Challenges for RANS Models in Turbomachinery Flows

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Turbulence Modeling Symposium

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Outline

- Motivation
  - Role of CFD in jet engine turbomachinery
- Some areas of particular interest for RANS model improvement
  - Flow separation
  - Endwall features – corner separation & clearance flows
  - Shock-boundary layer interaction
  - Thermal mixing
- Potential avenues for future advances

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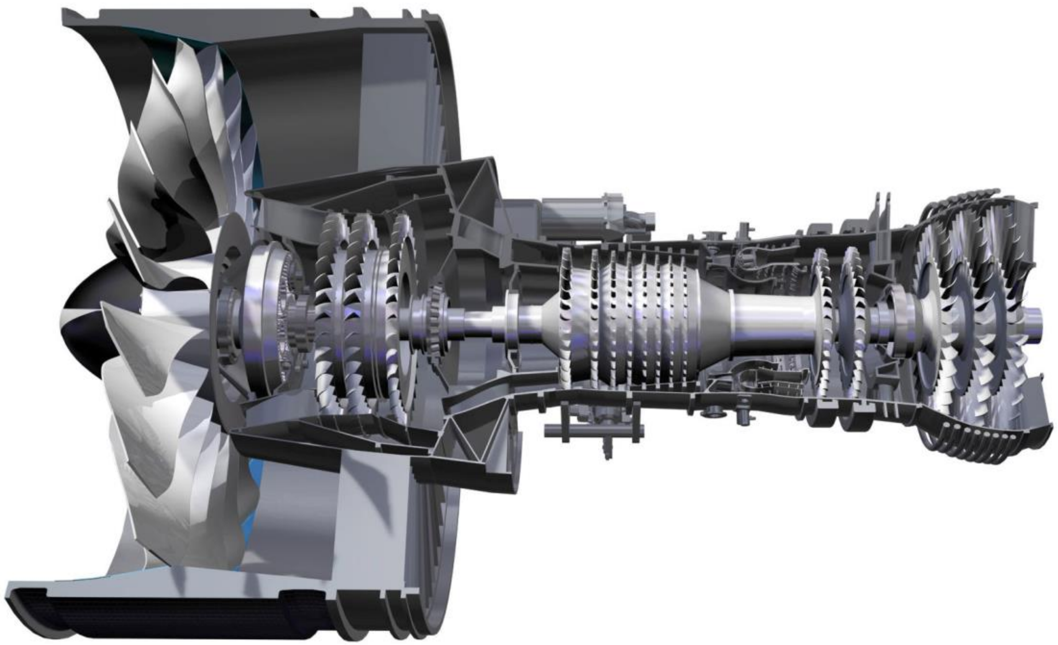
Motivation

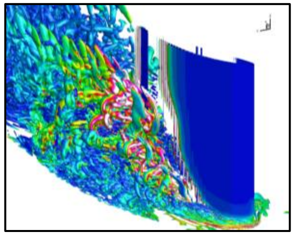
- Role of CFD in jet engine turbomachinery?



  - Becoming part of design-cycle; Prediction, not post-diction
  - Careful multi-row U-RANS represents state-of-the-art
  - Well-recognized limitations when it comes to transition, roughness, mixing, shock/BL, stress-anisotropy …

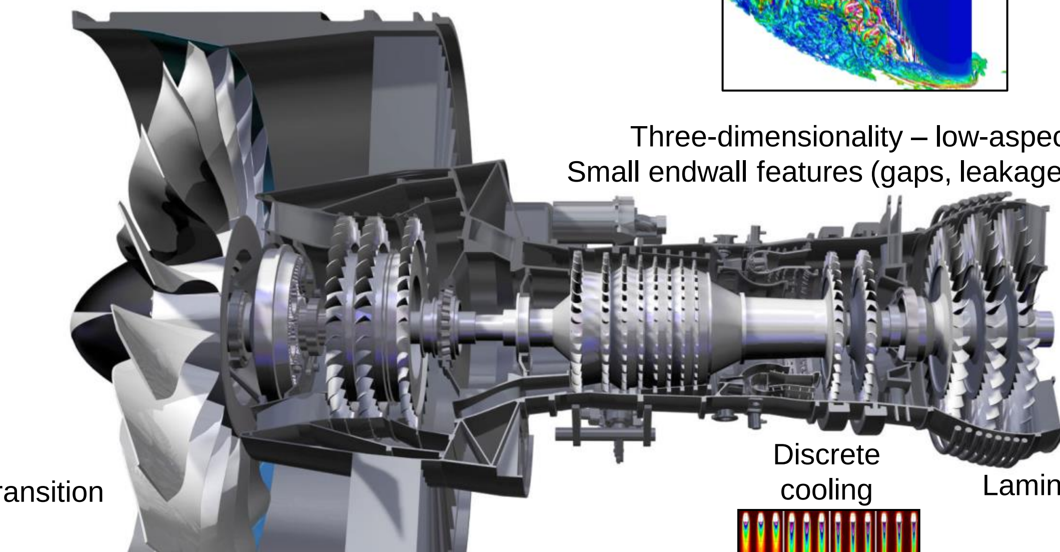
Motivation

- Complexities

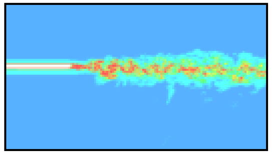


Three-dimensionality – low-aspect ratio
Small endwall features (gaps, leakages, vortices)

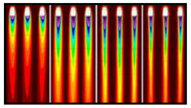
Laminar-to-turbulent transition



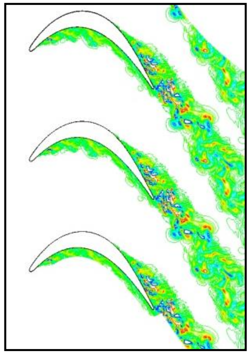
Exhaust
Mixing



Discrete
cooling

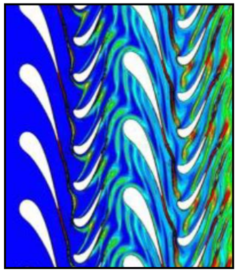


Laminar-to-turbulent transition



Intermittent disturbances

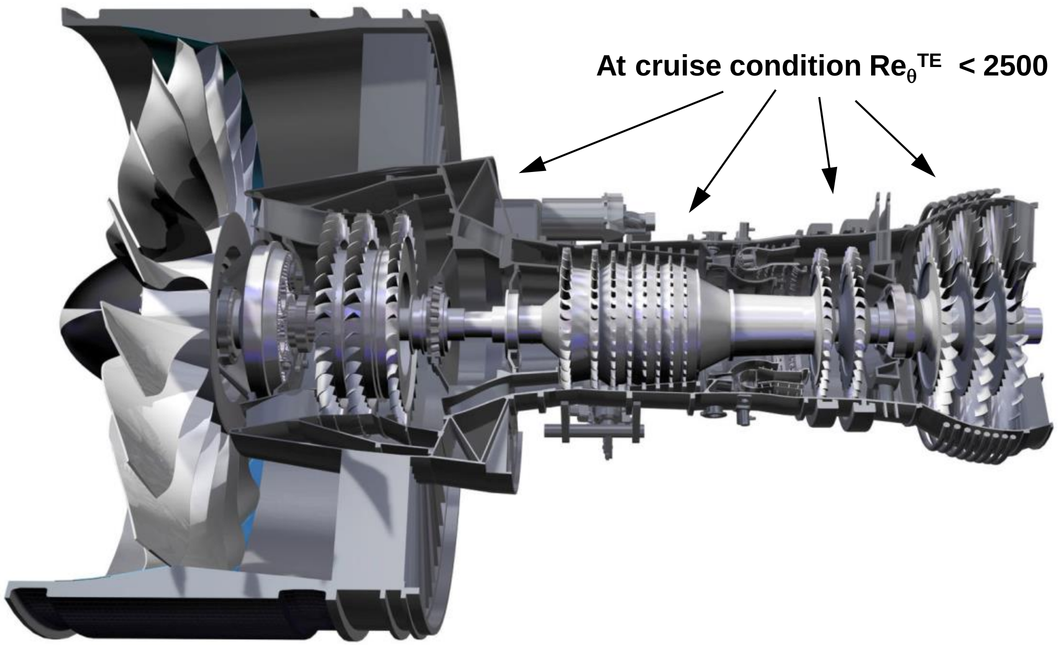
Inter-row interactions
need multi-row models



Roughness

Motivation

- Reynolds numbers lower than for external aero



- ➢ Allows brute-force wall-resolved LES of airfoils (<100K CPUhours)
- ➢ With endwalls, even for a single-row blade/vane, computational cost grows to millions of CPUhours
- ➢ Use high-fidelity CFD to advance hybrid methods & RANS models?

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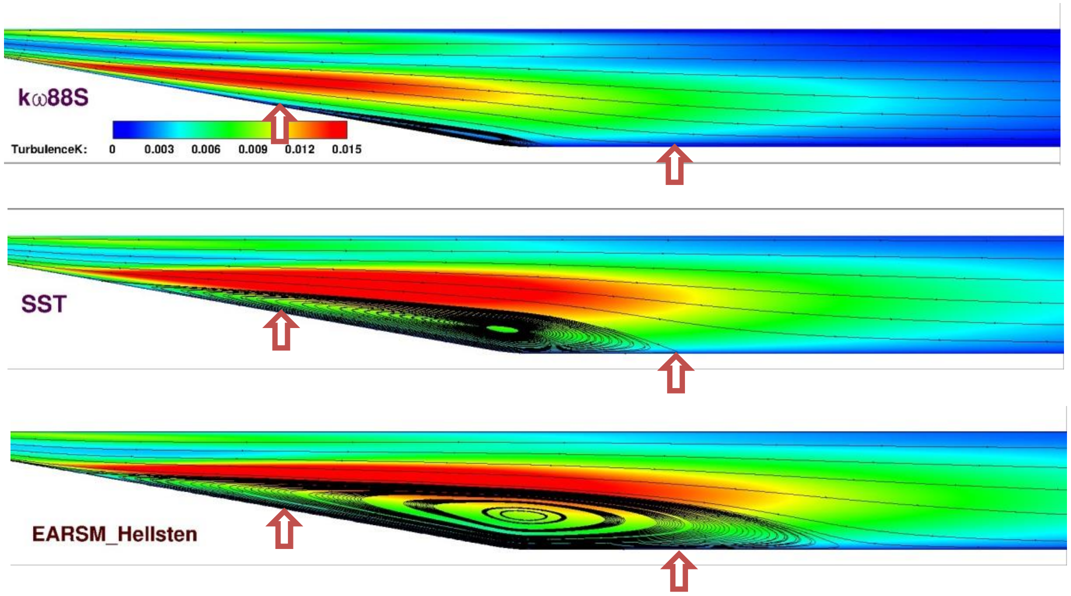
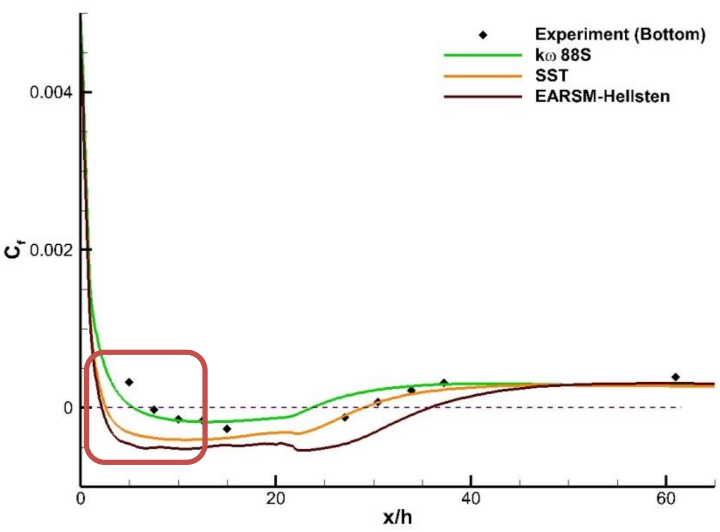
Flow separation

Separation onset – Buice diffuser

- In turbomachinery applications, designers avoid airfoil and endwall separation, however, at off design conditions, small pockets of separation start appearing
- Separation onset particularly hard to predict – strongly influenced by the state of the approaching boundary layer (transition, impact of pressure gradient)
- RANS models typically predict onset too early, even in well controlled conditions:

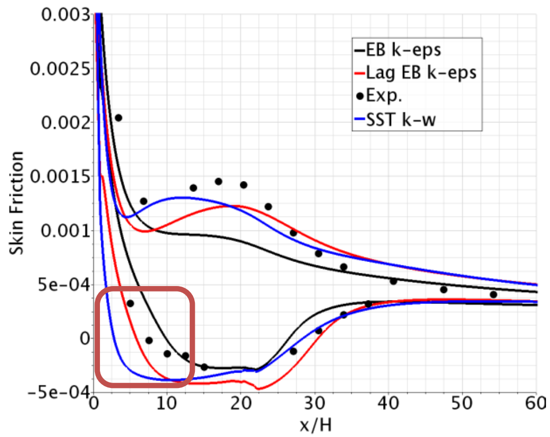




Flow separation

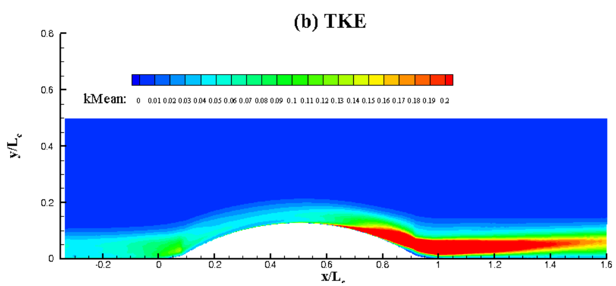
Separation onset – Buice diffuser

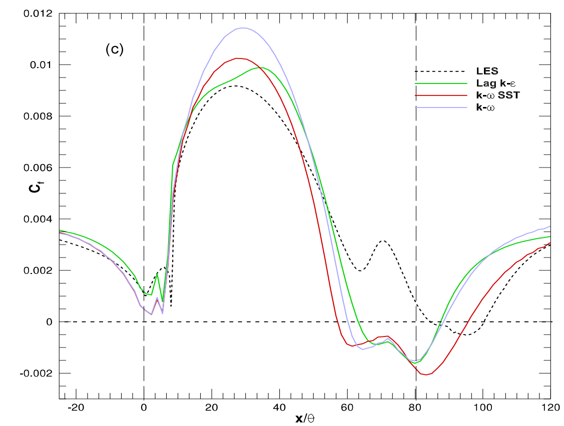
- Interesting new results that improve both separation onset and reattachment using elliptic blending lag model (k-ε-φ model) from UK; similar improvement for periodic hill and 2D-curved backward facing step – does this translate to airfoils/endwalls?



Sylvain Lardeau and Flavien Billard, Development of an elliptic-blending lag model for industrial applications, AIAA Paper AIAA-2016-1600.

- Recent study on LES and RANS for bumps of varying height by Prof. Durbin's team at Iowa State University:

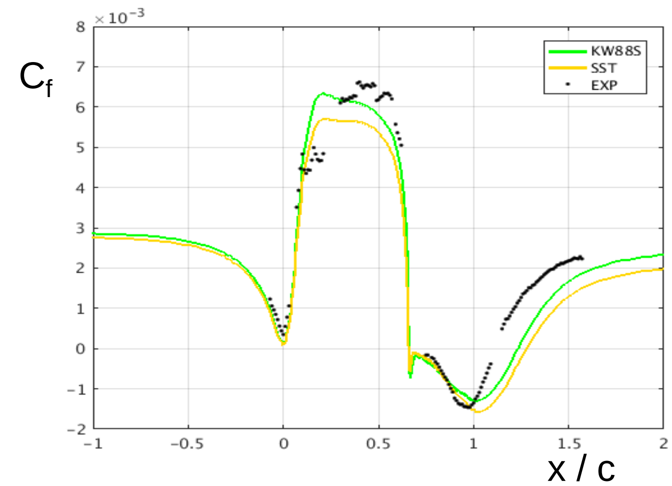


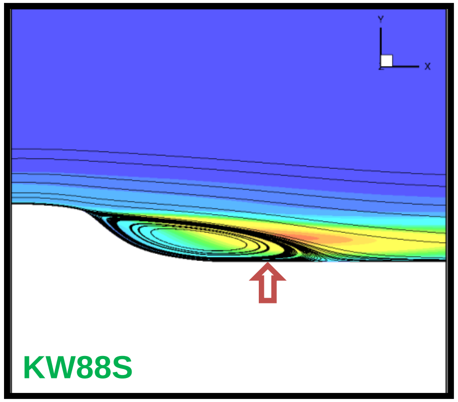


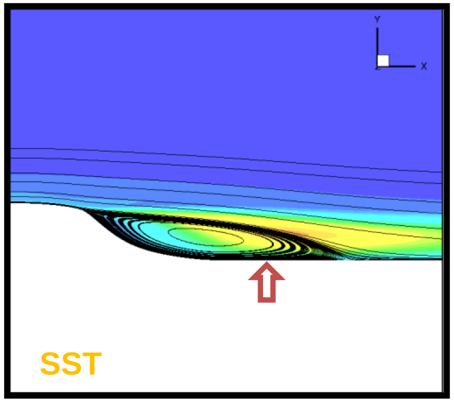
Flow separation

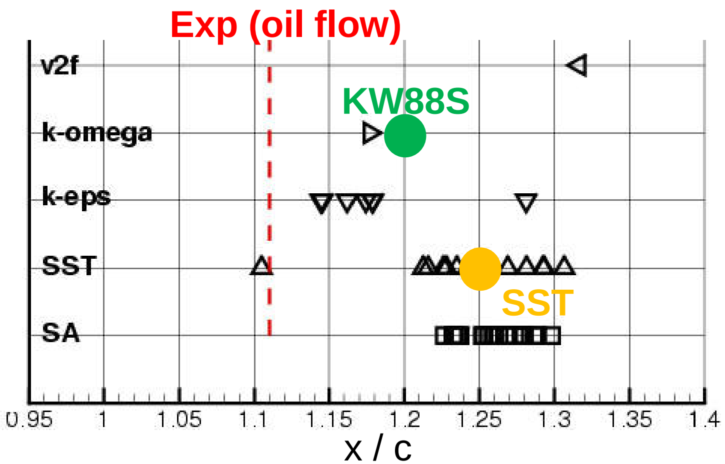
Reattachment – NASA hump

- With RANS, reattachment also usually delayed, and separation length over predicted by 20-30%
- Reports in literature on improved prediction of separation shear layer using hybrid RANS/LES (Shur, Spalart, Strelets & Travin, FTC, 2014)
  - Need to resolve/synthesize turbulent eddies in the oncoming boundary layer







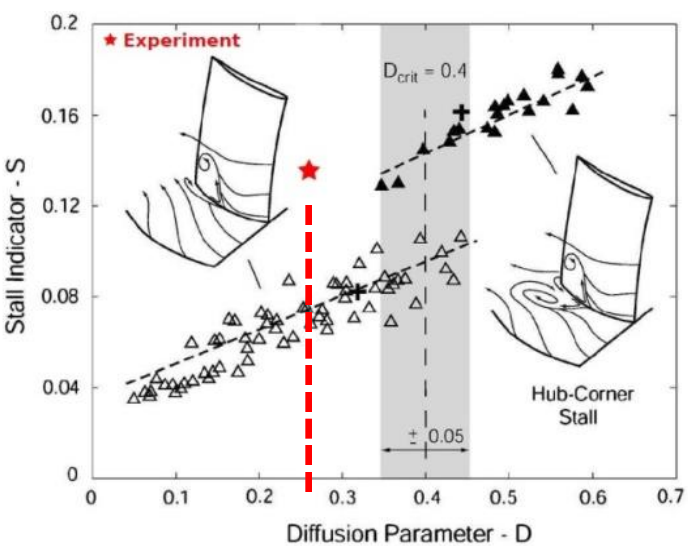


Endwall features

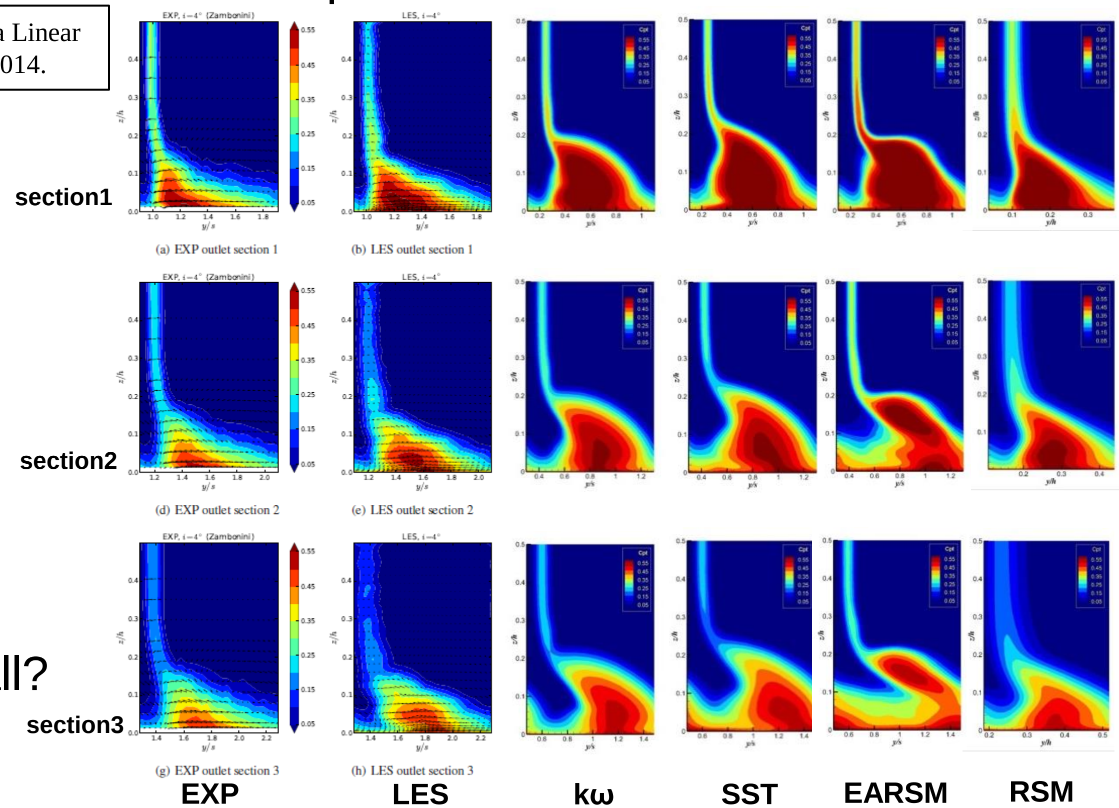
Ecole Centrale de Lyon compressor cascade

- RANS models tend to over-predict hub-corner stall events in axial compressors
- ECL team performed wall-resolved LES which matched the experimental data very well – is it really necessary to resolve all the boundary layers on endwall & airfoils?

Feng Gao, Advanced Numerical Simulation of Corner Separation in a Linear Compressor Cascade, PhD Thesis, Ecole Centrale de Lyon, France, 2014.



Total pressure loss coefficient downstream of TE

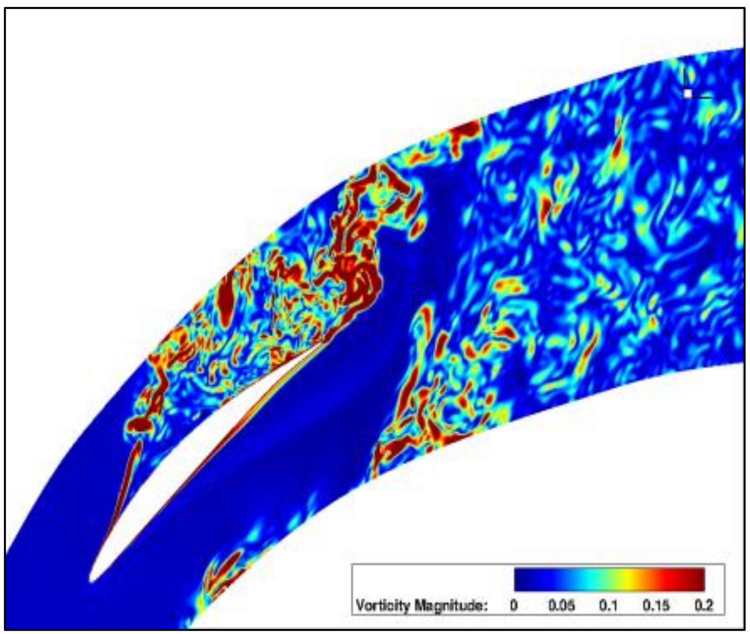


- Corner roll-up or hub-corner stall?

Endwall features

Ecole Centrale de Lyon compressor cascade

- Maybe resolving eddies in the corner separation region would help – try to apply hybrid RANS/LES!
- Results improved over RANS further downstream of TE, but not for section1



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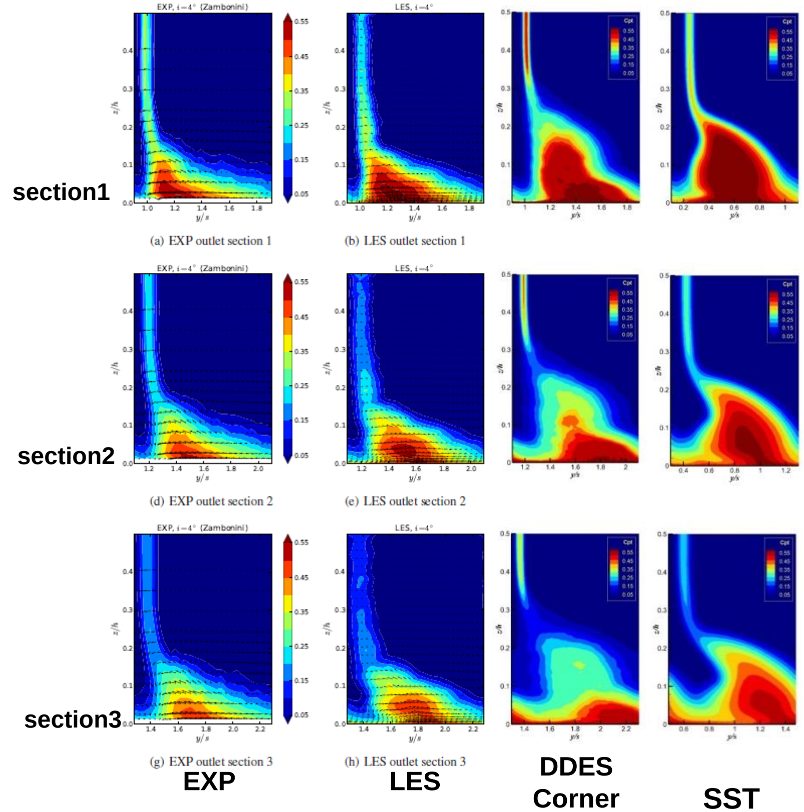
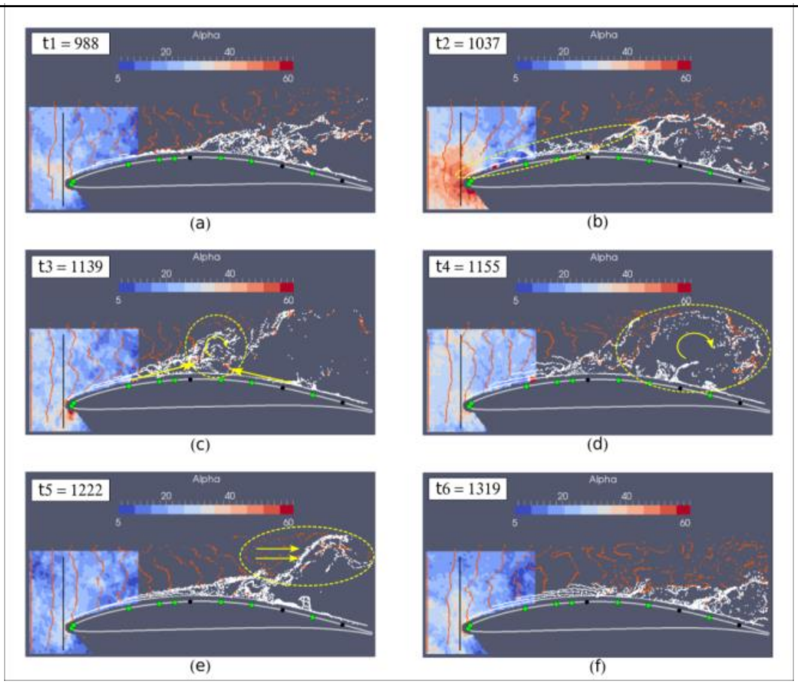


Endwall features

Ecole Centrale de Lyon compressor cascade

- Bi-modal nature of separation observed in experiments
- Horse-shoe vortex at LE also exhibits bi-modal behavior – how about resolving the horse-shoe vortex region in addition to the corner separation region?

Gherardo Zambonini, Xavier Ottavy, and Jochen Kreigseis, Corner Separation Dynamics in a Linear Compressor Cascade, ASME Paper GT2016-56454.



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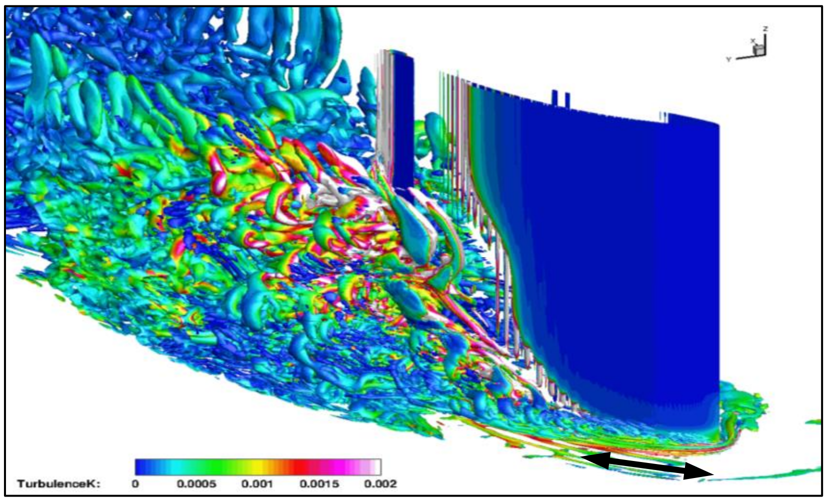
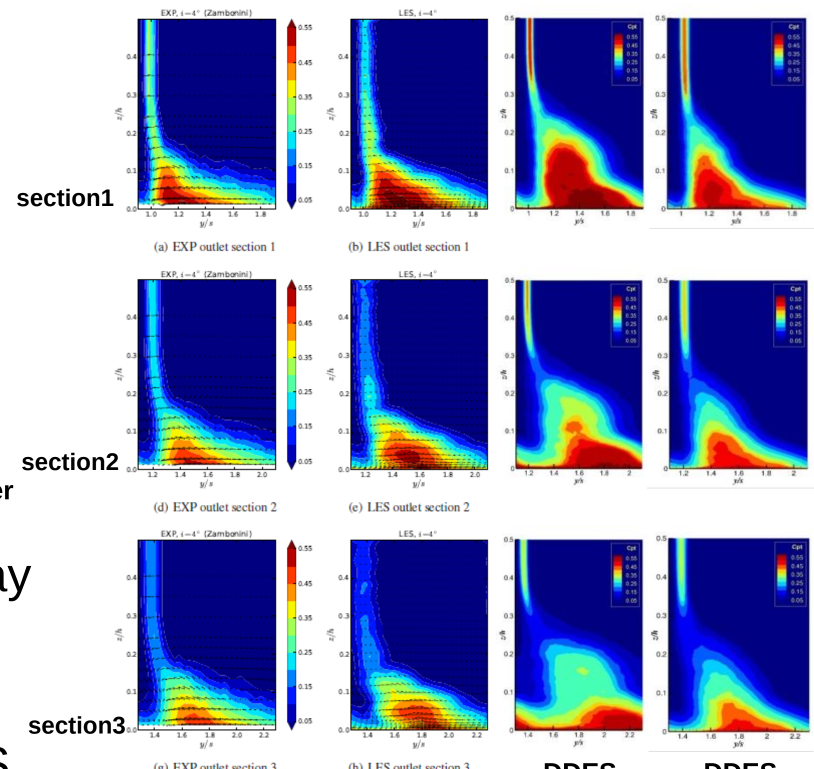


Horse-shoe vortex and corner separation “communicate”

Total pressure loss coefficient downstream of TE



- Targeted, embedded eddy-simulation may be sufficient to capture key physics at substantially lower cost (50-100X)
- 2017 INCITE project – wall-resolved LES

Endwall features – clearance vortex

Virginia Tech experiments (Devenport et al.)

- Compressor cascade with endgap; data for stationary and moving endwall
- Detailed velocity and turbulence measurements in the wake and clearance vortex – at multiple stations downstream of trailing edge

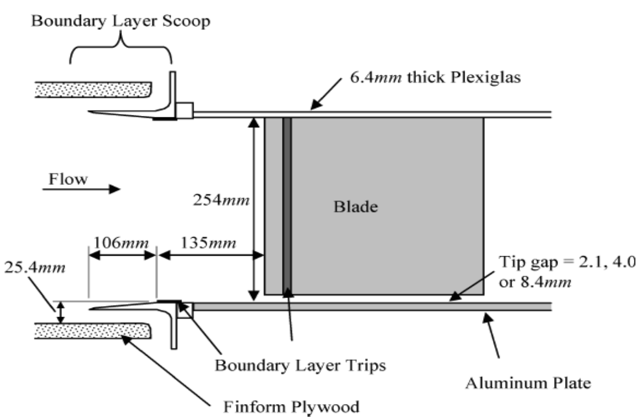
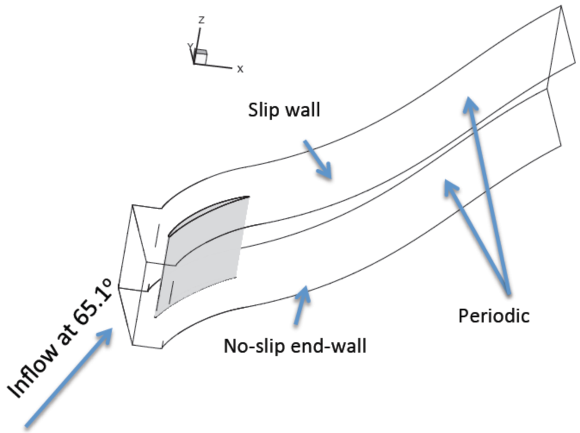


Fig. 2 Cross section through the cascade taken along the inlet flow direction.



GE rotor B cascade, stagger angle 56.9°

Tip gap size = 1.6% Chord

Chord-based freestream Re = $4 \cdot 10^5$

Turbulent inflow, with $Re_\theta = 780$

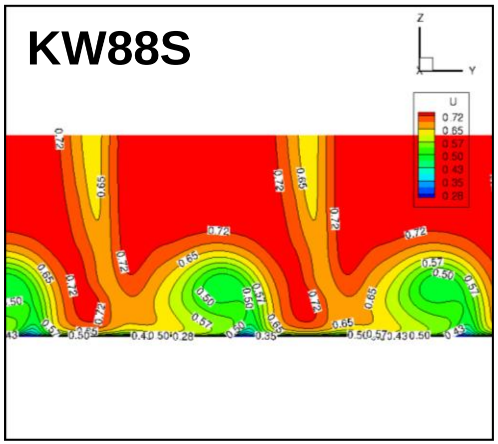
Endwall: Stationary

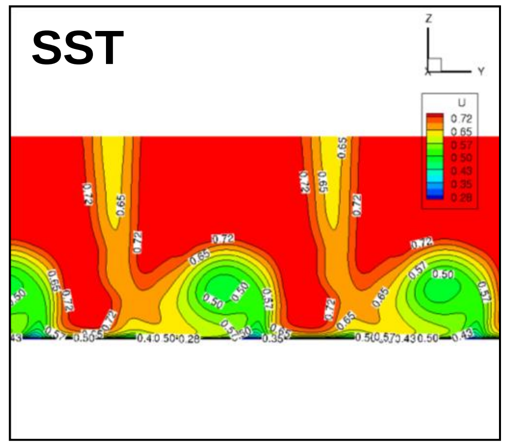
Endwall features – clearance vortex

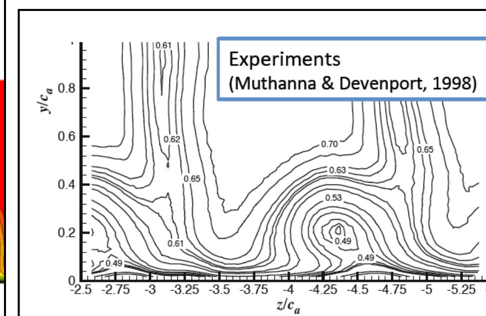
Virginia Tech experiments (Devenport et al.)

- Results indicate that RANS models are predicting trajectory of the vortex incorrectly, in particular for stationary endwall

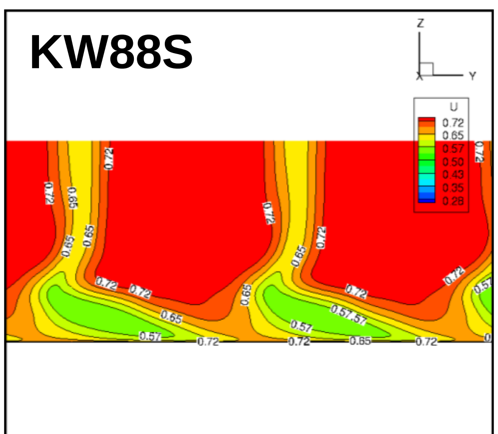
STATIONARY ENDWALL

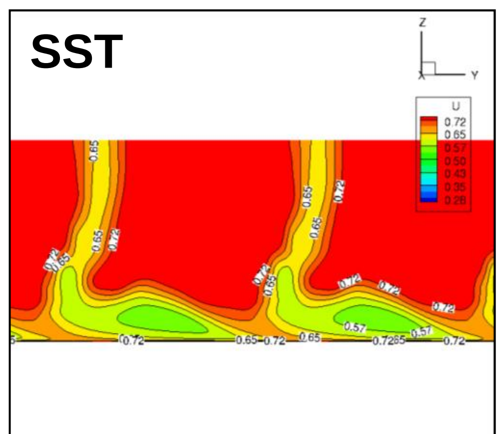


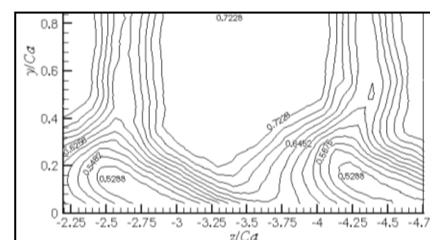




ROTATING ENDWALL



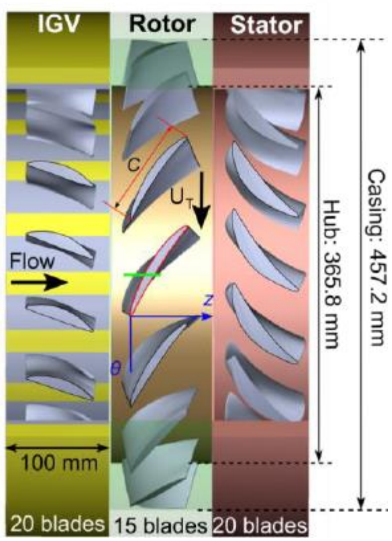




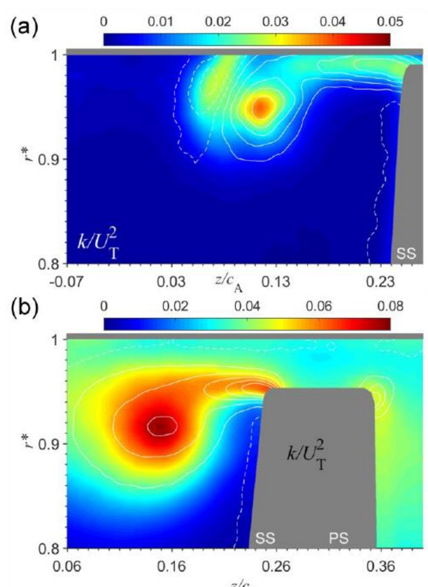
Endwall features – clearance vortex

Johns Hopkins University experiments (Katz et al.)

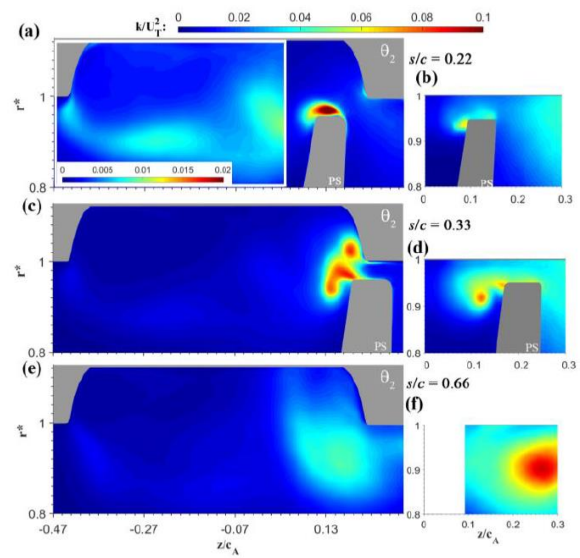
- One-and-a-half stage axial compressor, based on NASA LSAC; includes a configuration with casing treatment (axial, semi-circular, skewed grooves at LE)
- JHU refractive index-matching liquid facility allows for detailed measurement of flow in tip region where clearance vortex originates



Smooth Casing, varying clearance



Casing treatment, varying flow conditions



Yuanchao Li, Huang Chen, and Joseph Katz, Measurement and Characterization of Turbulence in the Tip Region of an Axial Compressor Rotor, ASME Paper GT2017-64114.

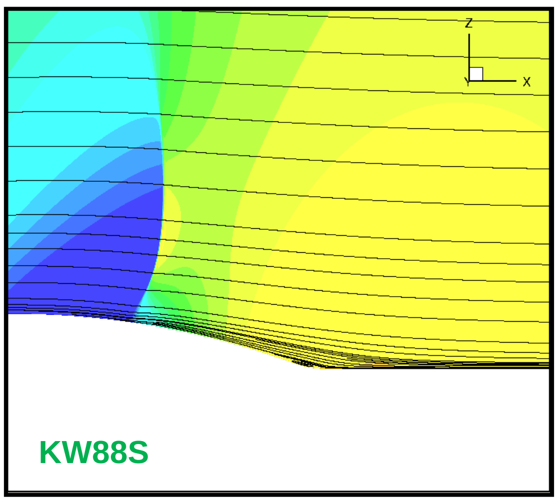
Huang Chen, Yuanchao Li, Subhra Koley, Nick Doeller, and Joseph Katz, An Experimental Study of Stall Suppression and Associated Changes to the Flow Structures in the Tip Region of an Axial Low-Speed Rotor by Axial Casing Grooves, ASME Paper GT2017-65099.

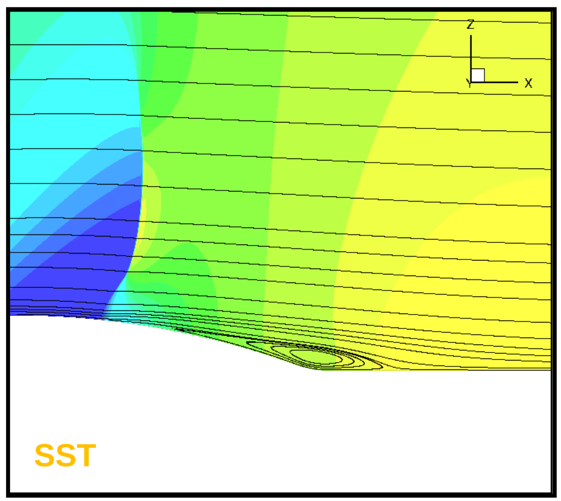
Shock-boundary layer interaction

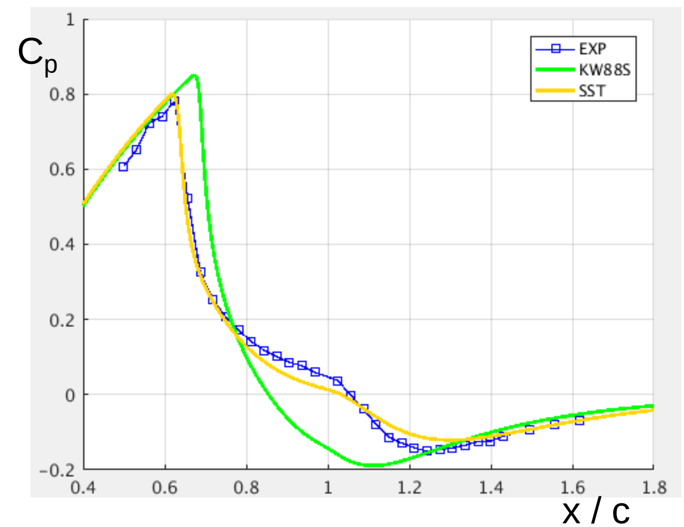
Bachalo-Johnson bump

- Shock-induced boundary layer separation represents another challenge for RANS models, even for hybrid RANS/LES (Spalart et al, ETMM-11, 2016)
  - Use DNS from ETMM-11 to inform RANS modeling, via Machine Learning?

- SST limiter calibrated to capture the separation for Bachalo-Johnson bump:







- However, in other cases SST too aggressive (e.g. 24º compression corner)

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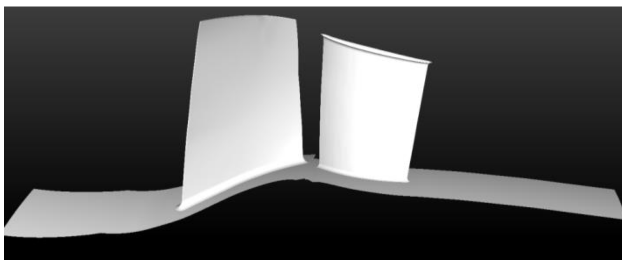
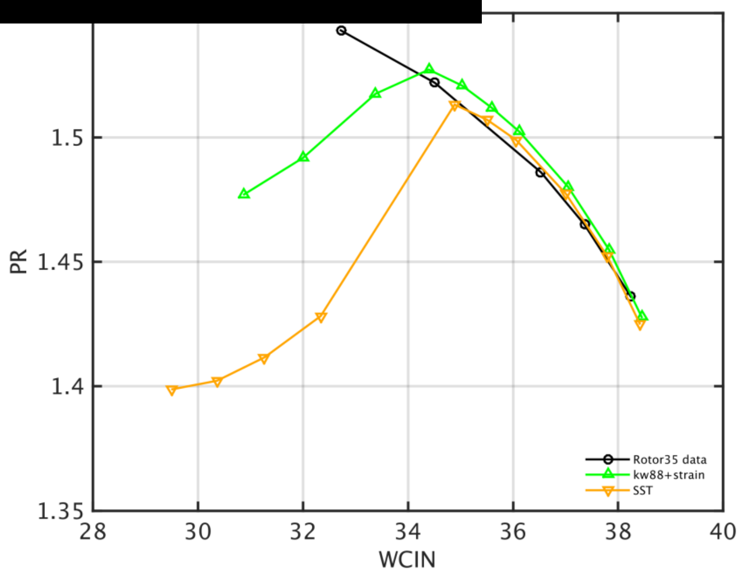
No technical data subject to the EAR or the ITAR.

Shock-boundary layer interaction

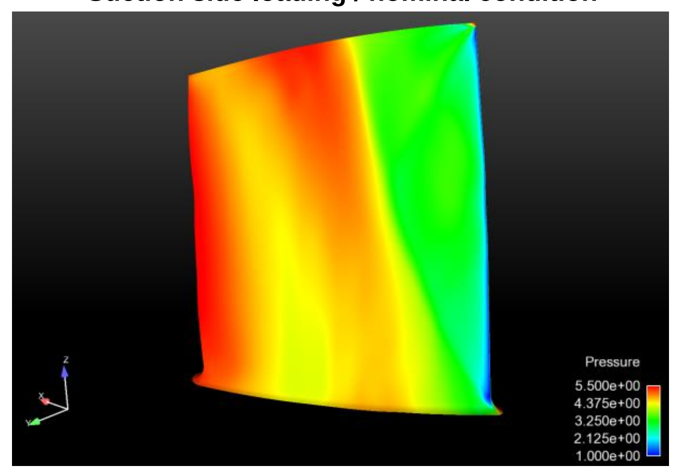
NASA Stage 35-37

- At off-design conditions, SST limiter designed to capture shock-induced boundary layer separation starts causing flow to separate elsewhere leading to an early roll-over of the stage characteristic



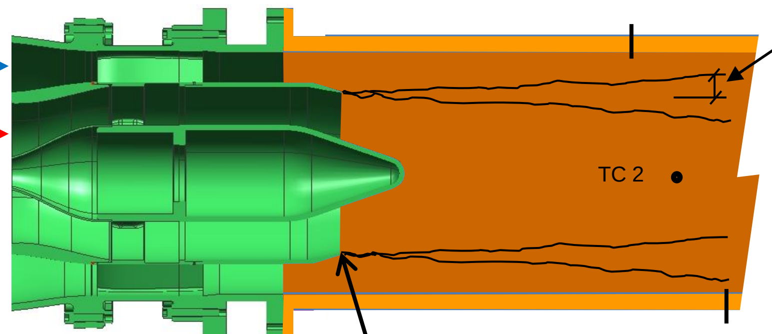


Suction side loading / nominal condition

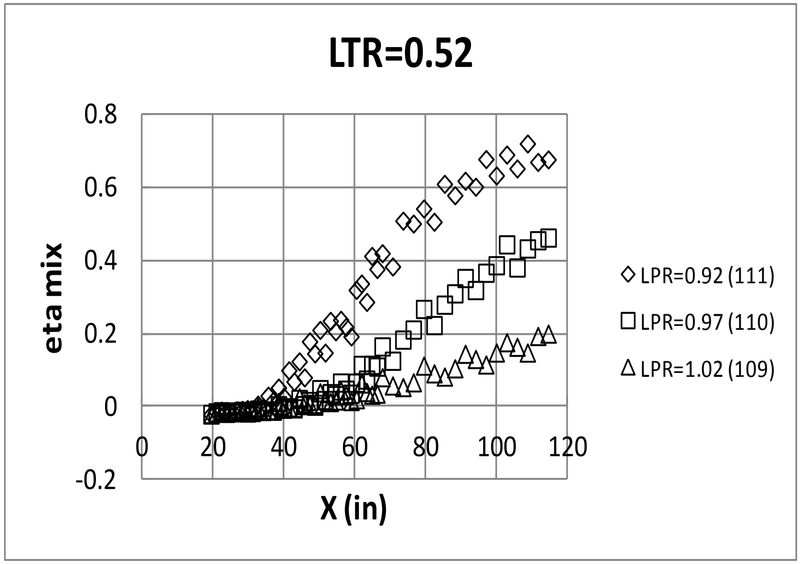


Thermal mixing

Co-annular duct experiment (NASA, 2012)



Robert H. Bush, Harry C. M. Culver, Dave Weissbein and Nicholas J. Georgiadis, Low Velocity Difference Thermal Shear Layer Mixing Rate Measurements, AIAA Paper AIAA-2013-1074.



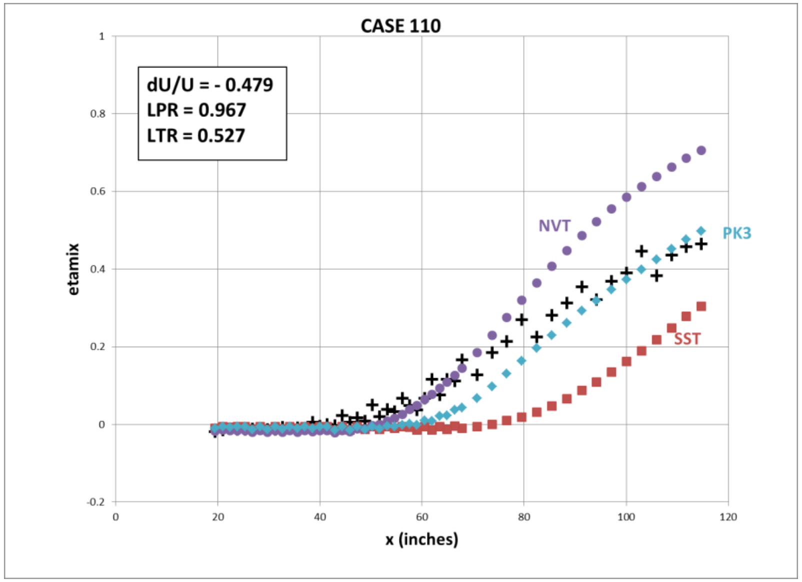
$$\eta_{mix} = \frac{T - T_{bypass}}{T_{mix} - T_{bypass}} \quad T_{mix} = \frac{W_{core}\,T_{core} + W_{bypass}\,T_{bypass}}{W_{core} + W_{bypass}}$$

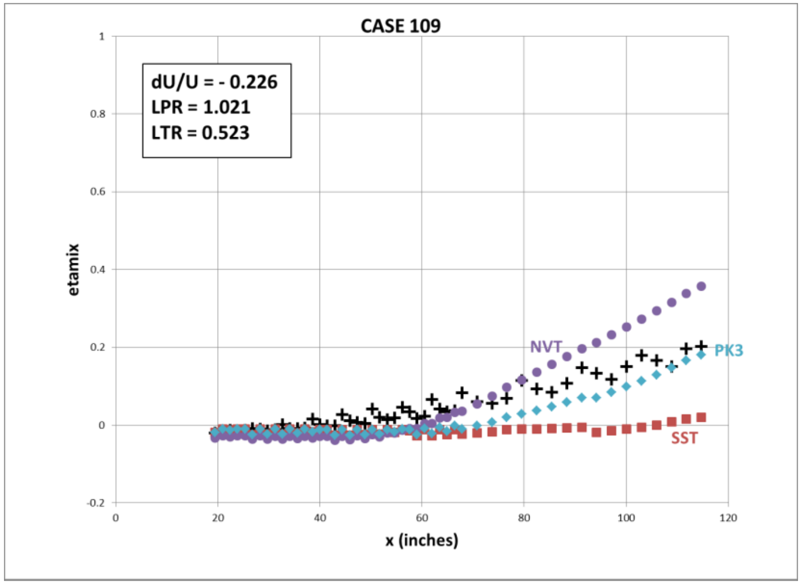
- Testing conducted at the NASA AAPL Hot Flow Jet Exhaust Rig
- Data taken for 26 conditions over a large range of shear layer conditions
  - Temperature ratios (LTR) of 0.31 to 0.7
  - Total pressure ratios (LPR) of 0.92 to 1.05
  - Velocity difference (dU/U) of 0.0 to 1.0

Thermal mixing

Co-annular duct experiment (NASA, 2012)

- RANS models tend to under predict the mixing and outer wall temperatures (η_{mix}):





- PK3 model – a density-gradient based term is added to production term P_k in the k-epsilon region of SST model:

$$P_k = 2\,\mu_t\,S_{ij}\,S_{ij} + \mu_t \left| \frac{\nabla \rho}{\rho} \times u \right|^2$$

Robert H. Bush, Turbulence Model Extension for Low Speed Thermal Shear Layers, AIAA Paper AIAA 2014-2086.

- NVT model: PK3 model + reduction in Pr_T to 0.5 in k-epsilon region of SST model

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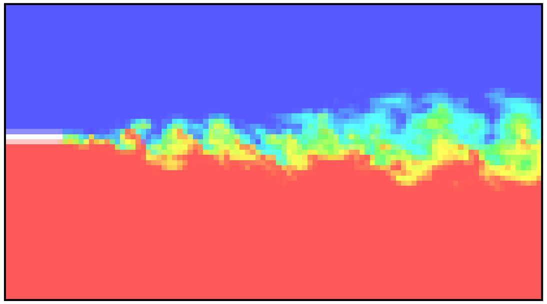
Thermal mixing

Co-annular duct experiment (UTRC, 2017)

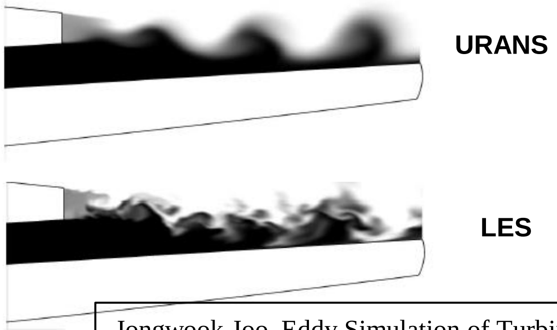
- New experiments and high-fidelity LES computations at UTRC in 2016/2017
  - Temperature (and turbulence?) profiles at multiple axial stations
  - Aiming to separate the contribution from changes to turbulent kinetic energy and turbulent heat flux

- Use LES to guide RANS model corrections:
  - LES predicts much more rapid mixing just downstream of splitter trailing edge via 3D vortical structures
  - Reminiscent of pressure side trailing edge slot cooling

Exhaust mixing



Trailing edge cooling



Jongwook Joo, Eddy Simulation of Turbine Trailing Edge Cooling, PhD Thesis, Stanford University, 2008.

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Potential avenues for future advances

- Machine learning for RANS model improvement
  - Data extraction combined with phenomenological modeling (Prof. Durbin's group)
  - If capturing unsteadiness / large (3D) turbulent structures matters, can RANS overcome that?

- Hybrid RANS/LES modeling
  - Where does it offer an advantage in turbomachinery flows?

- LES with wall-models to reduce cost
  - Challenge: boundary layer development a critical feature in turbomachinery!

Potential avenues for future advances

- RANS model improvement focus:
  - Transition modeling and suppression of turbulence (re-laminarization) in accelerating boundary layers
  - Roughness induced boundary layer thickening and separation
  - Systematic prediction of impact of shock-boundary layer interactions on the state of boundary layer
  - Additional terms in the k equation for compressible flows with large variations in density
  - Turbulent heat flux model – beyond GGDH with eddy-viscosity models?