Enhanced Prediction Techniques Based on Time-Accurate Simulations for Turbine Blade Internal Cooling

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SCIES Project 02- 01- SR100

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

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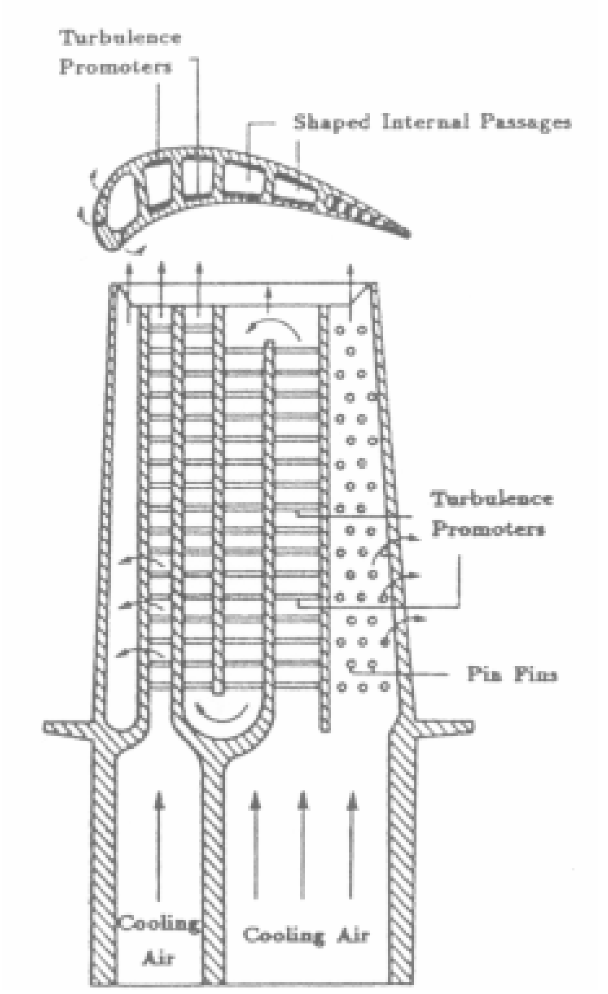
Project Awarded (5/1/02, 36 Month Duration)

$ 331,430 Total Contract Value ($331,430 DOE)

Gas Turbine Need

- **Need for higher thermal efficiencies result in higher gas temperatures**
- **Cooling technologies critical for increased durability**
- **Reliable prediction tools for design – reduce costs**



Project Objectives

- **Develop reliable prediction tools for internal heat transfer in turbine blades.**
  - **Heat transfer in rotating blades is difficult to measure experimentally.**
  - **Numerical or computer simulations are very cost-effective and attractive.**
  - **Increase the reliability and repeatability of computer simulations by using novel techniques based on time-accurate methods.**

Approach

Large-Eddy Simulations

Fully-developed regime

- Stationary ribbed duct
- Rotating ribbed duct with Coriolis Forces
- Rotating ribbed duct with Coriolis forces and centrifugal buoyancy

Developing Flow regime

- Stationary ribbed duct
- Rotating ribbed duct with Coriolis forces
- Rotating ribbed duct with Coriolis and centrifugal buoyancy

U-bend

- Stationary U-bend
- Rotating U-bend with Coriolis forces
- Rotating U-bend with Coriolis and centrifugal buoyancy

Detached-Eddy Simulations

- Implement RANS models under DES framework
- Test models at different mesh resolution and evaluate accuracy against LES and experiments.
  - Stationary duct
  - Rotating duct with Coriolis forces
  - Rotating duct with Coriolis and centrifugal buoyancy
- Two-Pass duct

Experiments

Velocity and turbulence measurements in developing, fully-developed, and 180 bend.

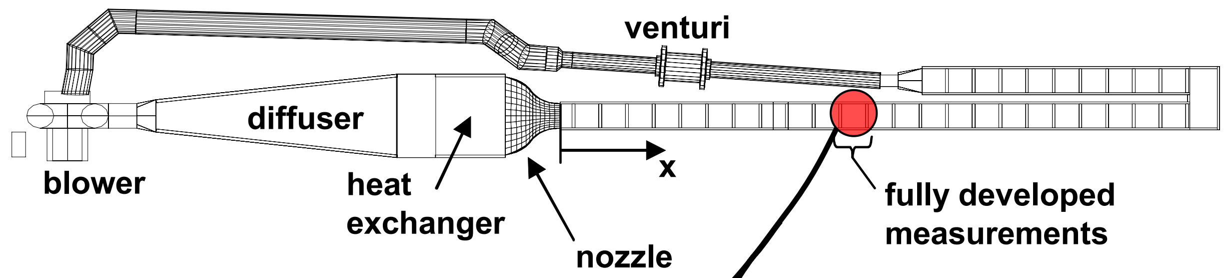
Accomplishments

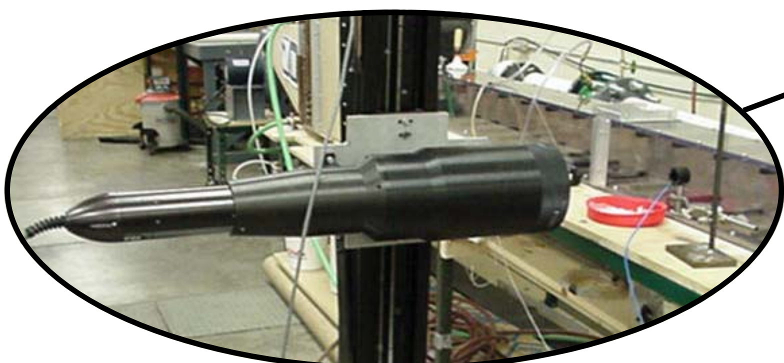
- Established that LES can be used to produce robust, repeatable, and accurate predictions of heat transfer in ribbed ducts
  - Established accuracy at Reynolds numbers up to 50,000, in normal as well as angled ribs, and at large rotation numbers with centrifugal buoyancy.
  - Applied for the first time to obtain a detailed description of developing flow and heat transfer at entrance and in 180 degree bend with rotation and buoyancy
- Detached Eddy-Simulations for the first time applied to predict heat transfer in ribbed duct shows favorable comparisons with LES at much lower cost. Model extensions for centrifugal buoyancy.

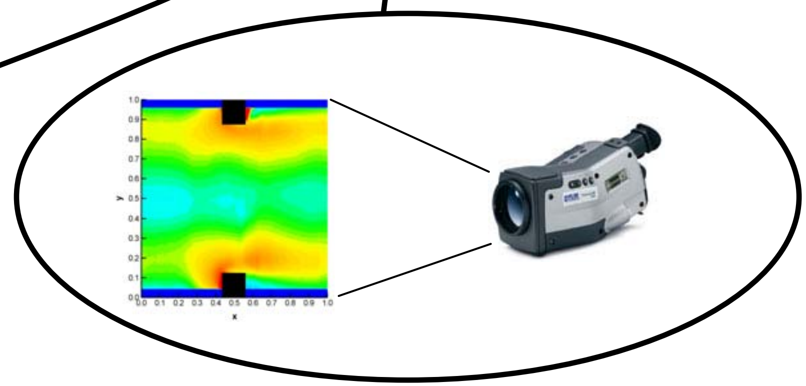
Computational Methodology

- **GenIDLEST – multi-block structured-unstructured Navier-Stokes and energy equation solver in generalized coordinate systems.**
- **Can be used in RANS, URANS, LES and DES or hybrid mode.**
- **Parallel and scalable for fast turnaround.**
- **Equipped with pre- and post-processing utilities.**
- **Over a decade of application to various problems**

Experimental Method





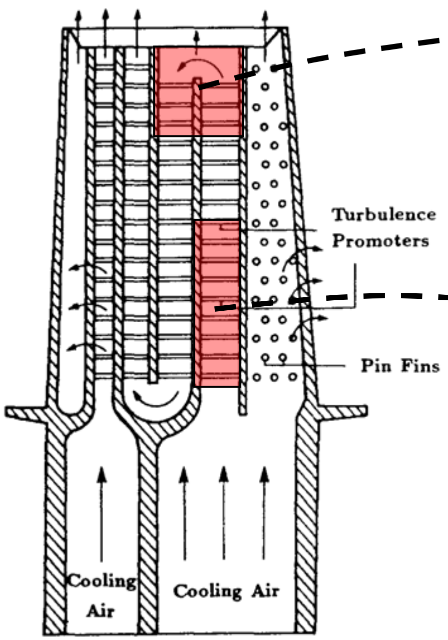


Flow measurements were carried out by Andrew Graham

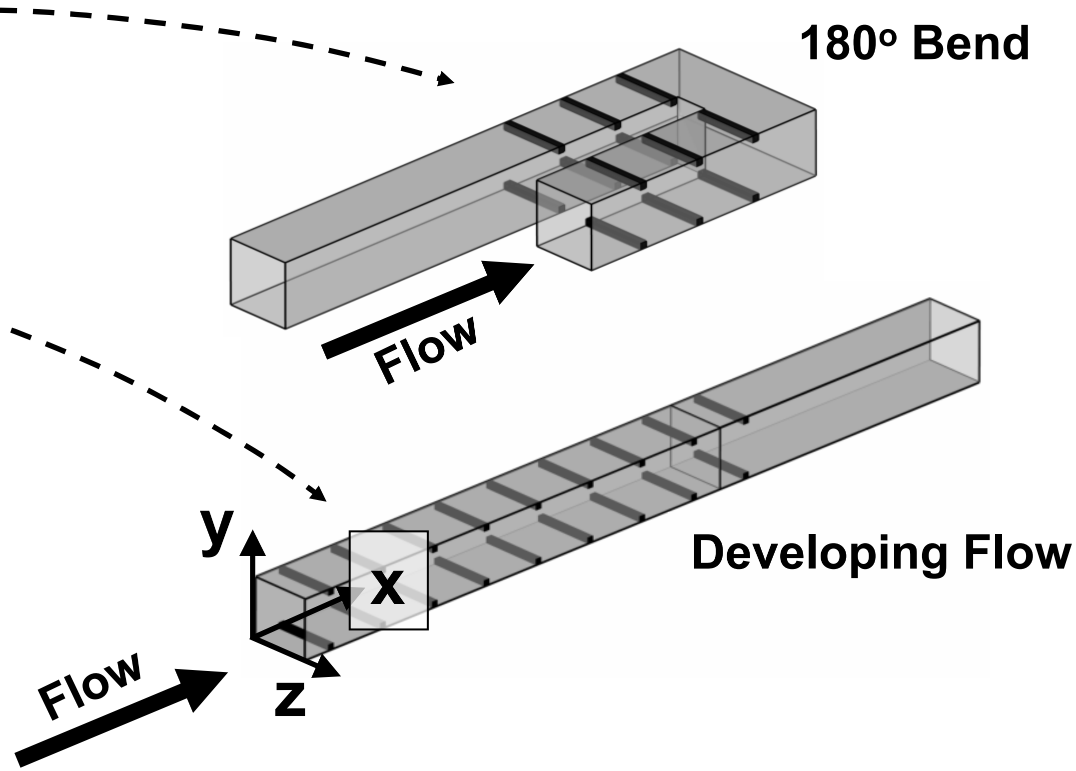
Heat transfer measurements were carried out by Sara Borka

2 component LDV

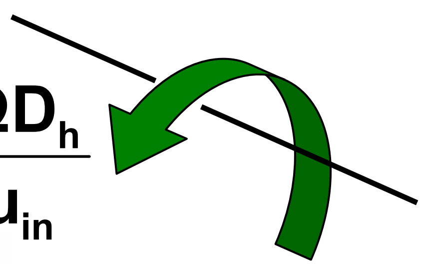
Summary of LES Results



J.C. Han (1988)



$$Ro = \frac{\Omega D_h}{u_{in}}$$



Re = 20,000
Ro = 0.2,0.35, 0.67
Bo = 0.00 → 0.65

Summary of LES Results

Tafti, D. K., Evaluating the Role of Subgrid Stress Modeling in a Ribbed Duct for the Internal Cooling of Turbine Blades, *Int. J Heat and Fluid Flow 26(1),* pp. 92-104, 2005.

Abdel-Wahab, S. and Tafti, D. K., Large Eddy Simulations of Flow and Heat Transfer in a 90º Ribbed Duct with Rotation - Effect of Coriolis and Centrifugal Buoyancy Forces, *J. Turbomachinery* 126(4), pp. 627-636, 2004.

Sewall, E.A., Tafti, D.K., Thole, K.A., Graham, A., Experimental Validation of Large Eddy Simulations of Flow and Heat Transfer in a Stationary Ribbed Duct, *Int. J. Heat and Fluid Flow*, accepted for publication.

Sewall, E.A., Tafti, D.K., Large Eddy Simulation of Flow and Heat Transfer in the 180º Bend Region of a Stationary Ribed Gas Turbine Blade Internal Cooling Duct, accepted for publication, *ASME J. Turbomachinery*, March 2005. (ASME Paper No. GT2005-68518)

Sewall, E.A., Tafti, D.K., Large Eddy Simulation of Flow and Heat Transfer in the Developing Flow Region of a Rotating Gas Turbine Blade Internal Cooling Duct with Coriolis and Buoyancy Forces, *ASME J. Turbomachinery*, submitted July 2005. (ASME Paper No. GT2005-68519)

Abdel-Wahab, S. and Tafti, D. K., Large Eddy Simulation of Flow and Heat Transfer in a Staggered 45º Ribbed Duct, GT2004-53800, ASME Turbo Expo: 2004, Vienna, Austria.

Abdel-Wahab, S. and Tafti, D. K., Large Eddy Simulations of Flow and Heat Transfer in a 90º Ribbed Duct with Rotation – Effect of Coriolis Forces, GT2004-53796, ASME Turbo Expo: 2004, Vienna, Austria.

Sewall, E, and Tafti, D. K., Large Eddy Simulation of the Developing Region of a Stationary Ribbed Internal Turbine Blade Cooling Channel, GT2004-53832, ASME Turbo Expo: 2004, Vienna, Austria.

Sewall, E, and Tafti, D. K., Large Eddy Simulation of the Developing Region of a Rotating Ribbed Internal Turbine Blade Cooling Channel, GT2004-53833, ASME Turbo Expo: 2004, Vienna, Austria.

Viswanathan, A.K., Tafti. D.K., Abdel-Wahab, S., Large Eddy Simulation of Flow and Heat Transfer in an Internal Coolingg Duct with High Blockage Ratio 45o staggered Ribs, GT 2005-68086, Proceedings of ASME Turbo Expo 2005, June 6-9, Reno-Tahoe,USA.

Viswanathan, A.K., Tafti. D.K., Large Eddy Simulation of Flow and Heat Transfer in a Ribbed Duct With Skewed Ribs of Rounded Cross-section, GT 2005-68117, Proceedings of ASME Turbo Expo 2005, June 6-9, Reno-Tahoe,USA.

Viswanathan, A. K. and Tafti D. K., Large Eddy Simulation of the fully developed flow and heat transfer in a rotating duct with 45° ribs, GT 2006-90229, ASME Turbo Expo 2006, 8- 11 May 2006, Barcelona, Spain.

LES Data Sets used at GE Global Research for validating RANS calculations

Detached Eddy Simulations

- LES grid resolution increases approximately as Re^2 for wall bounded turbulence to capture all the near wall scales of turbulence
- Initial DES formulation with Spalart-Allmaras model:
  - modeled near wall turbulence with RANS such that grid resolution could be relaxed considerably in wall parallel directions
  - Switch to LES based on distance from wall and mesh resolution – acted like wall model for LES
  - Initial development for separated boundary layer flows
  - Applications in external flow – only one wall normal direction.
- Extended to more general two-equation model formulation by Strelets
  - Use of turbulent length scale derived from turbulence model instead of distance from wall

DES – Switch in length scale based on the turbulent physics

Detached Eddy Simulation (DES) is a three-dimensional unsteady numerical solution using a single turbulence model, which functions as a sub-grid scale model in regions where it is fine enough for a LES and as a RANS model in regions where it is not. (Strelets et al. 2001)

k-equation

D^k

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma^* \nu_T\right)\frac{\partial k}{\partial x_j}\right]$$

ω-equation

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} \tau_{ij} \frac{\partial U_i}{\partial x_j} - \beta \omega^2 + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma \nu_T\right)\frac{\partial \omega}{\partial x_j}\right]$$

Length scale for RANS:

$$l_{k-\omega} = k^{1/2} \big/ (\beta^* \omega)$$

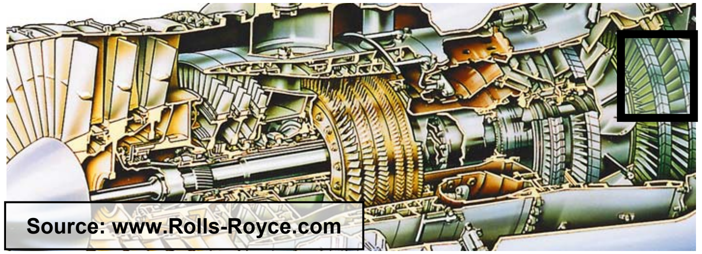
Modification for DES:

$$\delta = \min\left(l_{k-\omega}, C_{DES}\Delta\right)$$
$$\Delta = \max\left(\Delta_x, \Delta_y, \Delta_z\right)$$

Modified destruction term:

$$D^k = k^{\frac{3}{2}} \big/ \delta$$

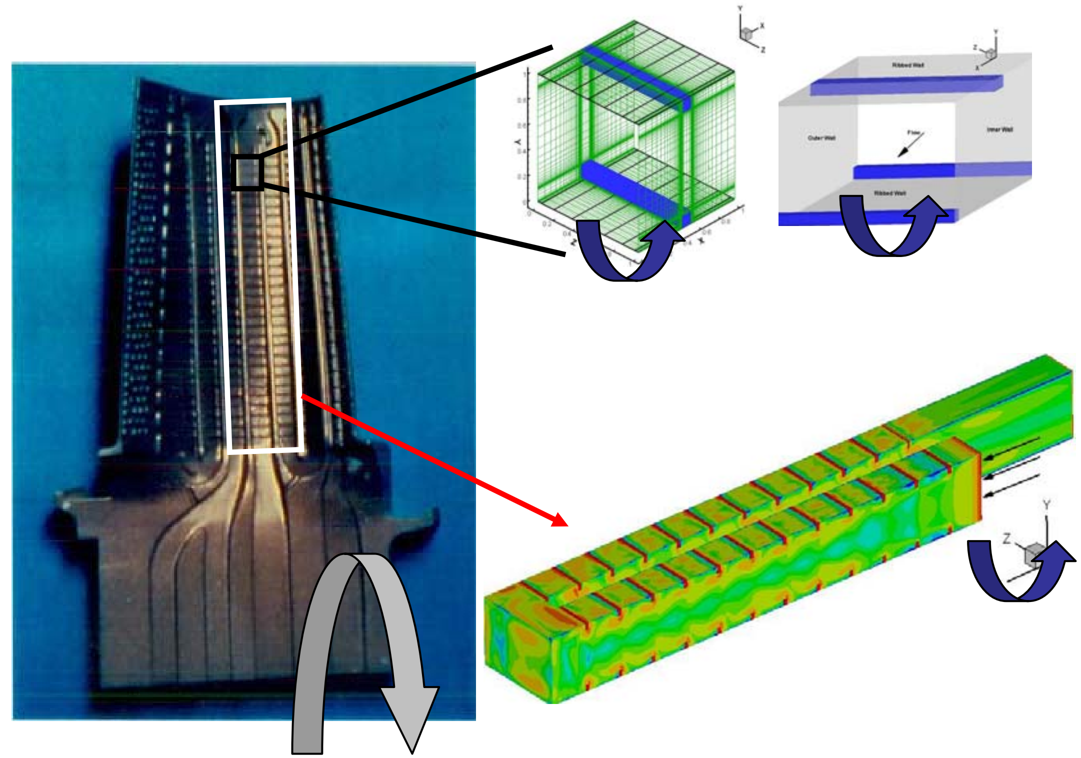
This is the first study to apply DES to flow and heat transfer in internal flows



DES in internal cooling ducts

In all computations DES of k-ω and/or SST are carried out, with appropriate modifications to the underlying RANS models

- Fully Developed duct – Normal ribs
  - Stationary
  - Rotating – Effect of Coriolis forces
  - Rotating – Effect of Coriolis forces and Centrifugal Buoyancy
- Fully Developed duct – Skewed ribs
  - Stationary
  - Rotating
- Complete 2 pass duct – Normal ribs
  - Stationary
  - Rotating



Computational details of the configurations in which DES is applied

- Normal ribs - Flow Re = 20,000
- e/D_h = 0.1, P/e = 10
- Coriolis force computations

  Ro (= $\Omega D_h/u_b$) = 0.18, 0.35, 0.67
- Centrifugal Buoyancy Computations

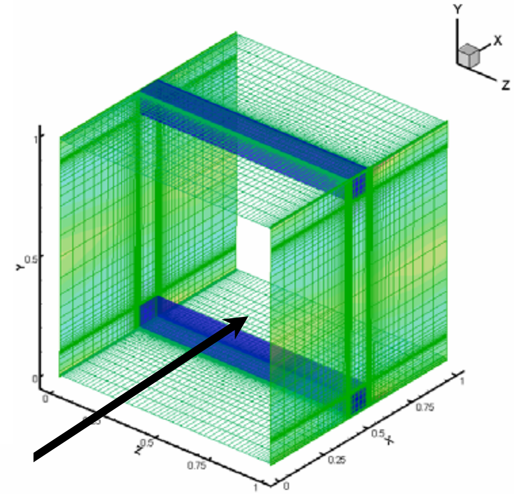
  Ro (= $\Omega D_h/u_b$) = 0.18, 0.35, 0.67

  Bo = 0.12, 0.29

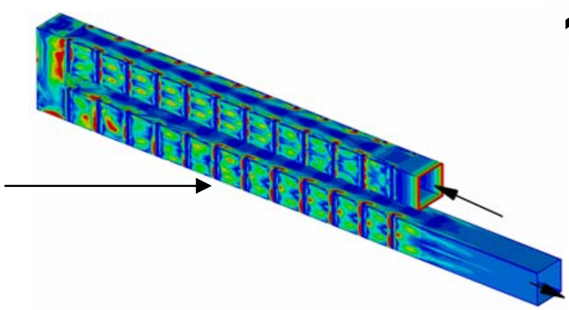
e – Rib height

D_h – Hydraulic Diameter

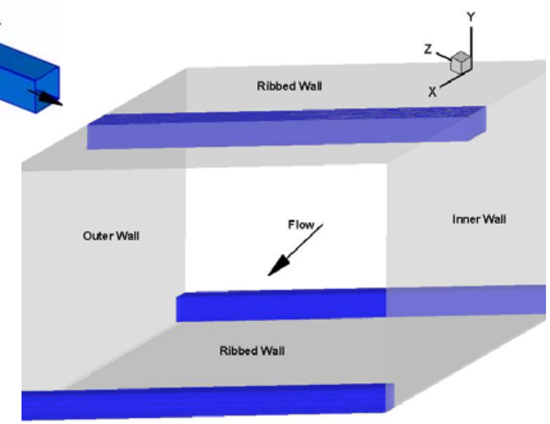
P – Rib pitch



- Normal ribs - Flow Re = 20,000
- 12 Ribs in either pass

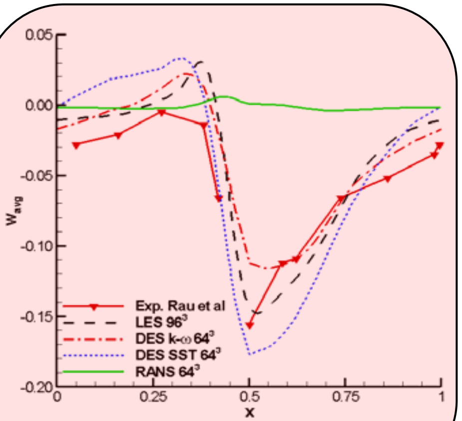


- Skewed ribs - Flow Re = 47,000
- e/D_h = 0.1, P/e = 10



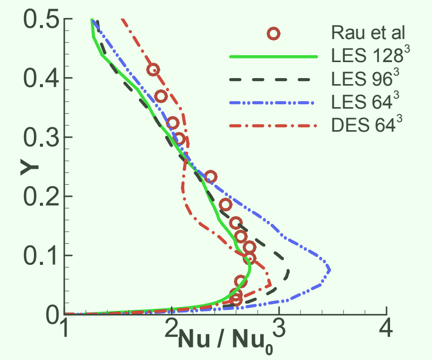
Summary of results - Normal Ribs : Stationary case, fully developed calculations

- LES results deteriorate as grid is coarsened from 128^3 to 64^3
- Use of DES on 64^3 mesh gives better results than LES on 64^3

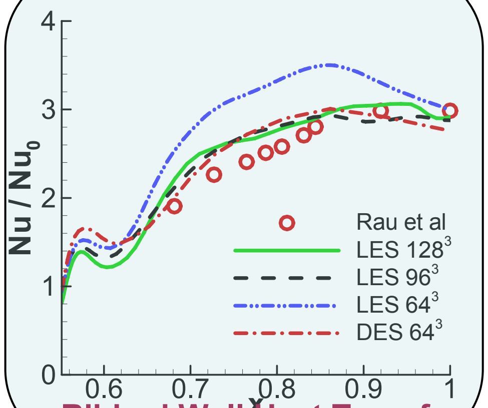


w-velocity above the rib

Reattachment Length	
DES 64^3	4.1e
LES 128^3	4.1e
LES 64^3	3.7e
Rau *et al.*	(4.0 – 4.25)e



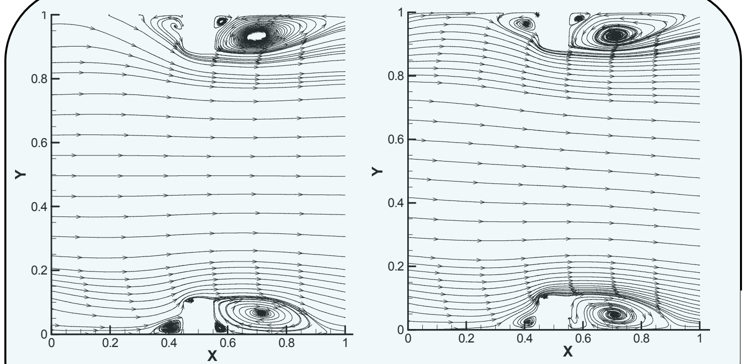
Side Wall Heat Transfer



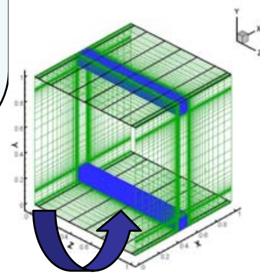
Ribbed Wall Heat Transfer

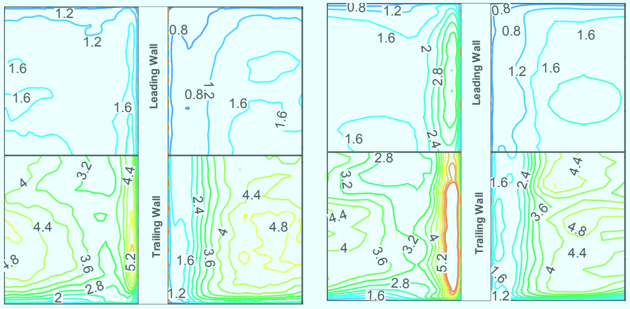
1. Viswanathan A.K., Tafti, D. K., 2004, Detached Eddy Simulation of Turbulent Flow and Heat Transfer in a Duct, HT-FED2004-56152, 2004 ASME Heat Transfer/Fluids Engineering Summer Conference, July 11-15, Charlotte.
2. Viswanathan A.K., Tafti, D. K., 2005, Detached Eddy Simulation of Turbulent Flow and Heat Transfer in a Duct, *J. Fluids Engineering*, 127, pp 888-896

Summary of results - Normal Ribs : Effect of Coriolis forces on fully developed ducts undergoing rotation



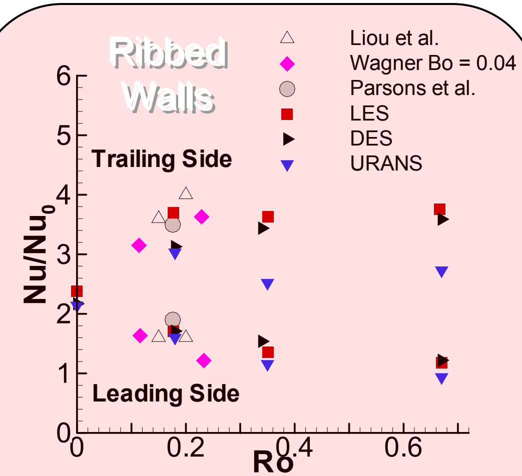
LES (Ro = 0.35) DES (Ro = 0.35)





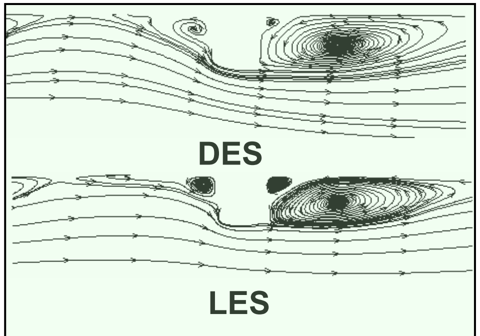
LES (Ro = 0.35) DES (Ro = 0.35)

- No modifications made to underlying RANS model
- DES much better than URANS on same mesh

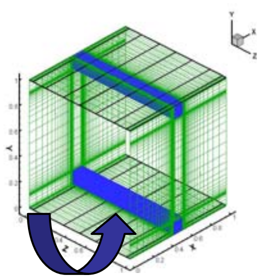


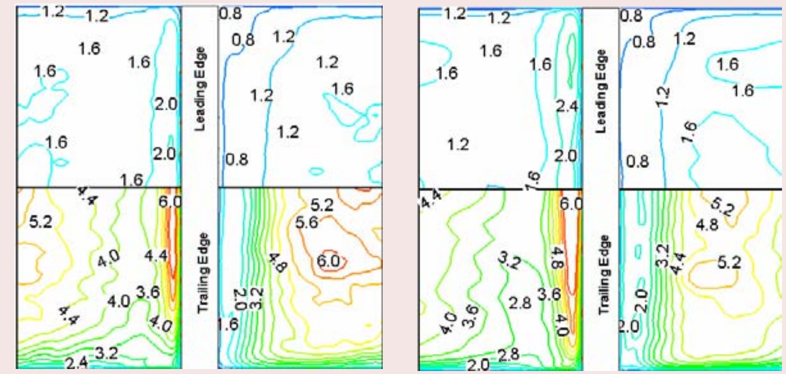
Viswanathan A.K., Tafti, D. K., 2005, Detached eddy simulation of turbulent flow and heat transfer in fully-developed rotating internal cooling channel with normal ribs under review, *Int. J Heat and Fluid Flow*.

Results - Normal Ribs : Effect of Coriolis forces and Centrifugal Buoyancy on fully developed ducts



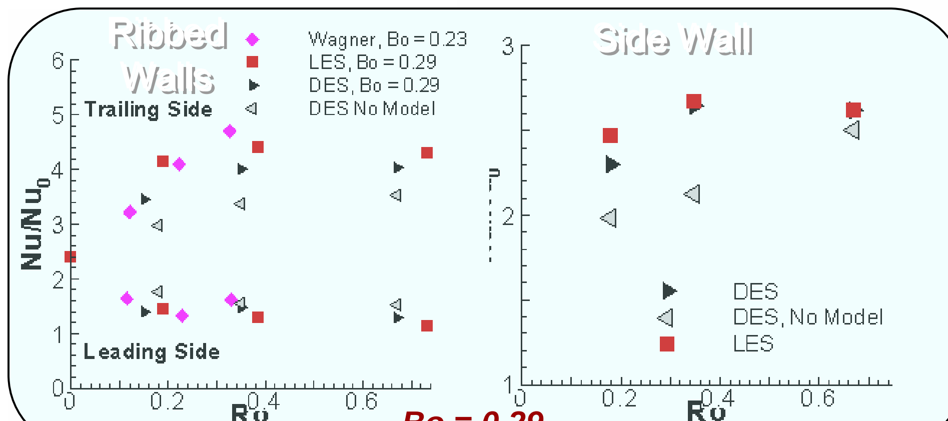
Ro = 0.35, Bo = 0.12





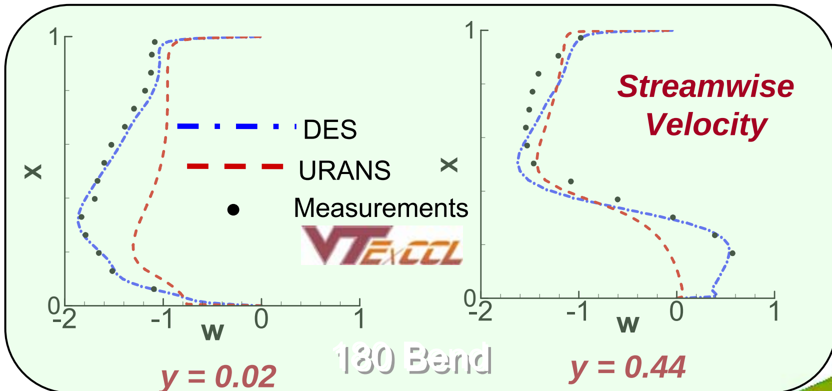
LES (Ro = 0.35, Bo = 0.12) *DES (Ro = 0.35, Bo = 0.12)*

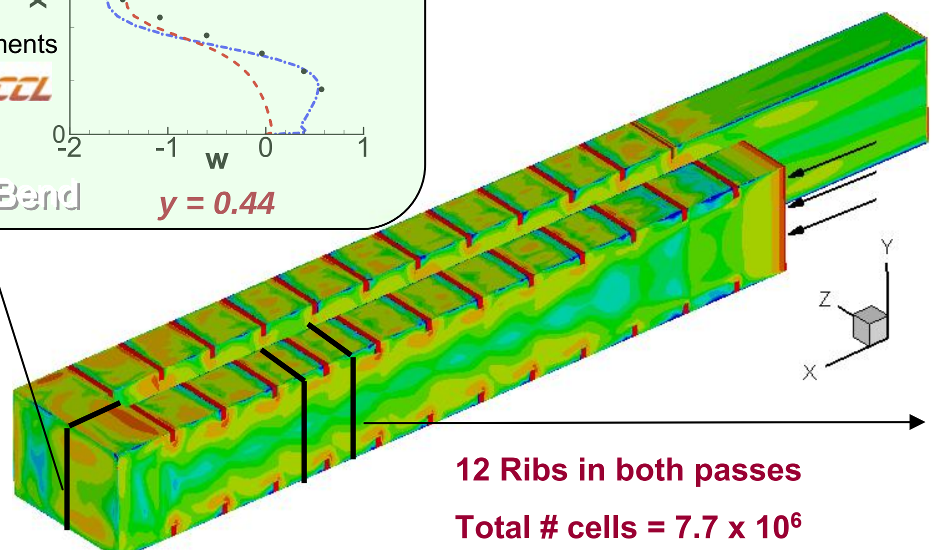
- Additional production term in RANS model for centrifugal buoyancy effects.
- Enhanced model gives better results than baseline RANS model



Bo = 0.29

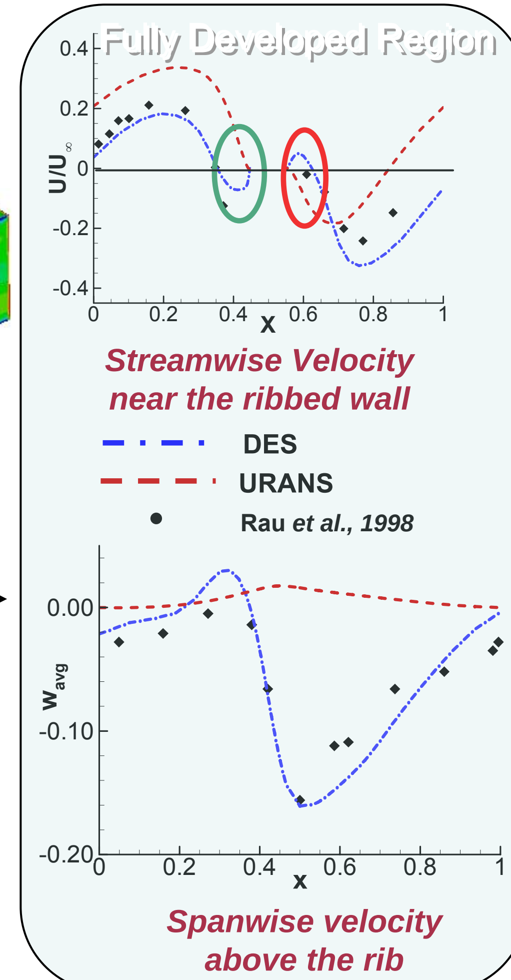
Summary of results - Normal Ribs : Stationary case, complete 2 pass duct calculations





12 Ribs in both passes

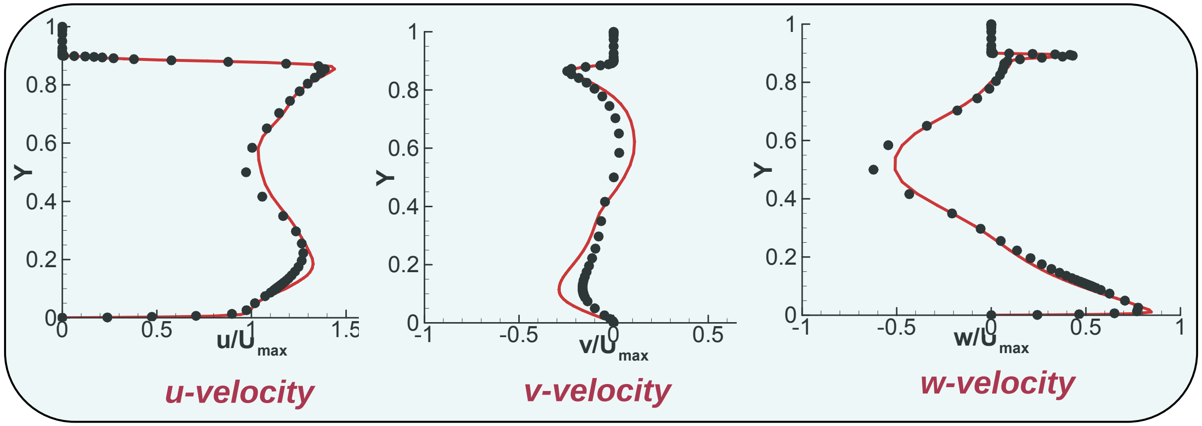
Total # cells = 7.7 x 10^6

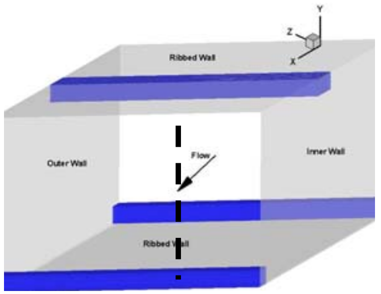


- DES transitions later than LES at entrance to duct.
- But compares well to LES and experiments after fourth rib

1. Viswanathan A.K., Tafti, D. K., 2005, Detached eddy simulation of turbulent flow and heat transfer in a two-pass internal cooling duct , In press *Int. J Heat and Fluid Flow*,26(6).
2. Viswanathan A.K., Tafti, D.K., A Comparative study of DES and URANS in a two-pass internal cooling duct with normal ribs, *IMECE2005-79288, ASME International Mechanical Engineering Congress and Exposition 2005, Nov 5-11, Orlando, Florida, USA.*

Summary of results - Skewed Ribs : Stationary case, fully developed calculations

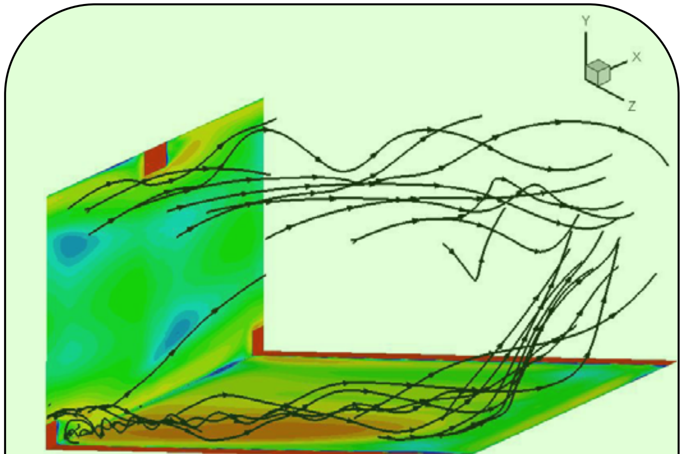




DES

Chanteloup *et al*.

- Flow not dominated by large recirculation regions as in normal ducts
- Is DES effective?

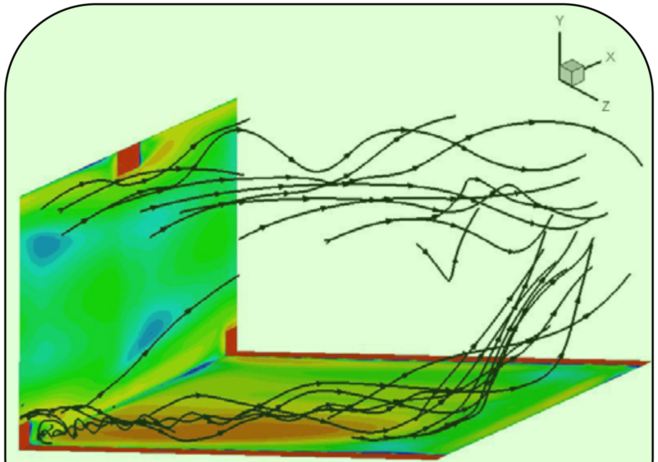


Flow features induced by the rib in the duct

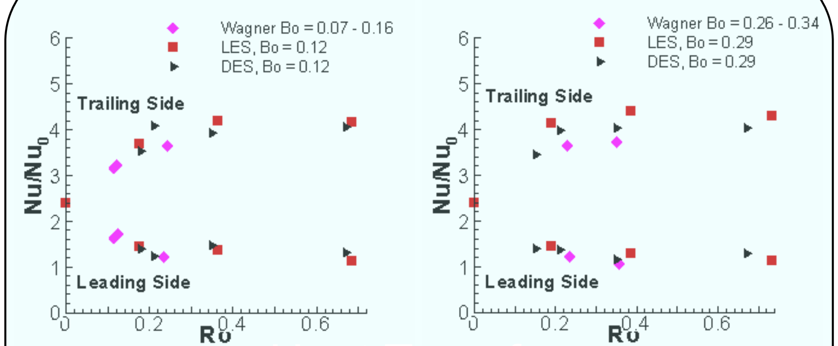
1. Viswanathan A.K., Tafti, D. K., 2004, Detached Eddy Simulation of Turbulent Flow and Heat Transfer in a Stationary Internal Cooling Duct with Skewed Ribs, ***GT2005-68118*** , 2005 ASME Turbo Expo, June 6-9, Reno, Nevada..

To conclude, DES was successfully extended to the effects of Coriolis forces and Centrifugal buoyancy

- DES predicts the flow features and the heat transfer accurately in the 90° and the 45° ribbed ducts
- The DES computation is <u>an order of magnitude more economical</u> than the LES computation for 90° case
- Extension of DES to the capture Coriolis forces was successful
- DES was successfully extended to capture the effects of centrifugal buoyancy to flows in ducts with normal ribs



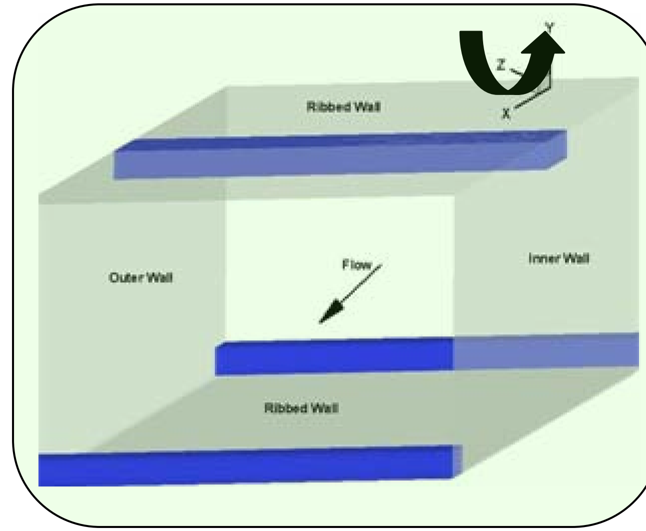
Flow features induced by the rib in the duct

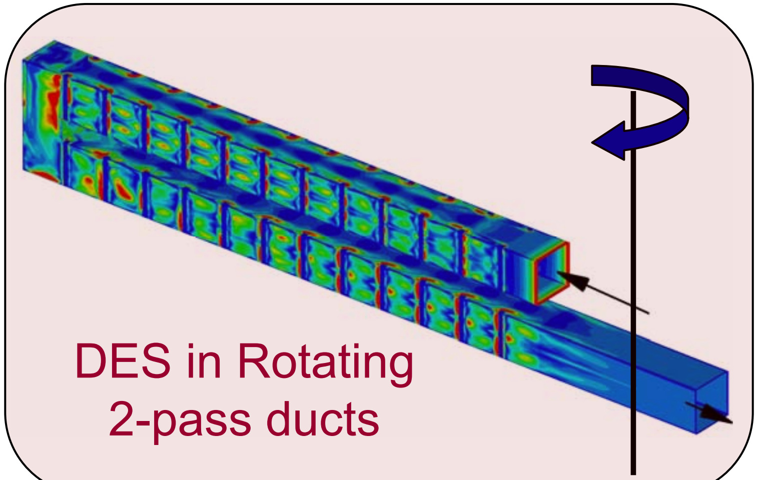


Heat Transfer

DES - Future Work

- Further DES model development and validation for Coriolis and centrifugal buoyancy effects in skewed ribs and 2 pass ducts





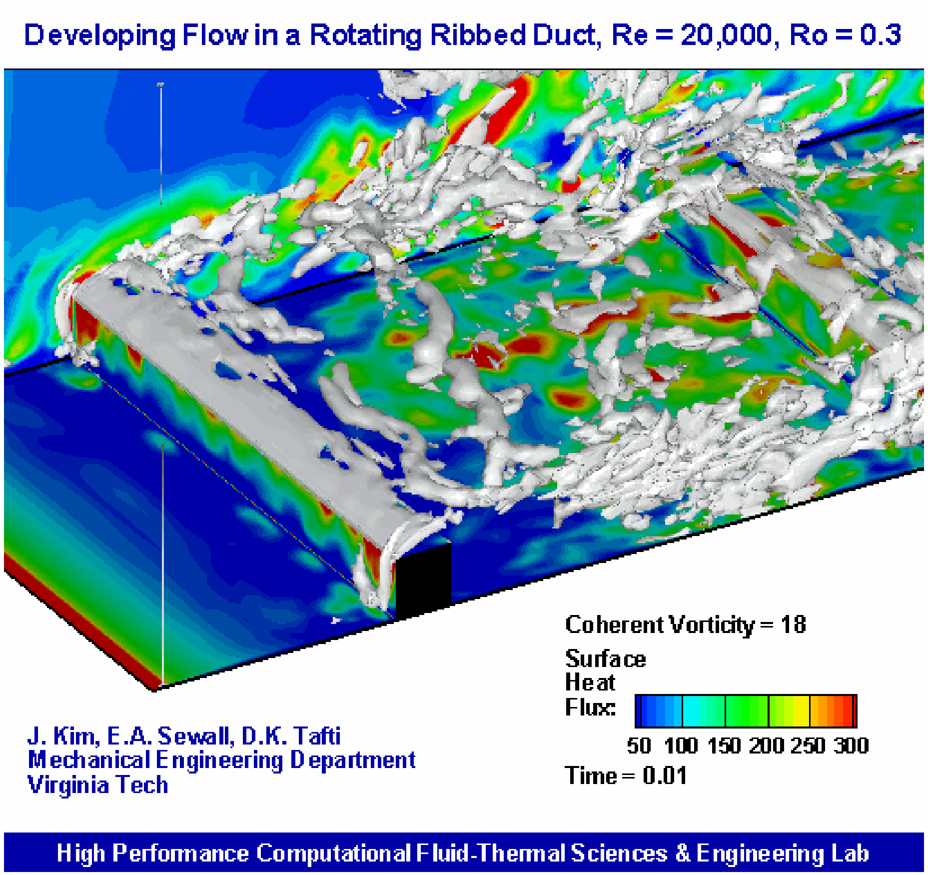
DES in Rotating 2-pass ducts

SUMMARY

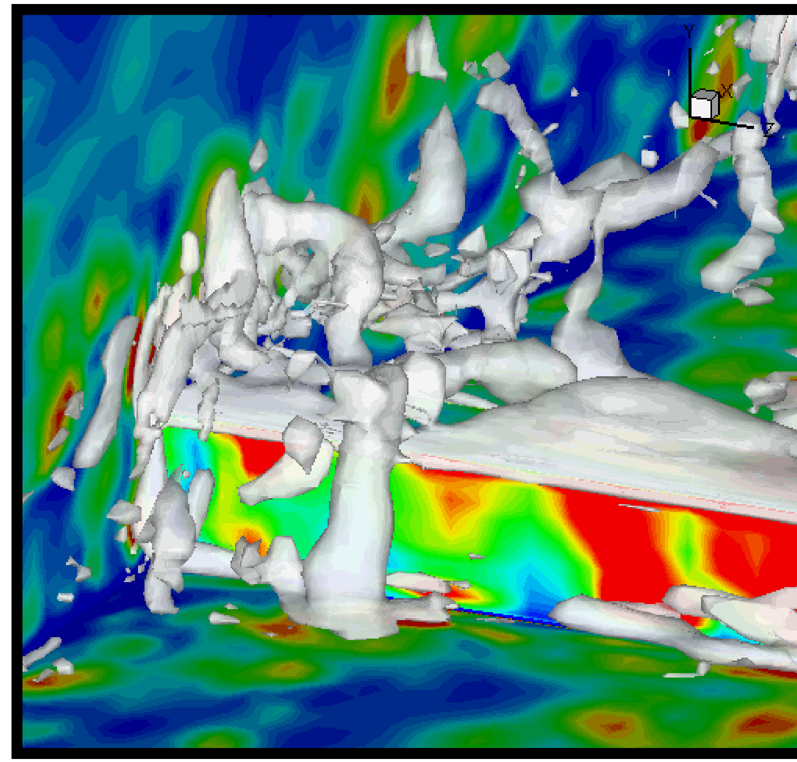
- The research project has enabled new advances in prediction technology for internal cooling flows.
- DES shows promise of being a good compromise between LES and URANS
- The project has resulted in:
  - Providing data to industry for benchmarking RANS calculations
  - 15 conference papers (IGTI, ASME HT)
  - 6 journal publications (ASME-JOT,IJHFF,ASME-FE)
  - 2 journal papers under review
  - 2 outreach articles in non-technical publications (VT-Research, NCSA-Access)
  - Invited presentation in NCSA booth at Supercomputing 04.
  - Trained 3 graduate students and 10 undergraduates
    - Samer Abdel-Wahab, MS, Florida Turbine Technologies (Dec 03)
    - Evan Sewall, Ph.D, GE Global Research (Dec 05)
    - Aroon Viswanathan, Ph.D, (Summer 06)

Thank You!
Questions?

Transition at first rib



Unsteady effects of secondary flow at rib-wall junction



Virginia Tech