}_{\text{Boussinesq}}}_{\text{implicit treatment}} \Rightarrow \frac{2}{3}k\delta_{ij} - \nu_t\left(\frac{\partial \bar{U}_i}{\partial \bar{x}_j} + \frac{\partial \bar{U}_j}{\partial \bar{x}_i}\right)$$

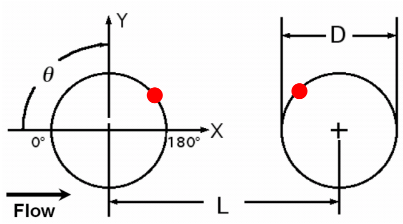
SAS Term revisited, 2d-hill (70000 cv's)

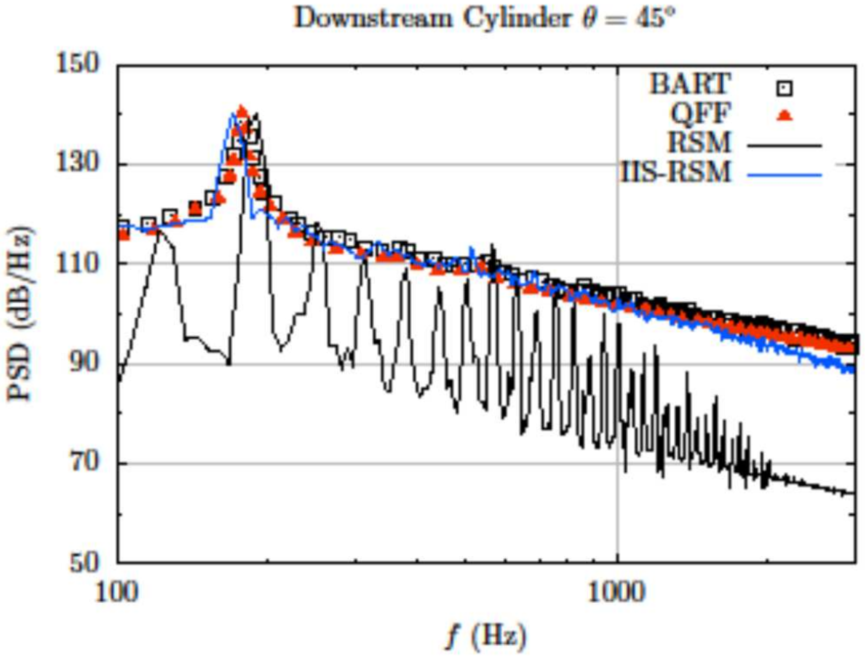
$$\frac{\overline{u^2}}{U^2{}_b}$$

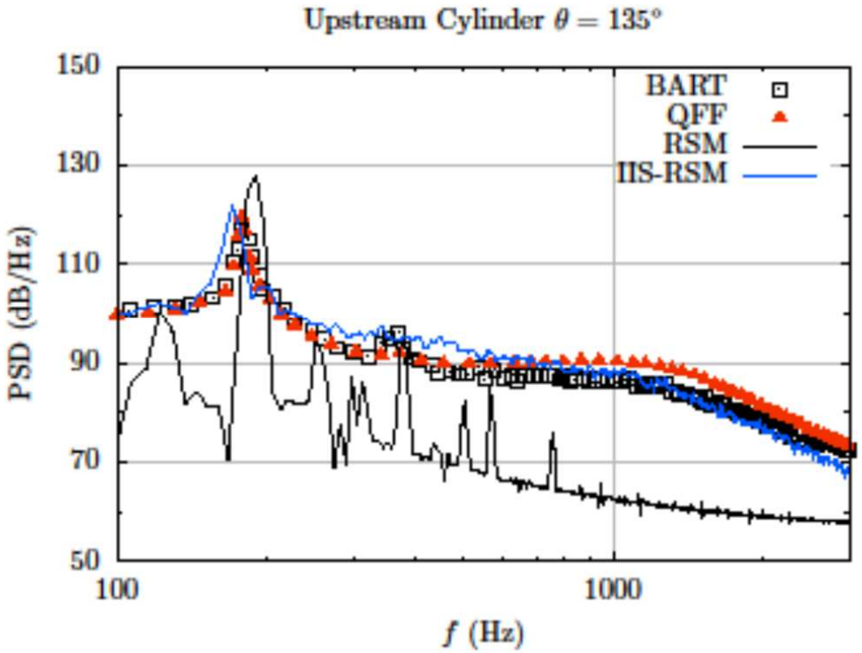
$$\frac{U}{U_b}$$



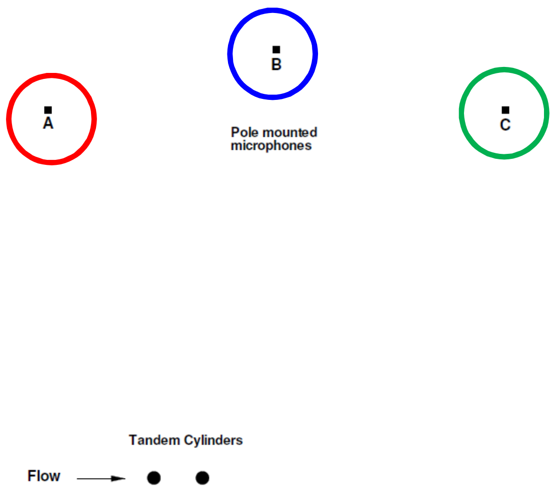
Tandem Cylinder: PSD surface pressure

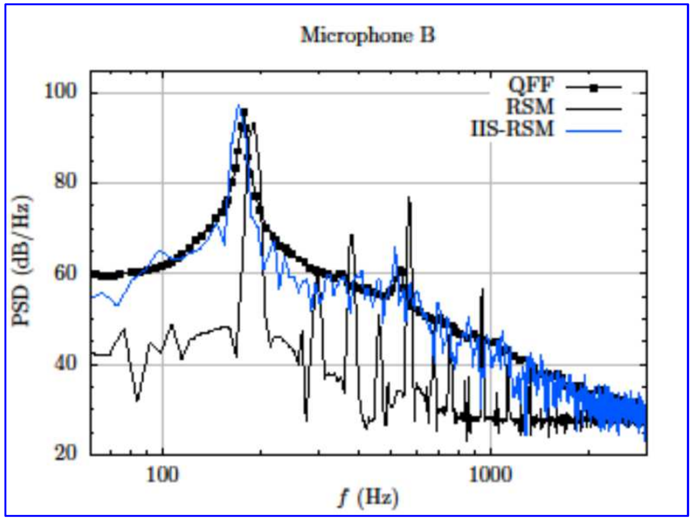


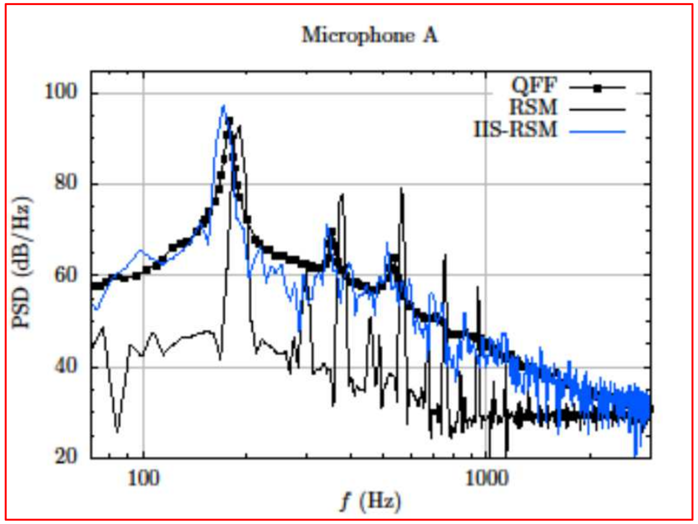


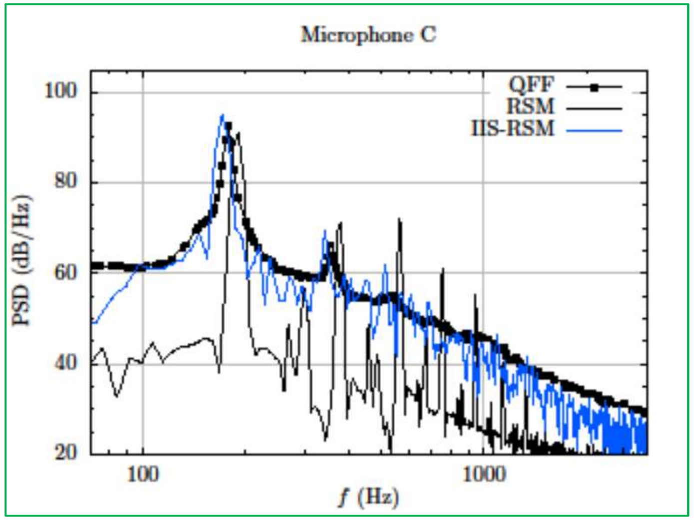


Tandem Cylinder: PSD sound pressure









Concluding remarks, IS-RSM, 1

TECHNISCHE UNIVERSITÄT DARMSTADT

- A „conventional“ , near-wall RANS-RSM model was extended in line with the SAS procedure resulting in an eddy-resolving turbulence model
- the enhancement of the ω_h production associated with the P_{SAS} term is, in line with the SAS proposal by Menter and Egorov (2010), particularly appropriate for highly unsteady separated shear layer regions.
- Herewith, an adequate suppression of the modelled turbulence intensity towards the corresponding sub-scale level is provided, enabling a turbulence activity intensification originating from the resolved motion
- It implies the model’s self-adaptation by balancing between the resolved and modelled (unresolved) contributions to the turbulence kinetic energy.

Concluding remarks, IS-RSM, 2

TECHNISCHE UNIVERSITÄT DARMSTADT

- All present computations have been performed by OpenFOAM Code; CDS scheme for diffusive transport; blended CDS(98%)/UDS(2%) scheme for convection; three-times level scheme for temporal discretization)
- In all periodic flows (channel, 2D hill) and bluff-body configurations (tandem cylinder) no initial fluctuations were imposed; the results of the steady RANS computations were applied as initial conditions.
- In the "finite-size" flow configurations (2D fence, 3D diffuser) a precursor simulations of fully-developed channel/duct flows have been performed using the same method (also here the results of the steady RANS computations were applied as initial conditions)
- In the meantime the model has ben formulated in conjunction with the equation governing the ε_h quantity

TECHNISCHE UNIVERSITÄT DARMSTADT

Thank you for your attention!

Questions?