THREE-DIMENSIONAL UNSTEADY SIMULATION OF AERODYNAMICS AND HEAT TRANSFER IN A MODERN HIGH PRESSURE TURBINE STAGE

Unsteady 3-D RANS simulations have been performed on a highly loaded transonic turbine stage and results are compared to steady calculations as well as to experiment. A low Reynolds number k-ε turbulence model is employed to provide closure for the RANS system. A phase-lag boundary condition is used in the tangential direction. This allows the unsteady simulation to be performed by using only one blade from each of the two rows. The objective of this work is to study the effect of unsteadiness on rotor heat transfer and to glean any insight into unsteady flow physics. The role of the stator wake passing on the pressure distribution at the leading edge is also studied. The simulated heat transfer and pressure results agreed favorably with experiment. The time-averaged heat transfer predicted by the unsteady simulation is higher than the heat transfer predicted by the steady simulation everywhere except at the leading edge. The shock structure formed due to stator-rotor interaction was analyzed. Heat transfer and pressure at the hub and casing were also studied. Thermal segregation was observed that leads to the heat transfer patterns predicted by steady and unsteady simulations to be different.

Three-Dimensional Unsteady Simulation of Aerodynamics and Heat Transfer in a Modern High Pressure Turbine Stage

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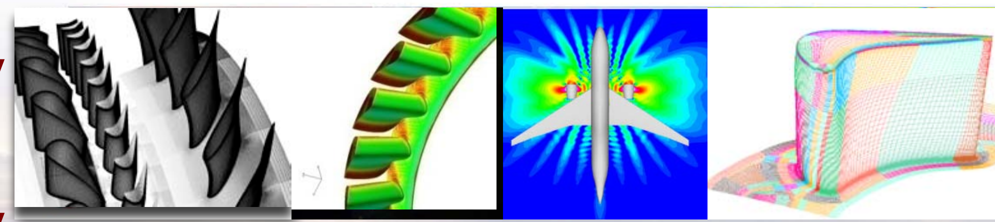
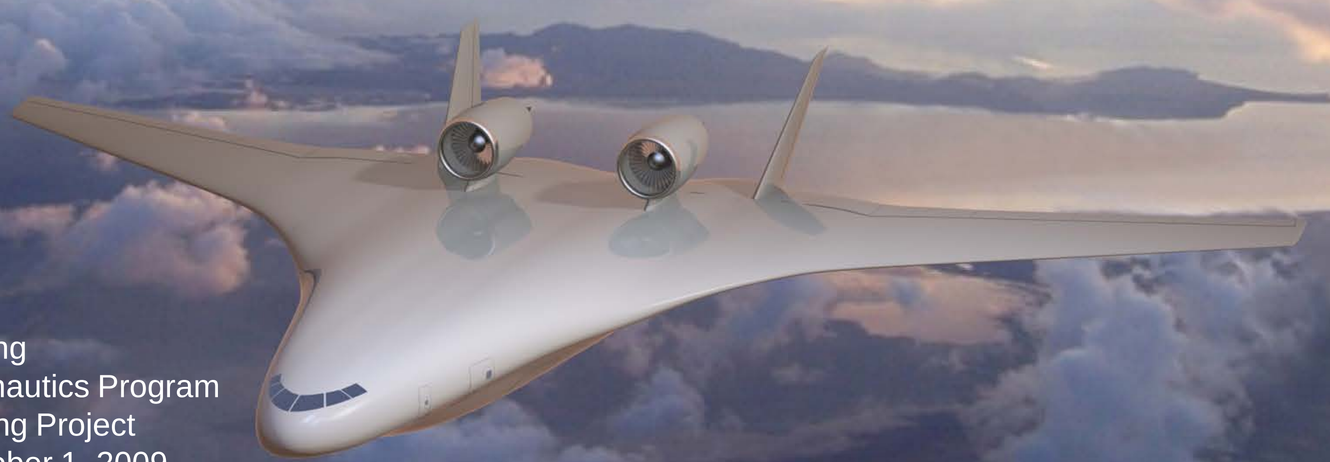




2009 Annual Meeting
Fundamental Aeronautics Program
Subsonic Fixed Wing Project
September 29-October 1, 2009

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6

** Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

SFW Approach

- Conduct Discipline-based Foundational Research

- Investigate Advanced Multi-Discipline Based Concepts and Technologies

- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes

- Enable Major Changes in Engine Cycle/Airframe Configurations

About this work…

- 3-D URANS simulations performed on highly loaded transonic turbine stage using TURBO (Chen et al.)
- Results are compared to steady calculations as well as experiment (Tallman, Haldemann et al. at OSU GTL).
- Effect of unsteadiness studied
  - shock structure
  - rotor heat flux
  - hub and casing heat flux
  - thermal segregation

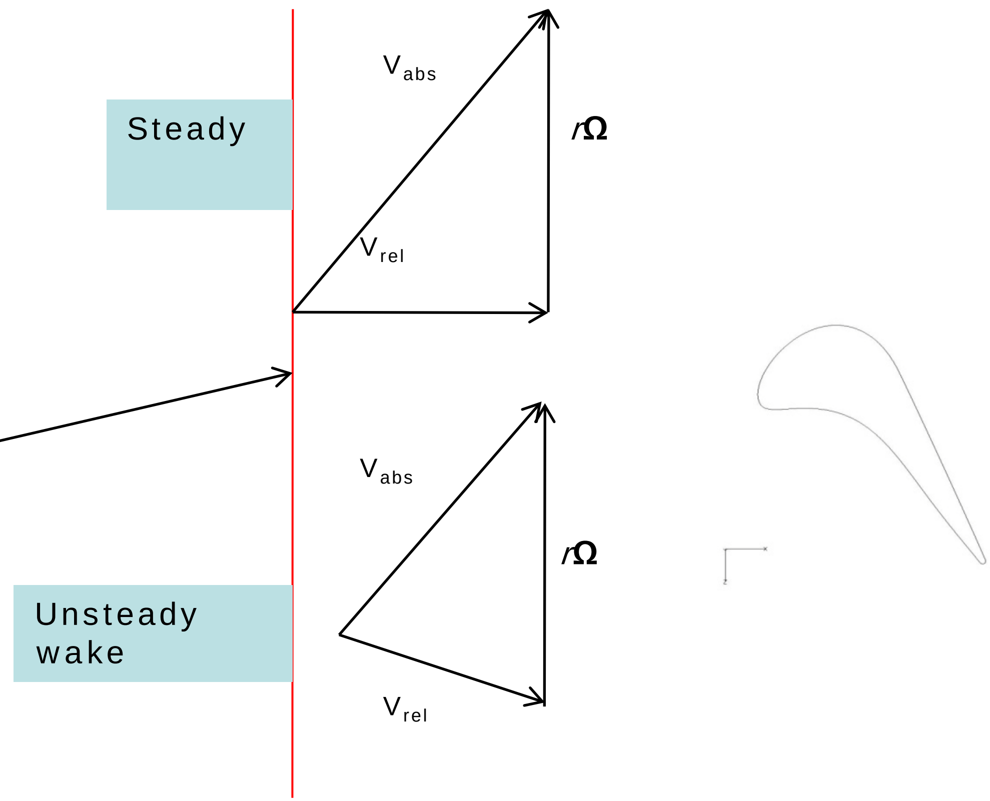
Background

- HPT flow is unsteady due to wake passage and shock-wake interactions
- Stagnation point on rotor moves away from LE
- Shock moves from rotor crown to leading edge as wake passes (Denos et al., Paniagua et al.)
- Thermal segregation could occur (Shang and Epstein, Ameri et al., Kerrebrock and Mikolajczak)

Segregation

Velocity diagrams in the wake.
$T_{time\_average} < T_{steady}$

Rotor-Stator interface



Lower temperature in wake directs cooler gas to suction side

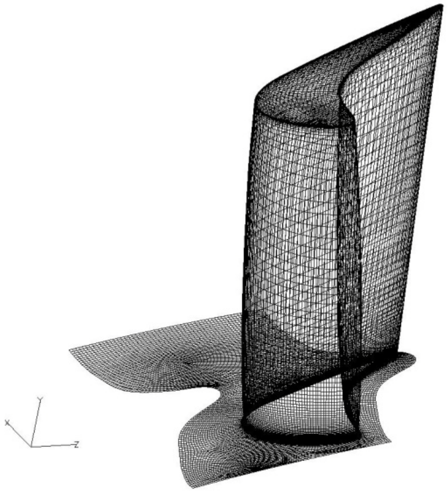
TURBO

- Upwind Roe scheme with Newton sub iterations
  -No artificial dissipation
- Fully parallelized to use MPI
- Only need one blade per row using Phase lag
- Phase lag - ideal for single-stage simulation (Van Zante et al.)
- Uses low Re k-ε turbulence model
- Heat transfer simulation made possible by incorporating isothermal BC

Phase lag

Uses blade count of neighboring blade row to determine frequency

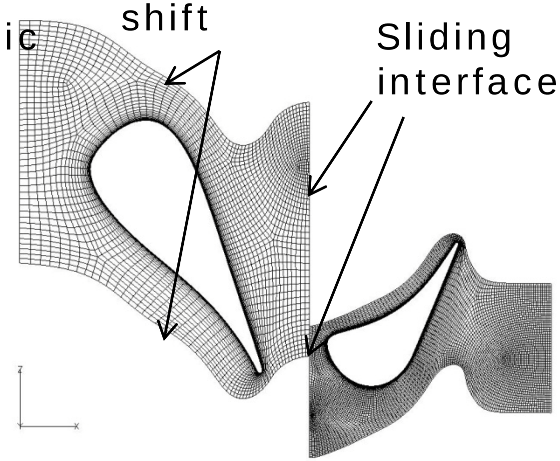
The Grid



Rotor grid.

- 38 Stators, 72 rotor blades
- ~2.5M cells (very fine grid)
- y+<1 (at first point off wall)
- Coarser grids have shown satisfactory results (e.g. Green et al.)

Rotor Features
- 2.1% tip clearance
- blade speed ~ 9000 rpm
- Re ~ 3 x 10^6 / m

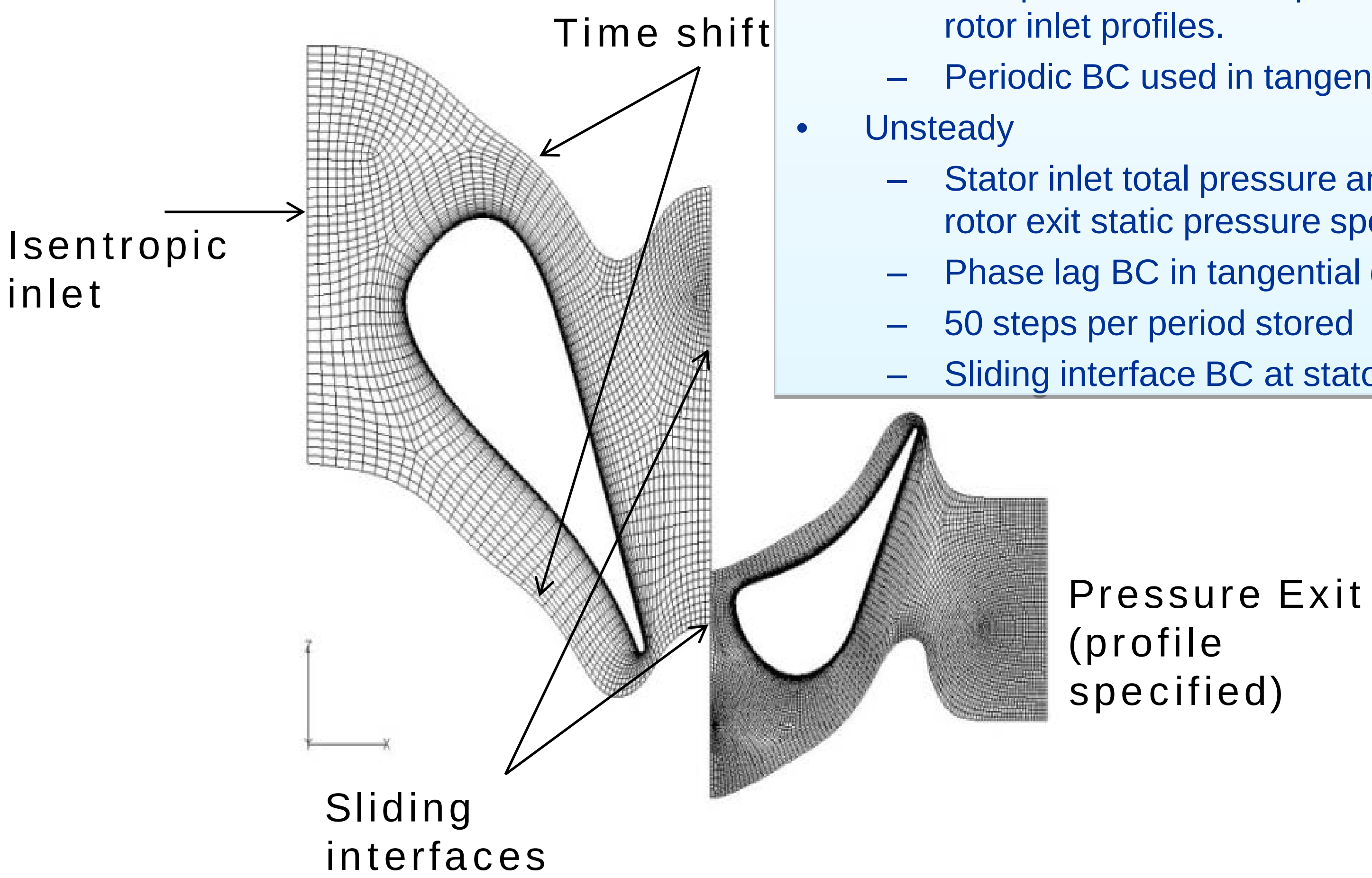


Convergence determined using mass flow and surface heat transfer

Relative stator-rotor positioning for unsteady case and boundary conditions

Simulations

- Steady
  - Used circumferentially averaged vane exit total pressure and temperature profiles as rotor inlet profiles.
  - Periodic BC used in tangential direction
- Unsteady
  - Stator inlet total pressure and temperature, rotor exit static pressure specified
  - Phase lag BC in tangential direction
  - 50 steps per period stored
  - Sliding interface BC at stator-rotor interface



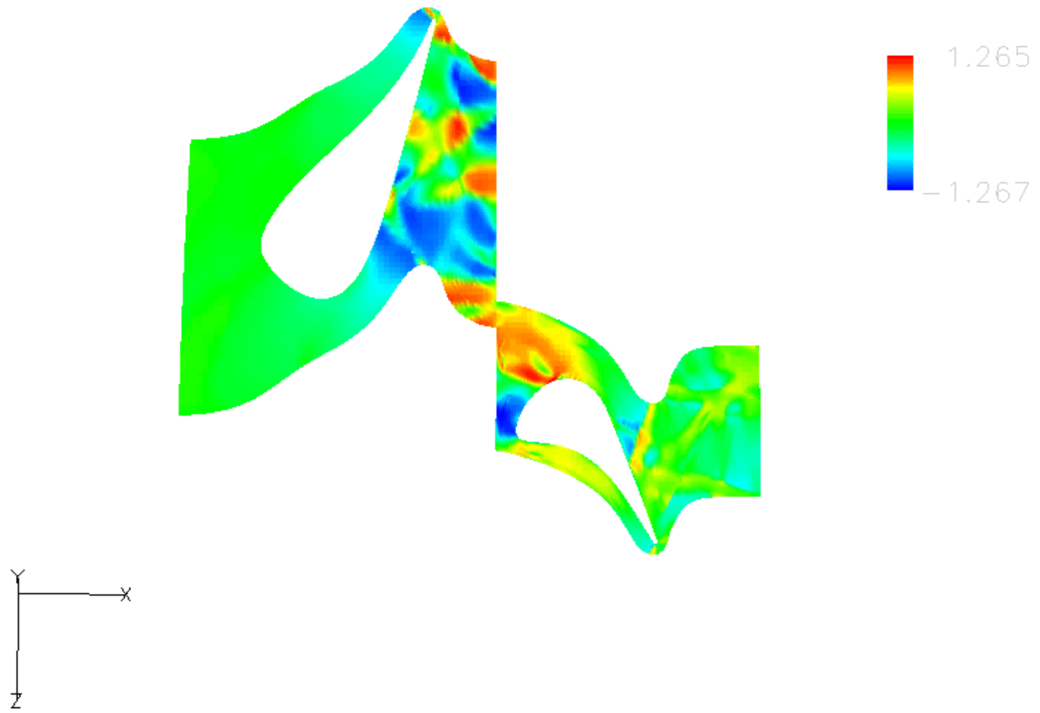
RESULTS

Shock Function at 15% span

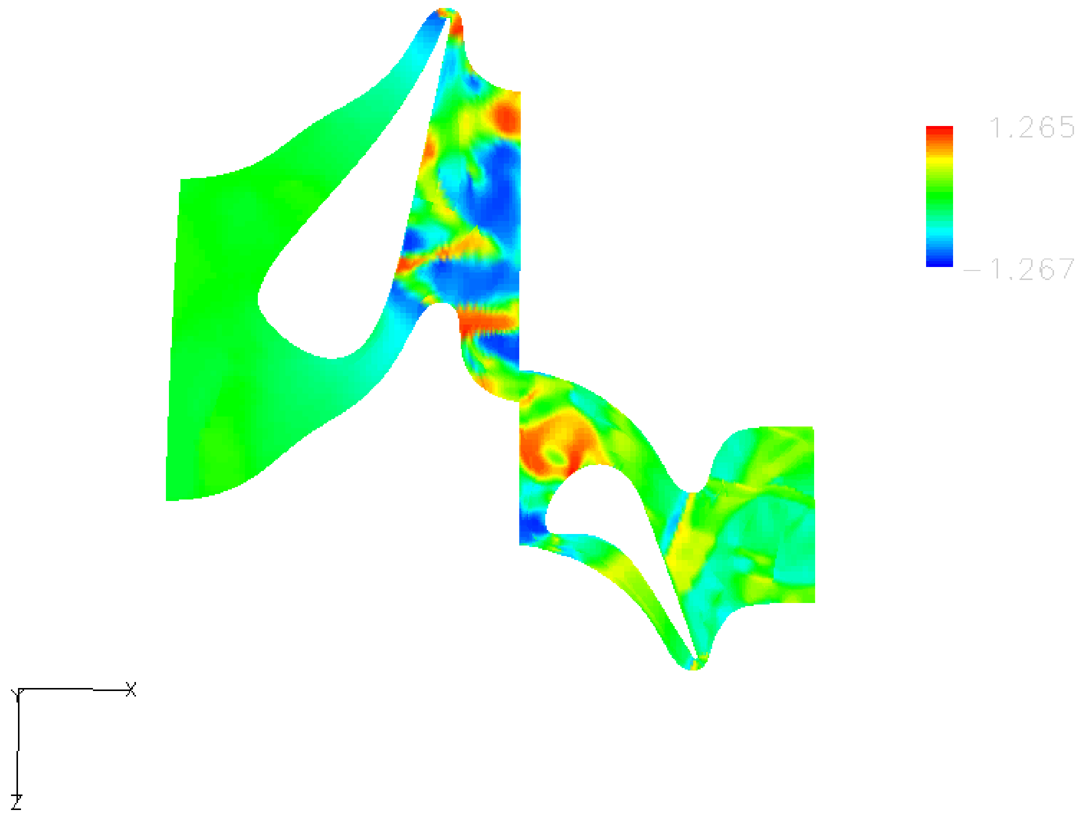
$$SF = \vec{V} \cdot \nabla p$$

- Boundaries of red regions are shocks

(Large pressure gradient is in direction of flow velocity)



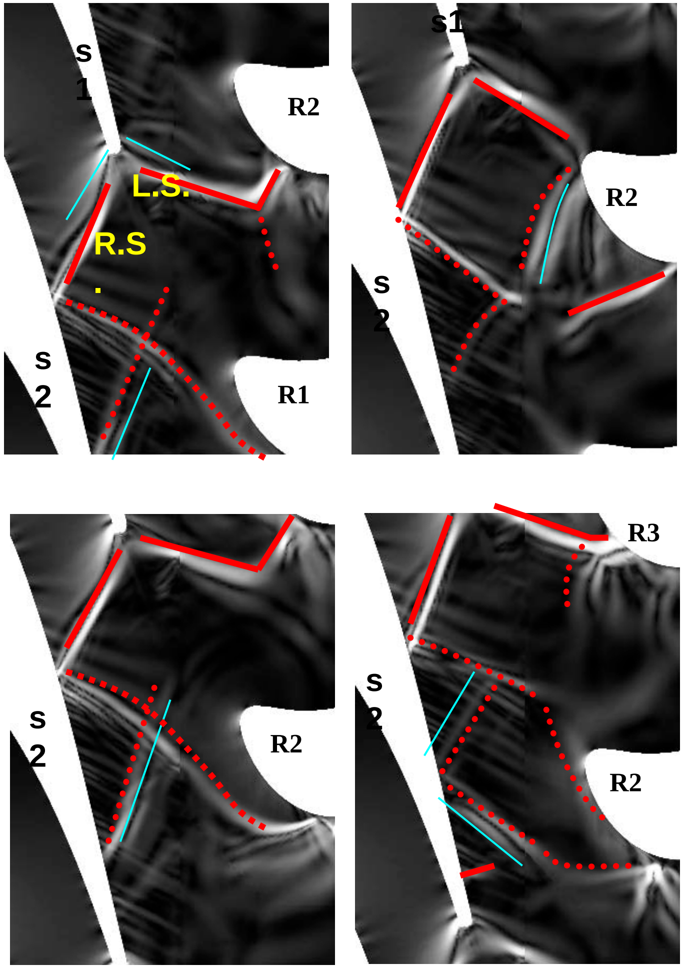
Shock Function at Mid-Span



Vane trailing edge shock sweeps across crown and LE of rotor

Minimum unsteadiness on suction side of rotor

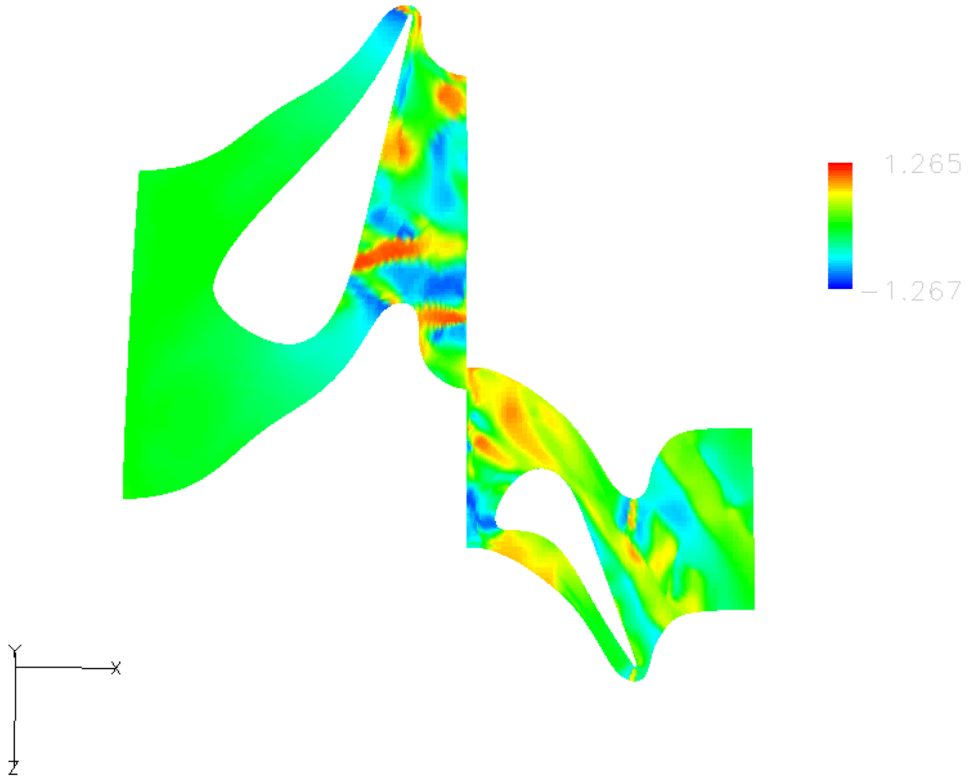
Comparison with Schlieren



Dotted lines are reflected shocks

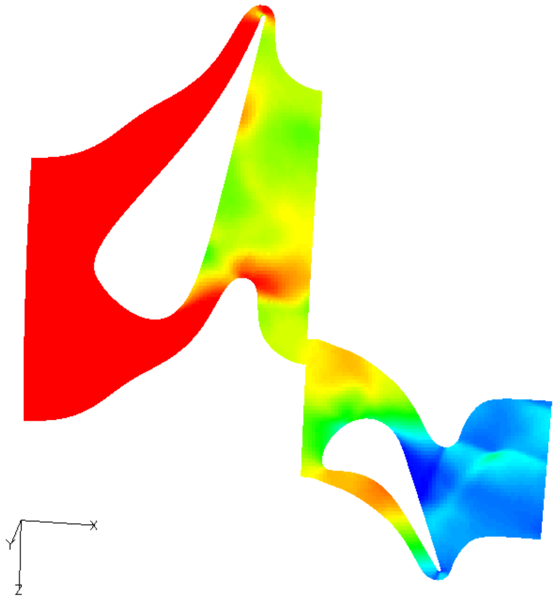
De la Loma, Paniagua, Verrastro, Adami, GT2007-27101

Shock Function at 90% Span

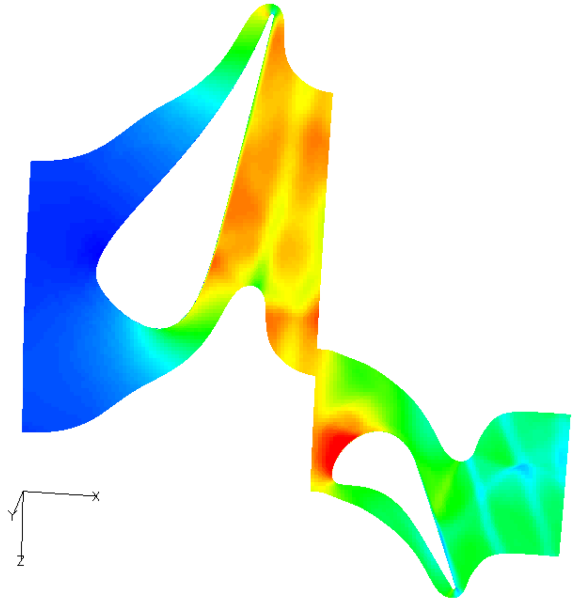


Vane trailing edge shock interacts with rotor trailing edge shock

Mid-span Pressure and Mach Number

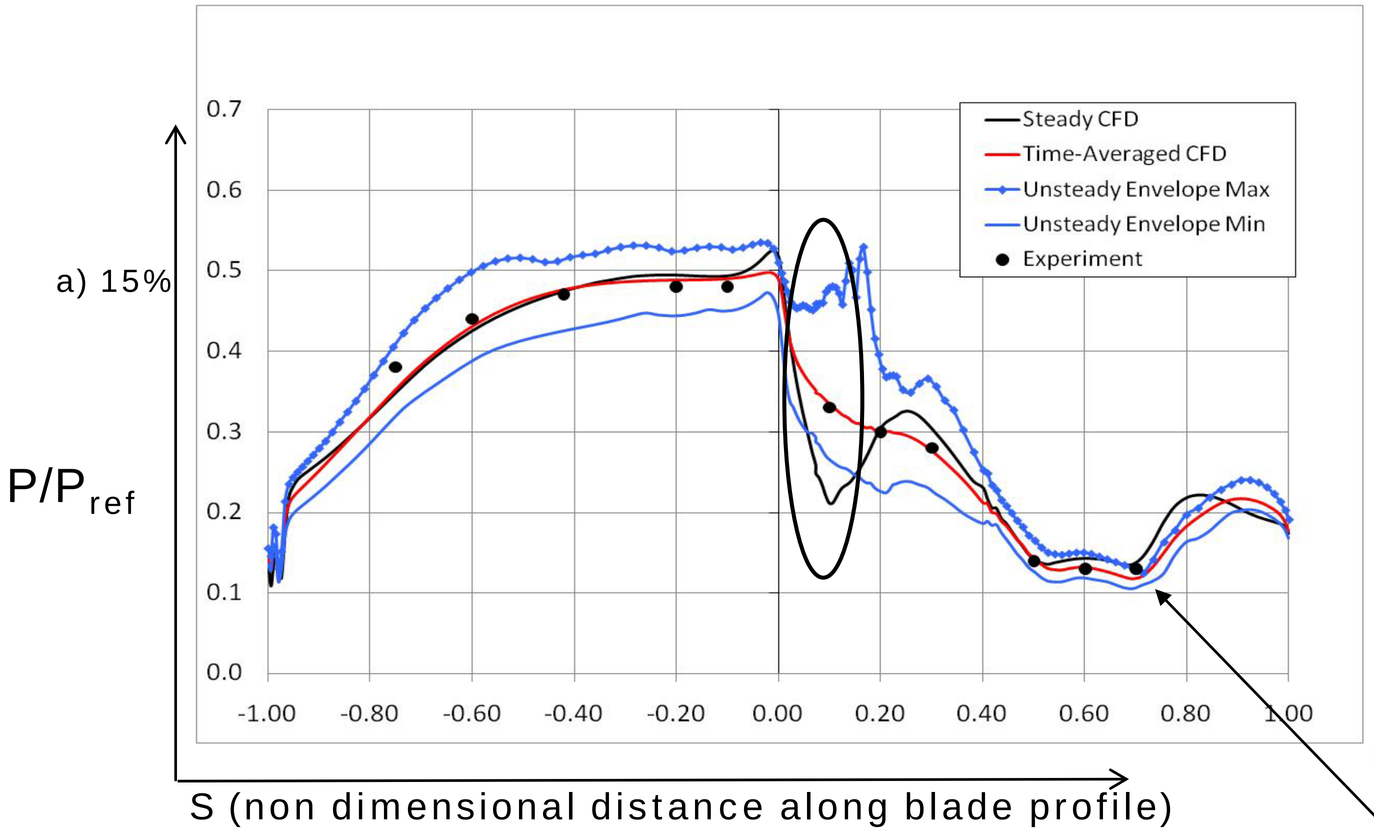


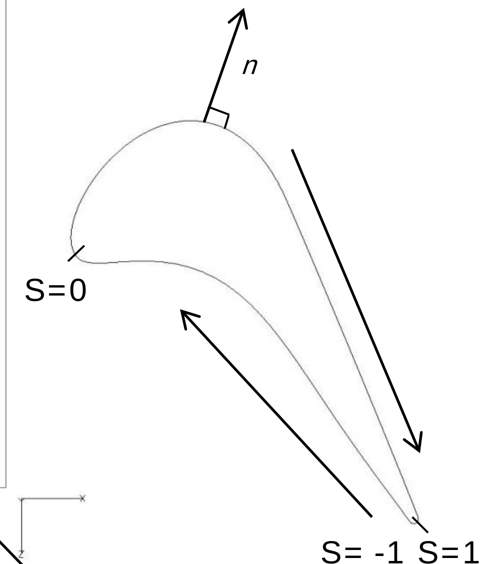
Pressure



Mach no.

Pressure Profiles





Unsteady envelope widest near LE, narrows towards TE

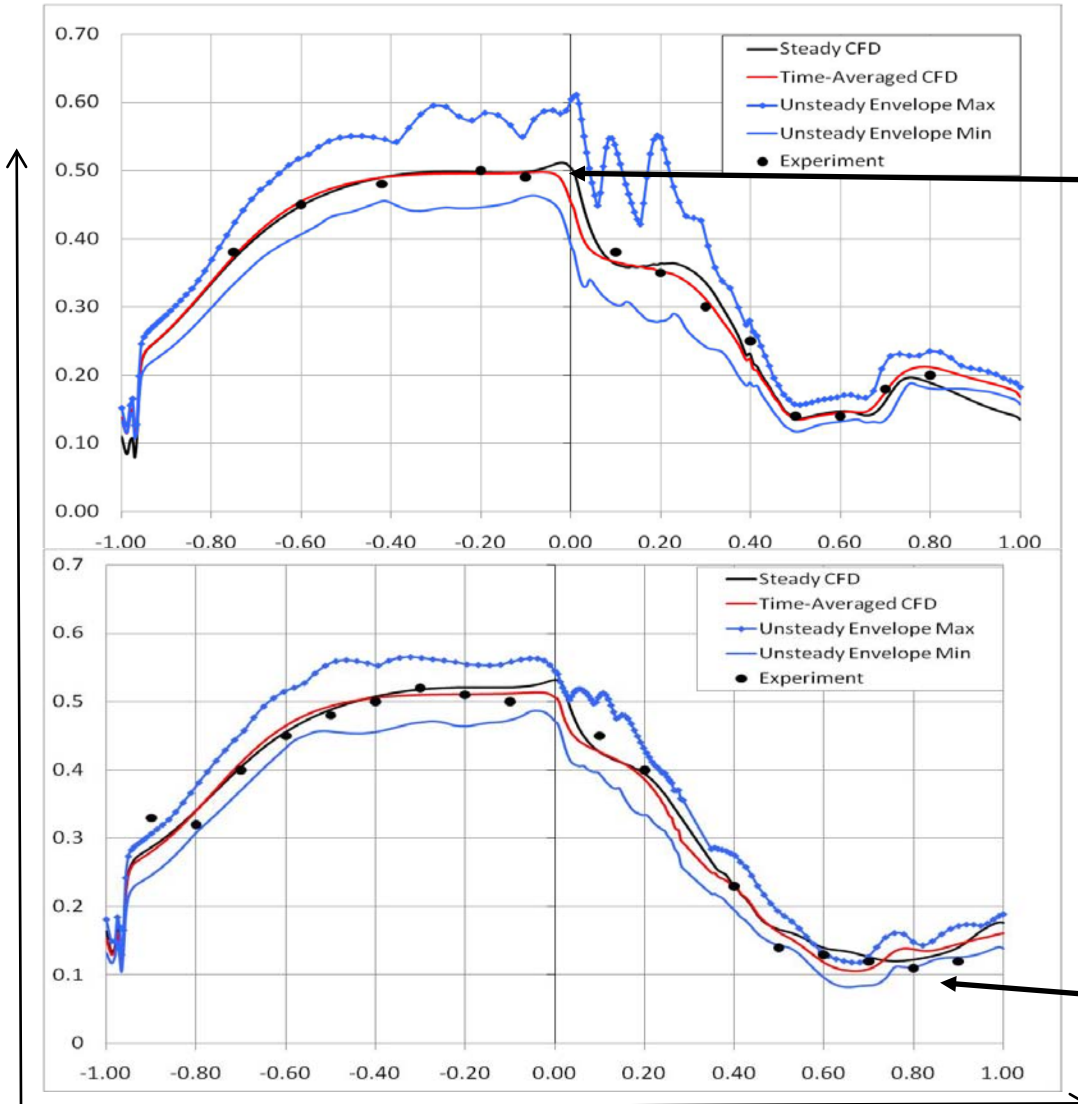
Rotor trailing edge shock

Pressure Profiles

b) 50%

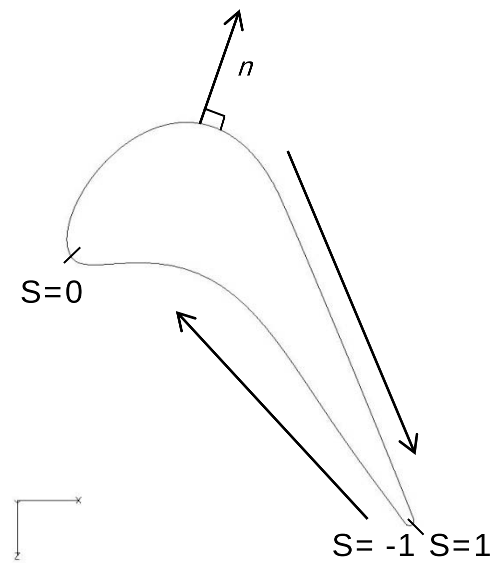
P/P$_{ref}$

c) 90%



S (non dimensional distance along blade profile)

Stag. Point moved to pressure side

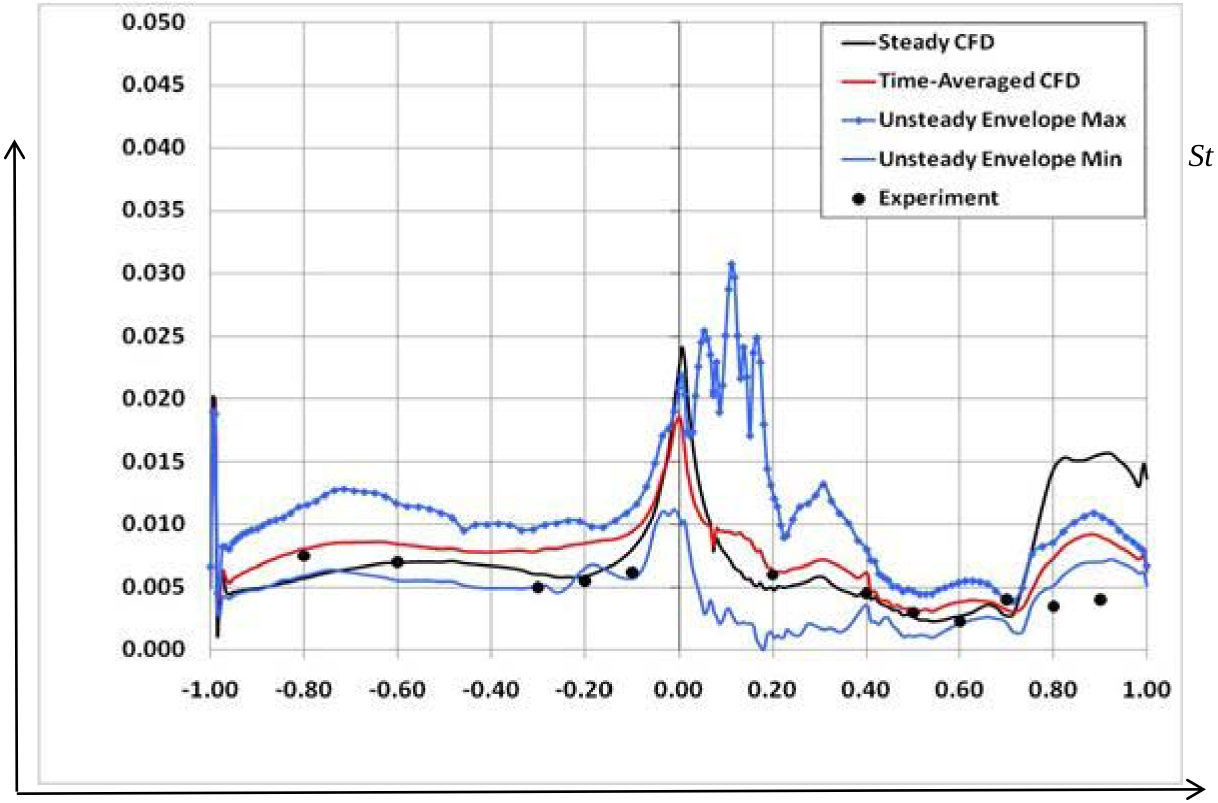


- No shock near tip
- Thin envelope

Stanton Number Profiles

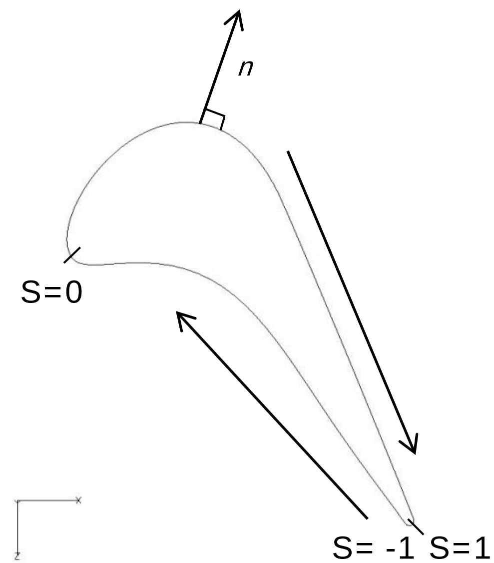
a) 15%

St

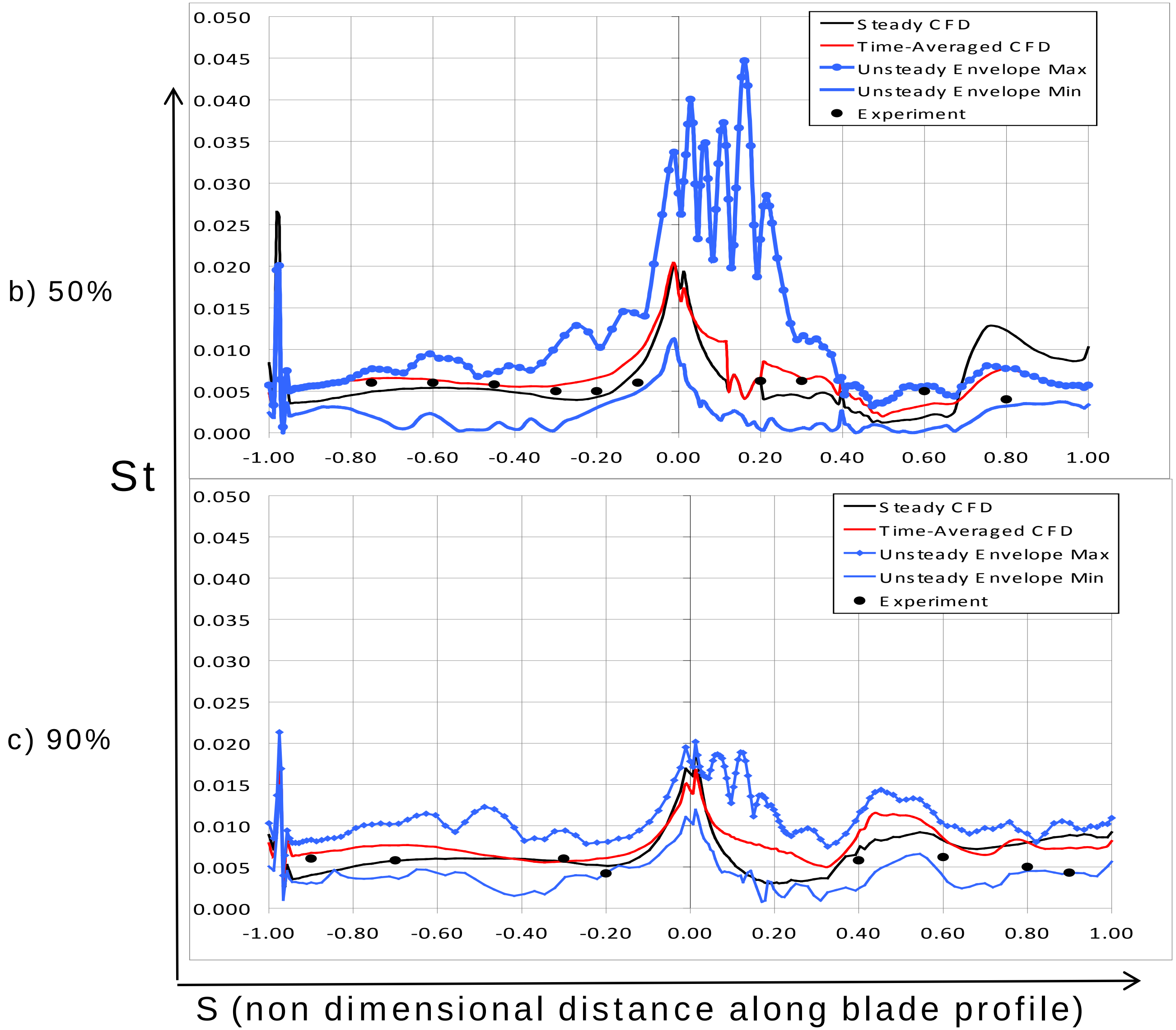


S (non dimensional distance along blade profile)

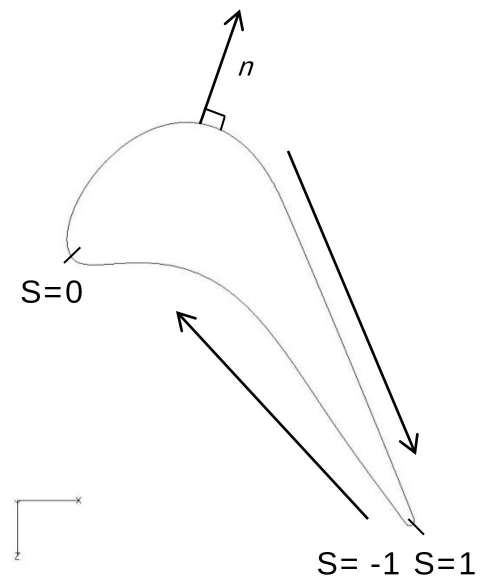
$$St = -\left[\frac{\left.\frac{dT}{dn}\right|_{wall}}{T_{wall} - T_{ref}}\right] \cdot \left[\frac{\mu_{wall}}{(\rho V)_{inlet}}\right] \cdot \frac{1}{Re_{ref} \cdot Pr}$$



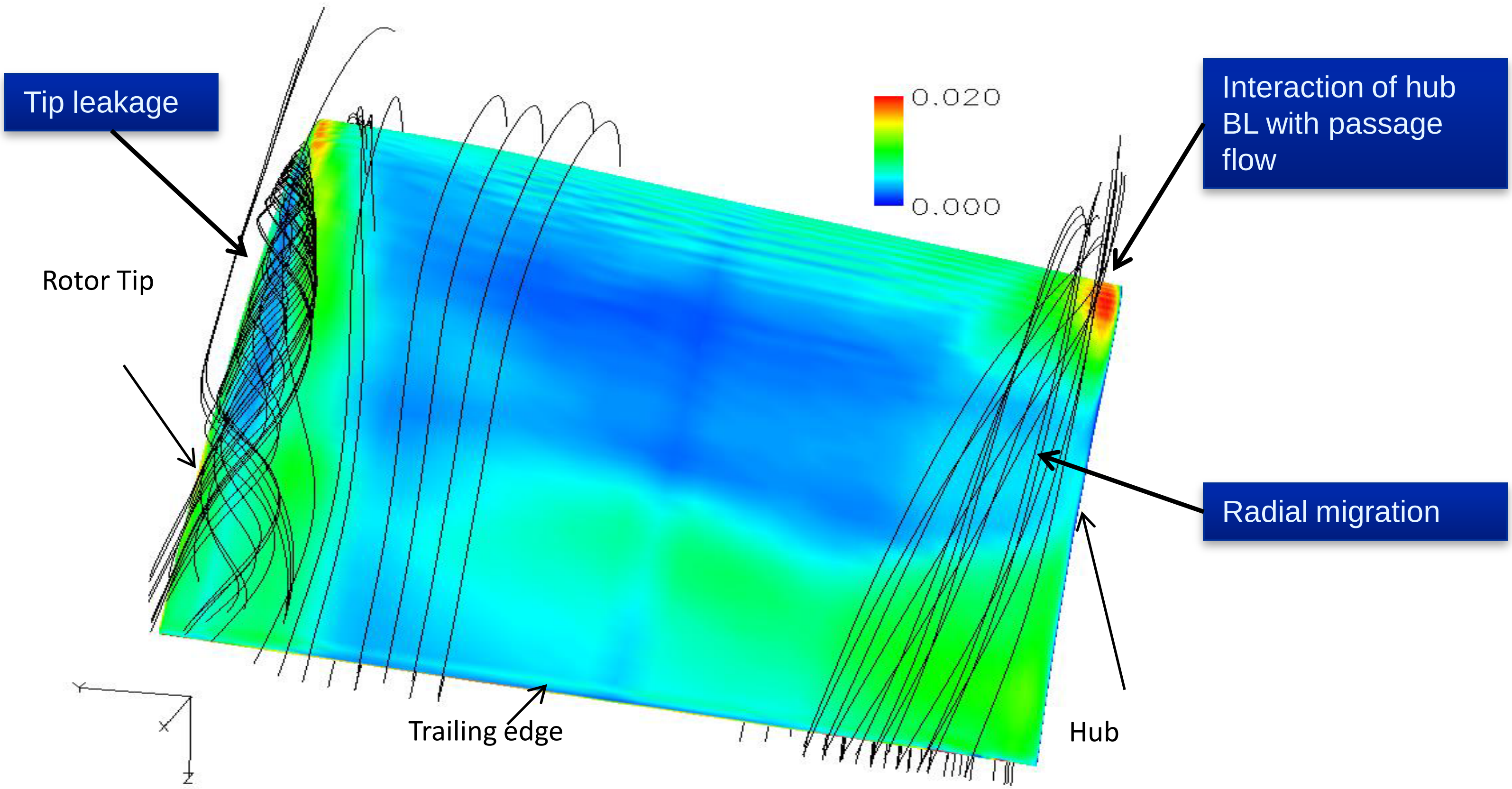
Stanton Number Profiles



$$St = -\left[\frac{\left.\frac{dT}{dn}\right|_{wall}}{T_{wall} - T_{ref}}\right] \cdot \left[\frac{\mu_{wall}}{(\rho V)_{inlet}}\right] \cdot \frac{1}{\mathrm{Re}_{ref} \cdot \mathrm{Pr}}$$

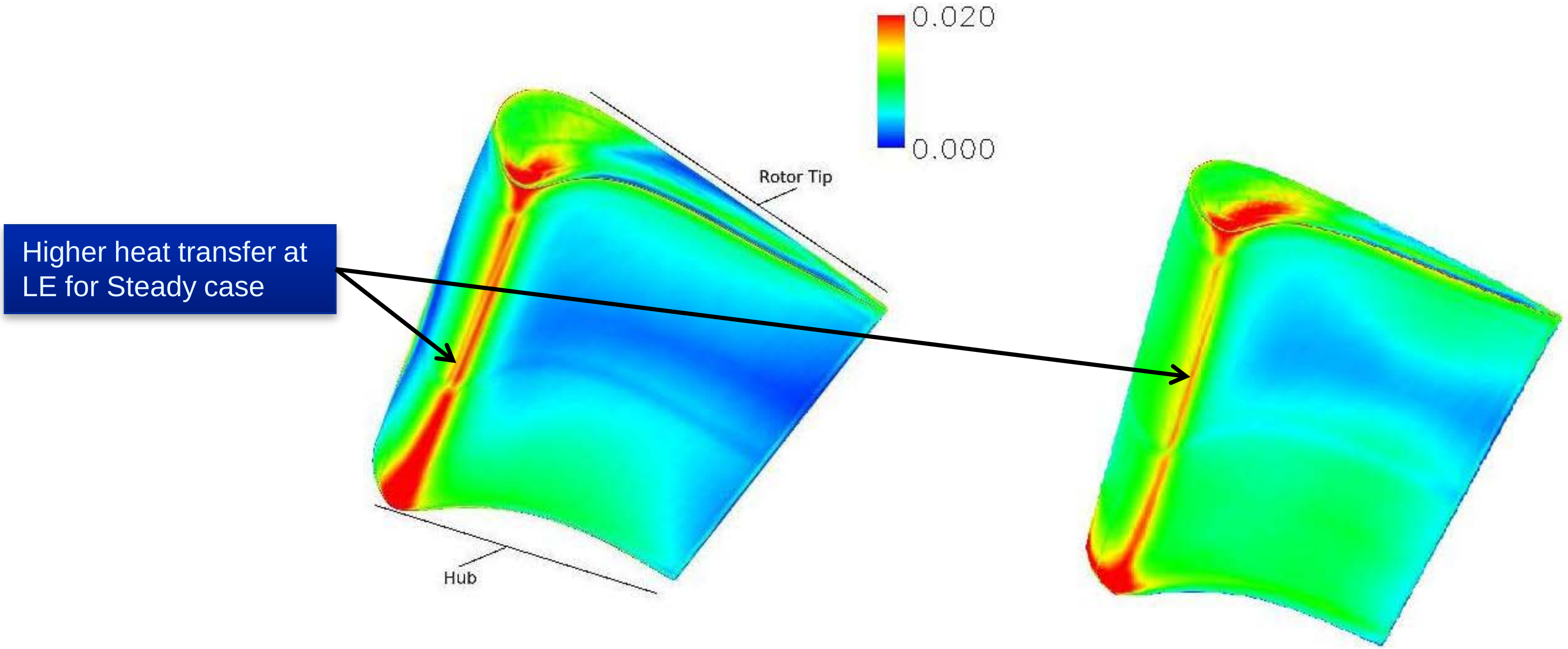


Streamlines



Streamlines of relative velocity over suction side of rotor blade with rotor blade showing Stanton number contours.

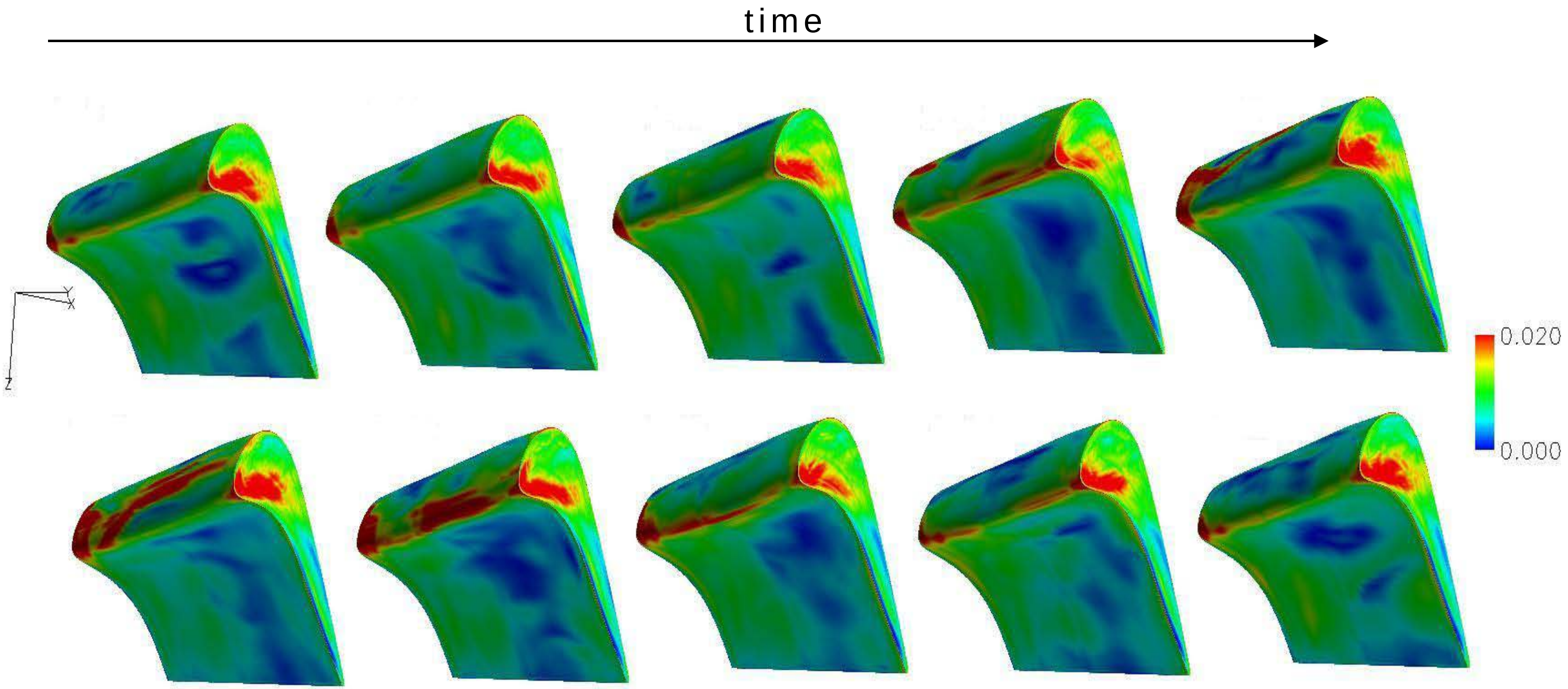
Surface Heat Flux



a) Steady **b) Time-averaged**

Comparison between steady and time-averaged Stanton number distribution on rotor blade pressure side.

Snapshots of Unsteady Heat Flux



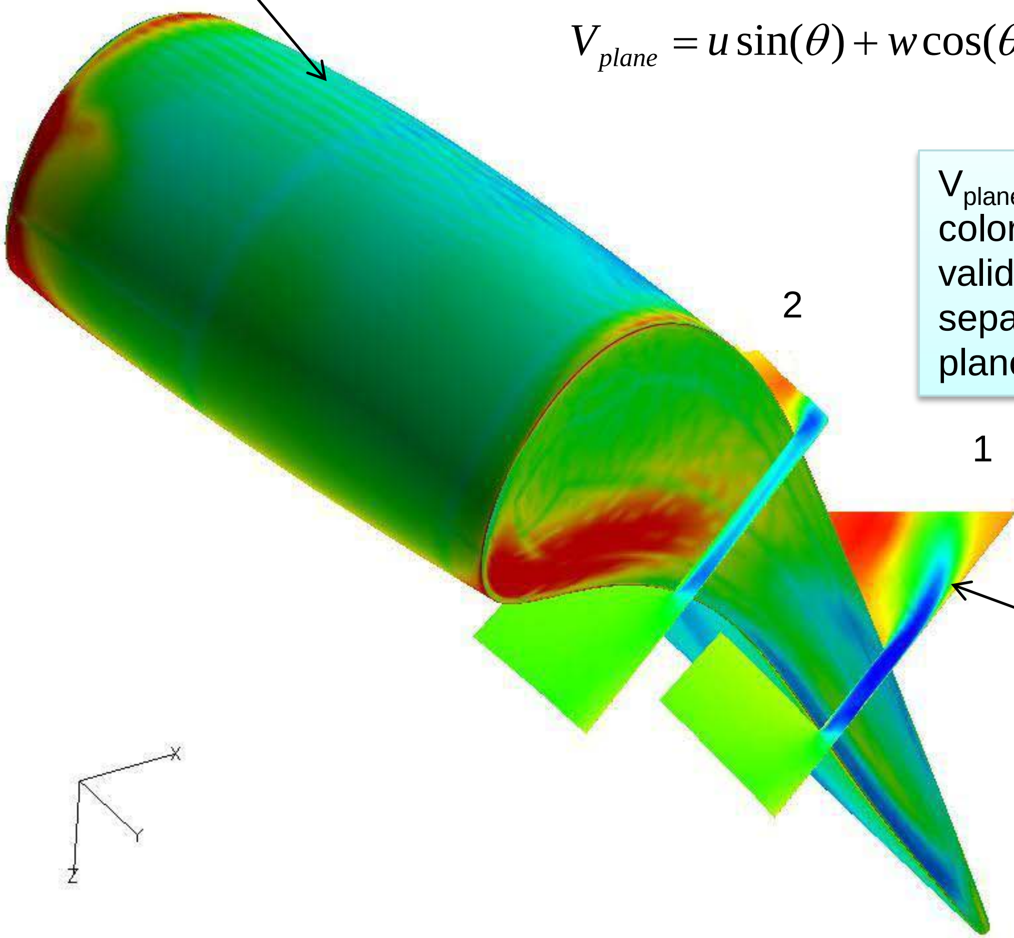
In the Tip Gap

Stanton number on blade

$$\theta = \tan^{-1}\left(\frac{u}{w}\right)$$

$$Isosurface : x - z\tan(\theta) = c$$

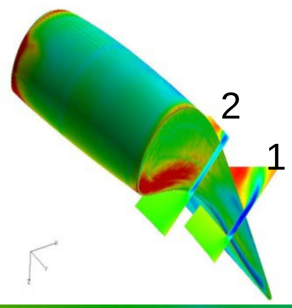
$$V_{plane} = u\sin(\theta) + w\cos(\theta)$$

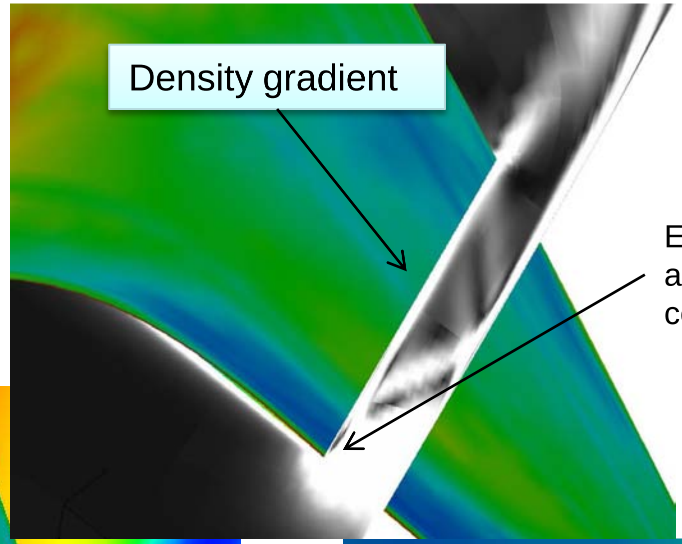


V_{plane} is positive (yellow through red colors) if flow is separated. This is only valid in the tip gap, where flow separation can be measured in the z-x plane

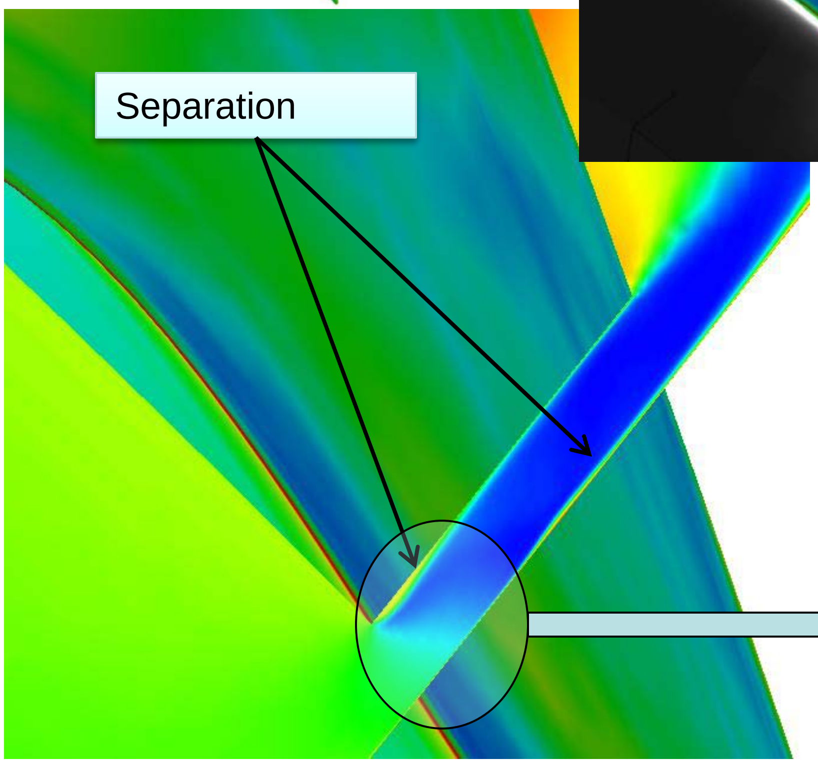
V_{plane} on Iso planes of *c*

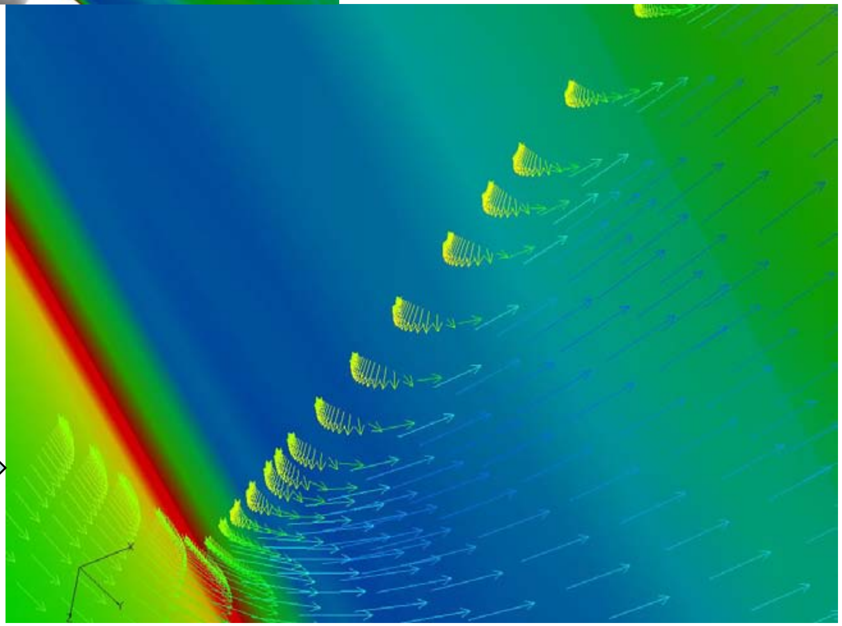
In the Tip Gap – Plane 1



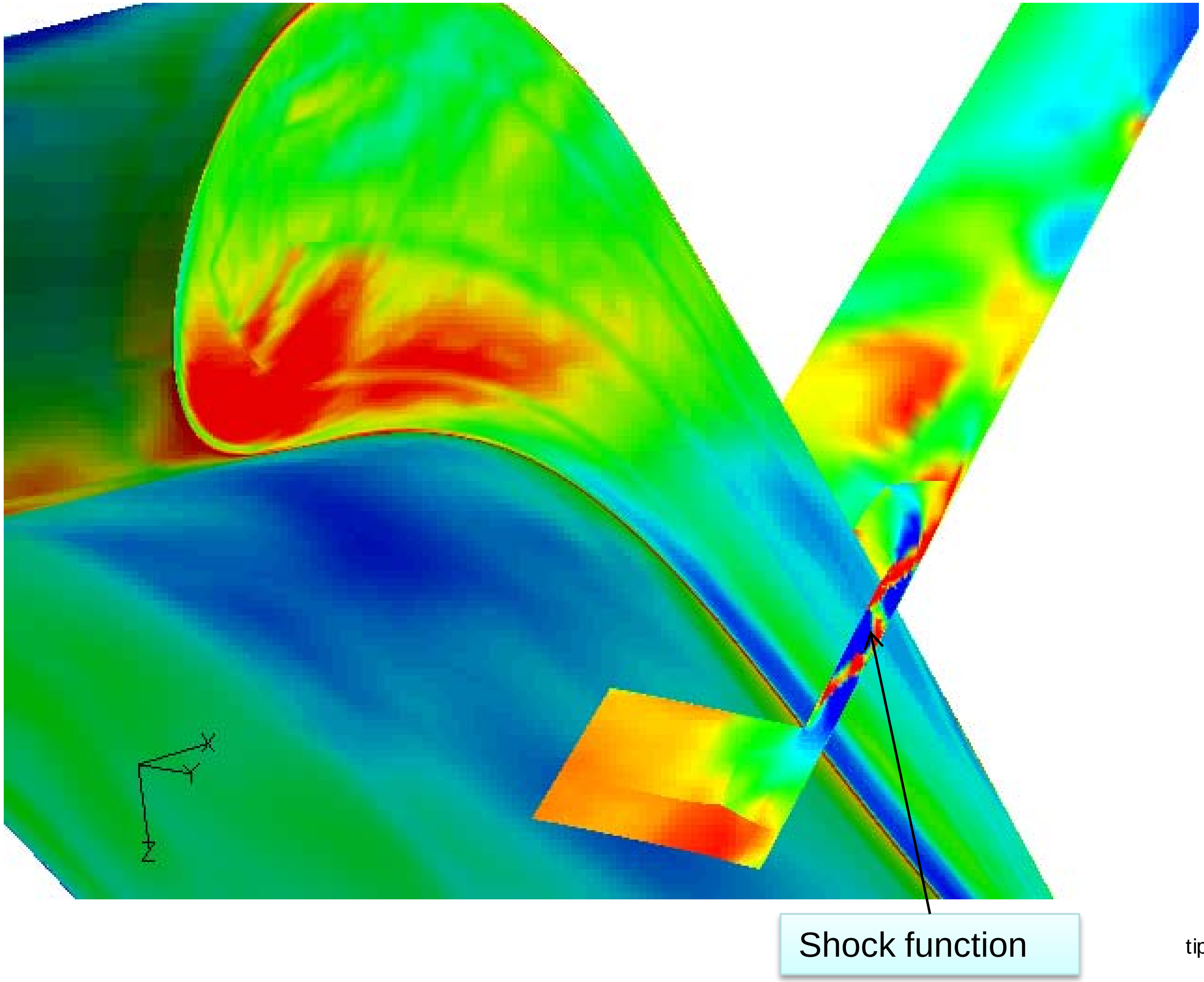


Expands to pressure lower than suction side and then goes through series of compressions and expansions



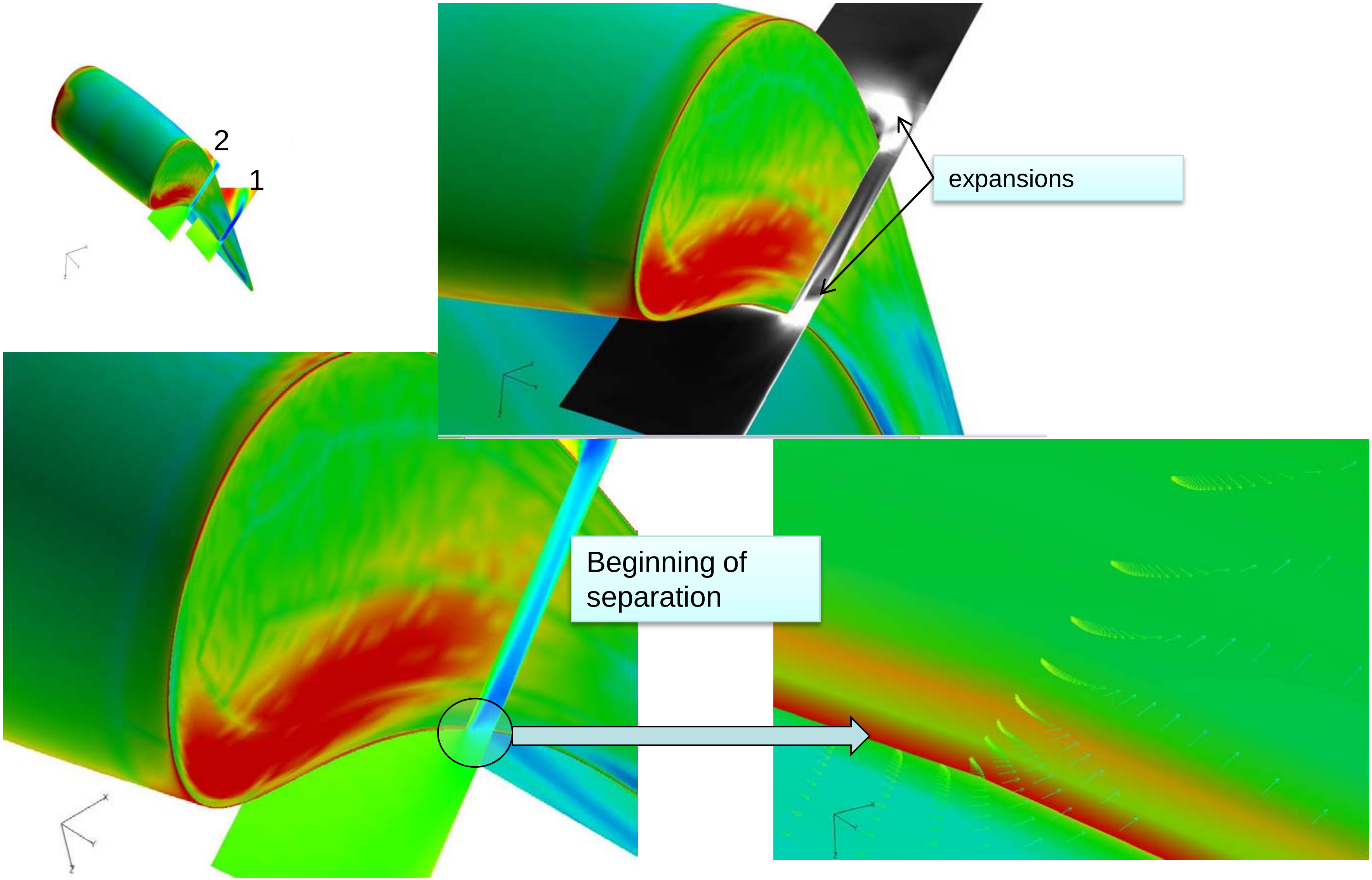


In the Tip Gap – Plane 1 - Unsteady



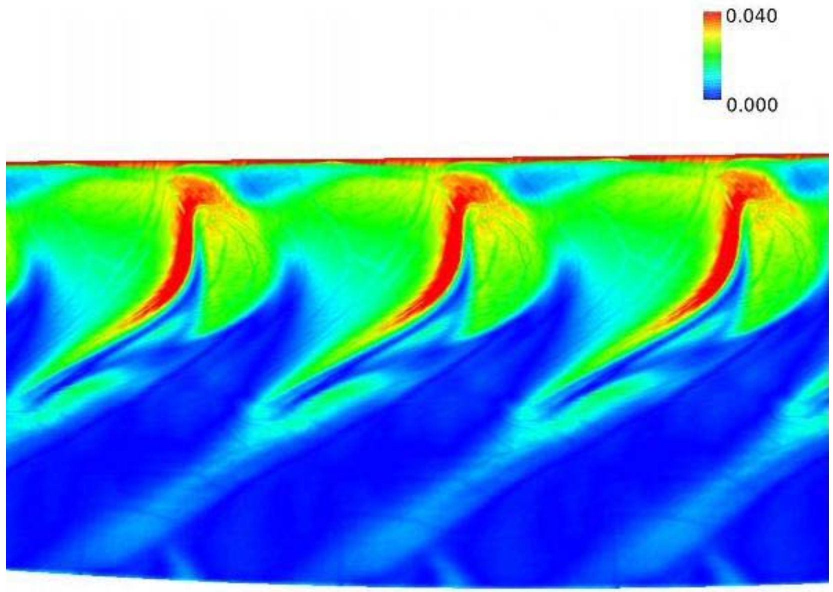
tip_shock3.avi

In the Tip Gap – Plane 2

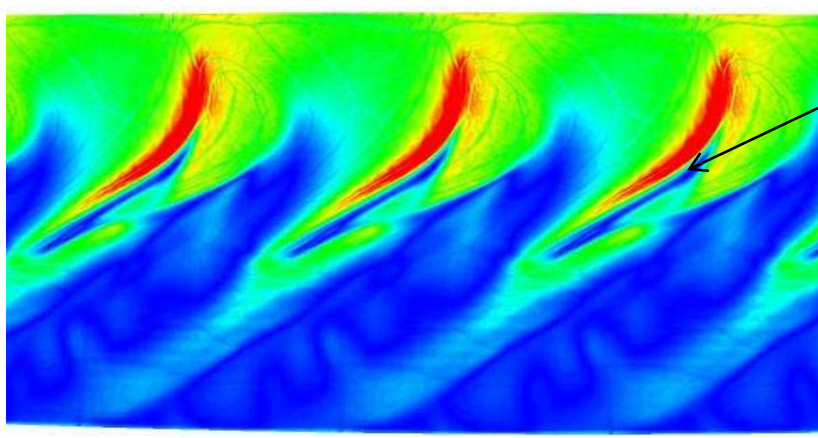


Casing Heat Transfer

Steady



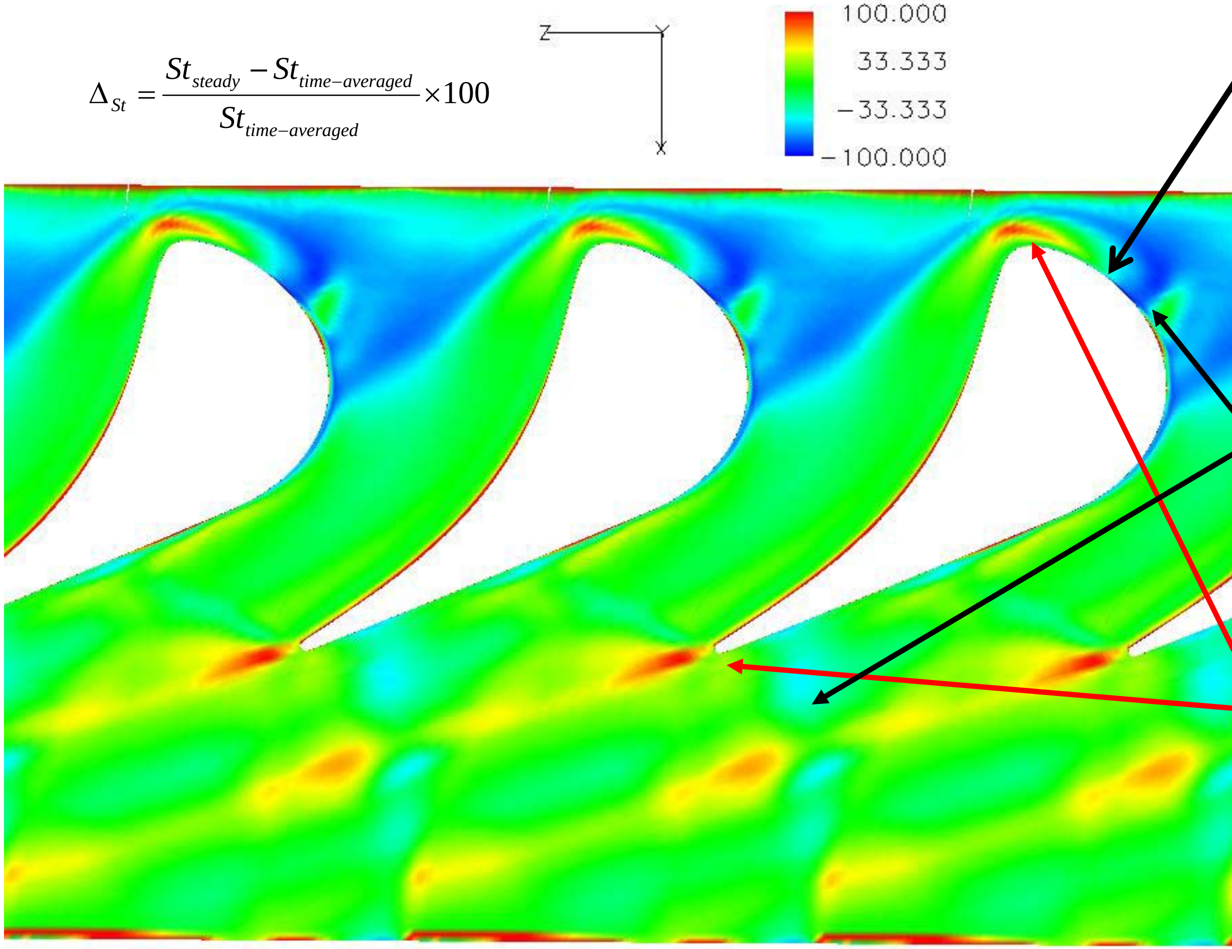
Time-averaged



Corresponds to separation

Hub Heat Transfer

$$\Delta_{St} = \frac{St_{steady} - St_{time-averaged}}{St_{time-averaged}} \times 100$$



Segregation effect

Blue: Time-averaged heat transfer higher

Red: Time-averaged heat transfer lower

Percent difference between steady and time-averaged Stanton number on rotor hub.

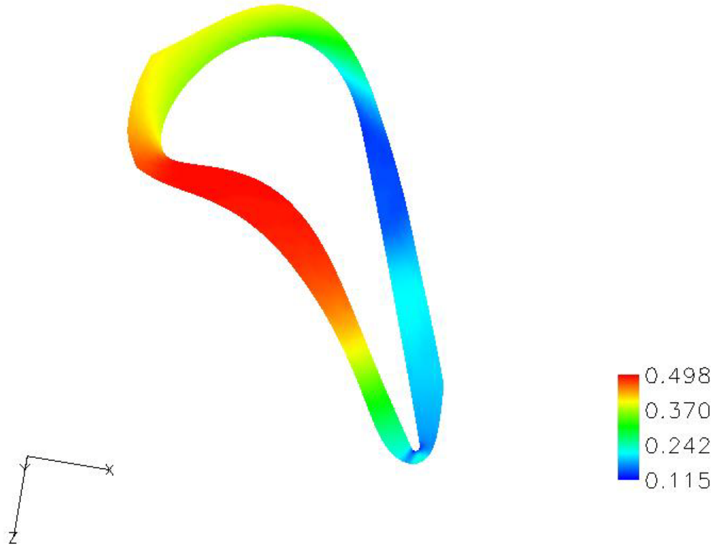
Conclusions

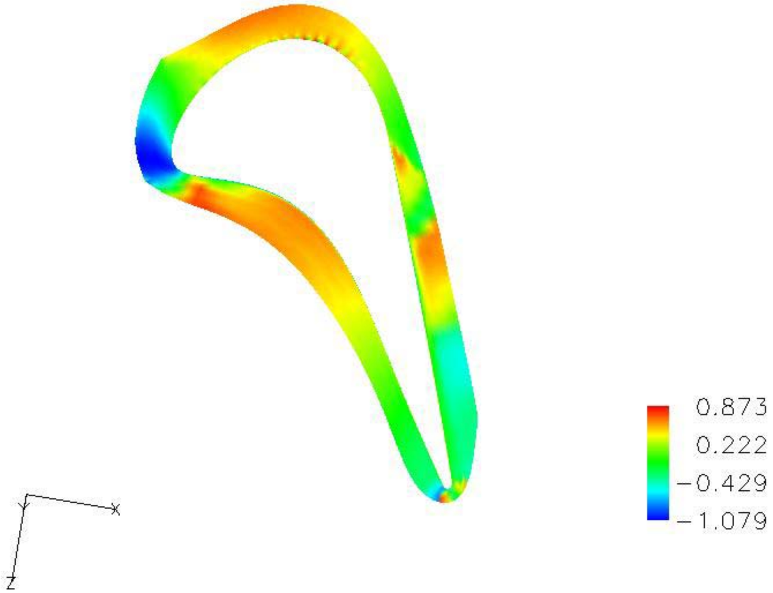
- Over most of blade surface, steady simulation is accurate
- Thermal wake causes unsteady heat transfer over most of the blade to be higher than steady heat transfer except at leading edge.
- At the leading edge the effect of unsteadiness is most prominent
- Thermal redistribution was observed at the hub and on the blade surface
- Pressure and heat transfer distribution over blade is highly 3D

NASA

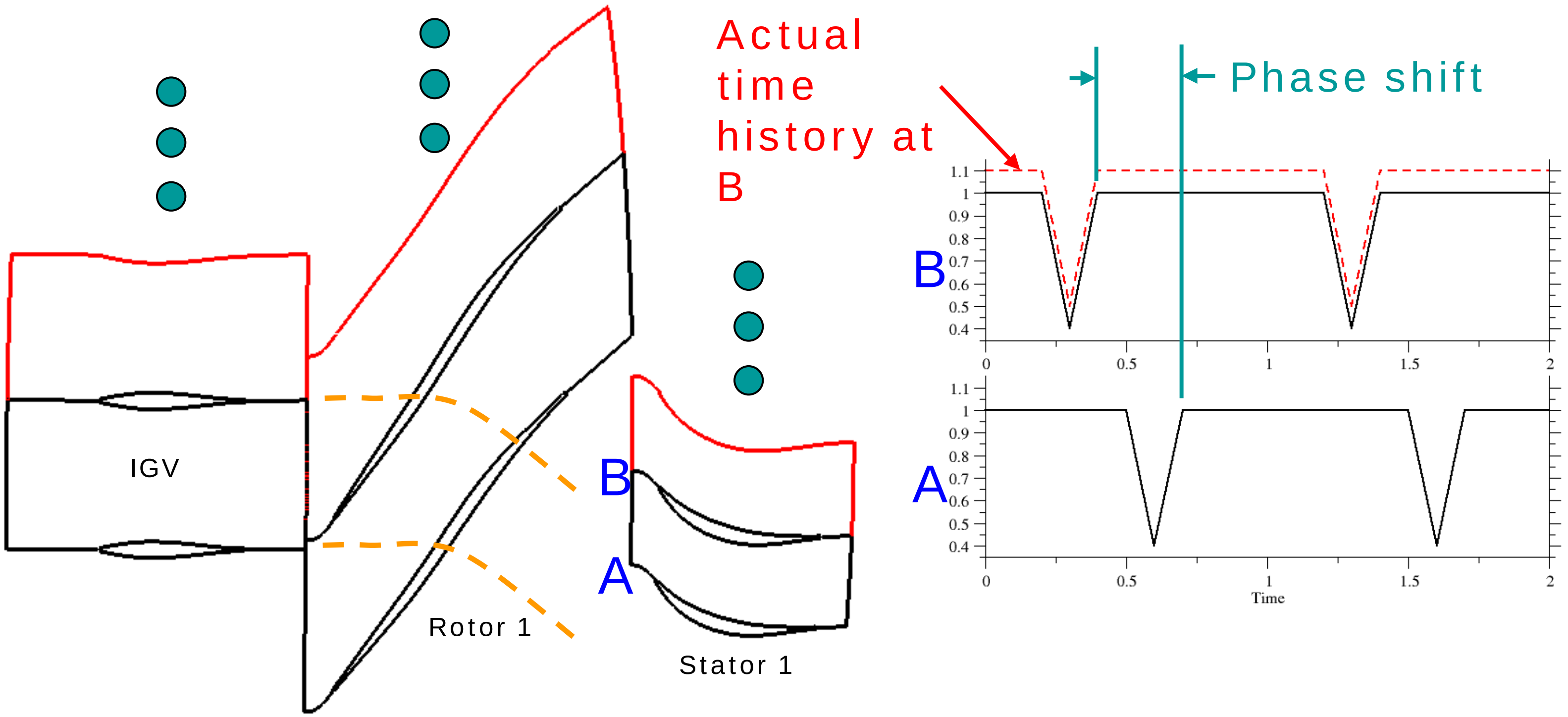
Backup slides

Time averaged P and Shock @ 50% span





The phase lag boundary condition for more than two blade rows

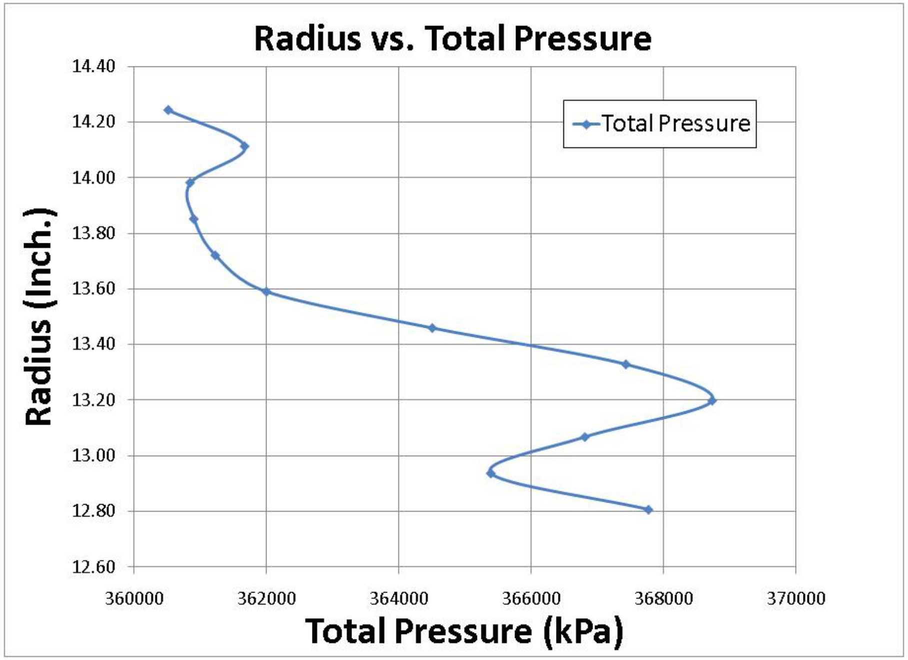


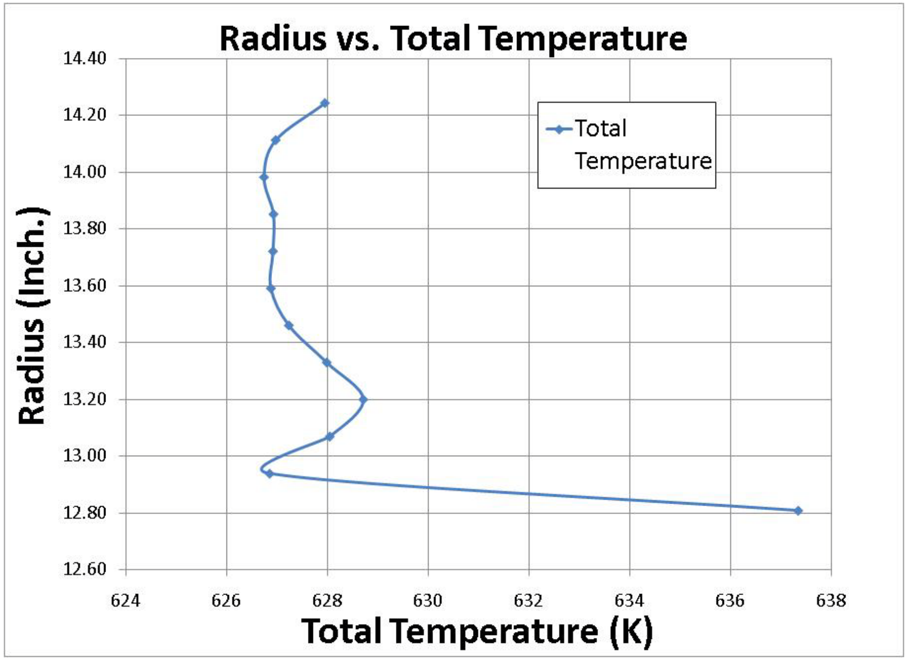
• In this example, adding the IGV wakes creates circumferential non-uniformities at the entrance to stator 1.

• At ‘B’ the phase lag boundary condition will apply the time history of ‘A’ with a phase shift but not the necessary change in the mean.

• This results in a spatial filtering of information for stator-stator (and rotor-rotor) interactions.

Pressure and Temperature Profile at Interface





Stanton No. Derivation

$$St = \frac{h}{c_p \cdot \rho \cdot V} \qquad \text{since } h = \frac{q_{wall}}{T_{wall} - T_{ref}}, \text{ and knowing } \dot{m} = \rho \cdot A \cdot V$$

$$St = \frac{q_{wall}}{\left(\frac{\dot{m}}{A}\right) \cdot c_P \cdot \left[T_{wall} - T_{ref}\right]}$$

$$St = \frac{1}{\rho \cdot V \cdot C_P} \cdot \frac{-k \cdot \frac{dT}{dn}\big|_{wall}}{T_{wall} - T_{ref}}$$

knowing:

$$Pr = \frac{\mu_{wall} \cdot C_P}{k}$$

$$\mu_{wall} = \frac{Pr \cdot k}{C_P}$$

$$\mu_{wall} = \rho_{wall} \cdot \nu_{wall}$$

multiply and divide by μ_{wall} and simplify to obtain:

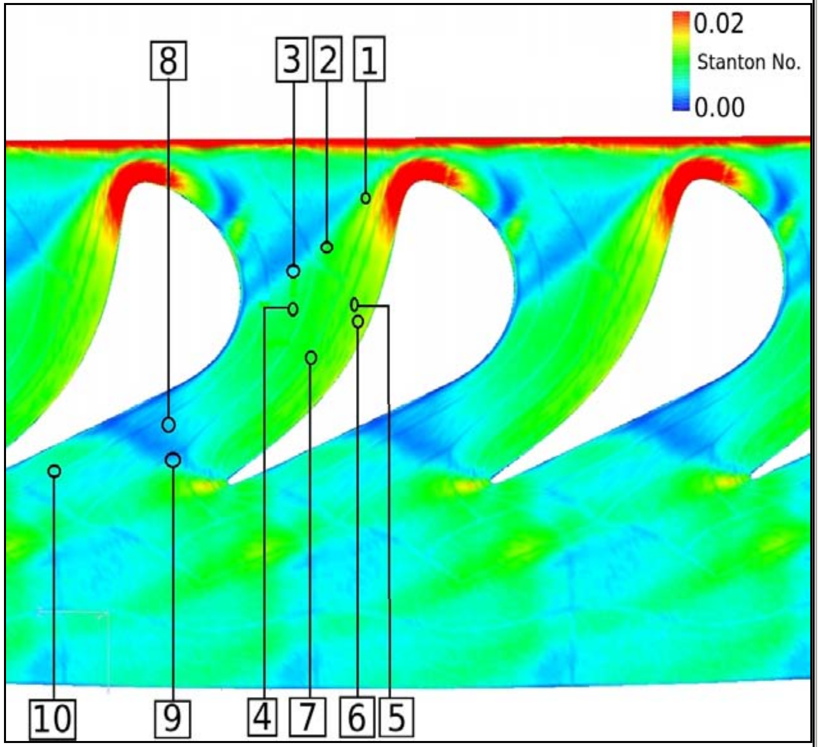
$$St = \frac{-\frac{dT}{dn}\big|_{wall}}{T_{wall} - T_{ref}} \cdot \frac{\mu_{wall}}{\rho \cdot V} \cdot \frac{1}{Pr}$$

An expression in nondimensional terms:

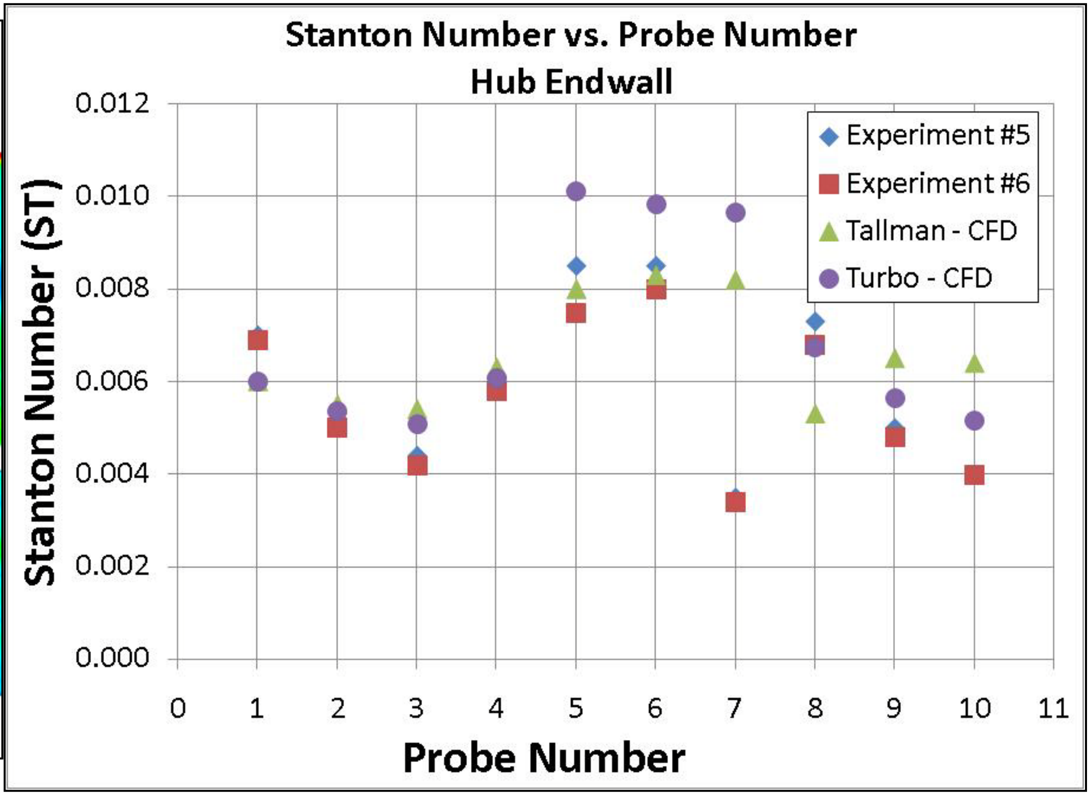
$$St = -\left[\frac{\frac{d\bar{T}}{dn}\big|_{wall}}{\bar{T}_{wall} - \bar{T}_{ref}}\right] \cdot \left[\frac{\bar{\mu}_{wall}}{\bar{\rho} \cdot \bar{V}}\right] \cdot \left[\frac{1}{Pr}\right] \cdot \left[\frac{\mu_{ref}}{\rho_{ref} x_{ref} a_0}\right]$$

Rotor Hub Surface Heat Transfer - Steady

TURBO predictions

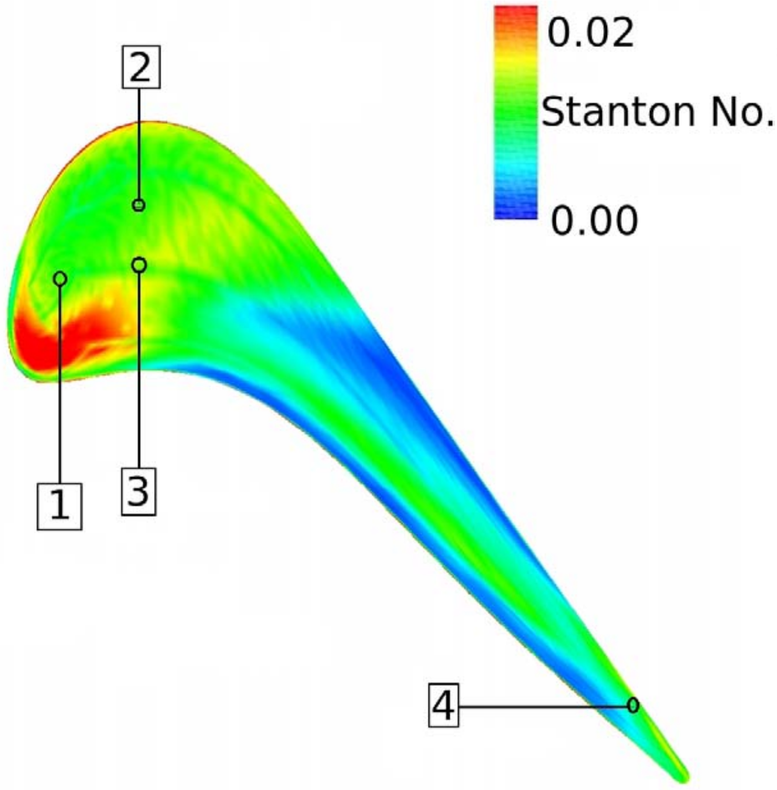


Stanton No. Comparisons

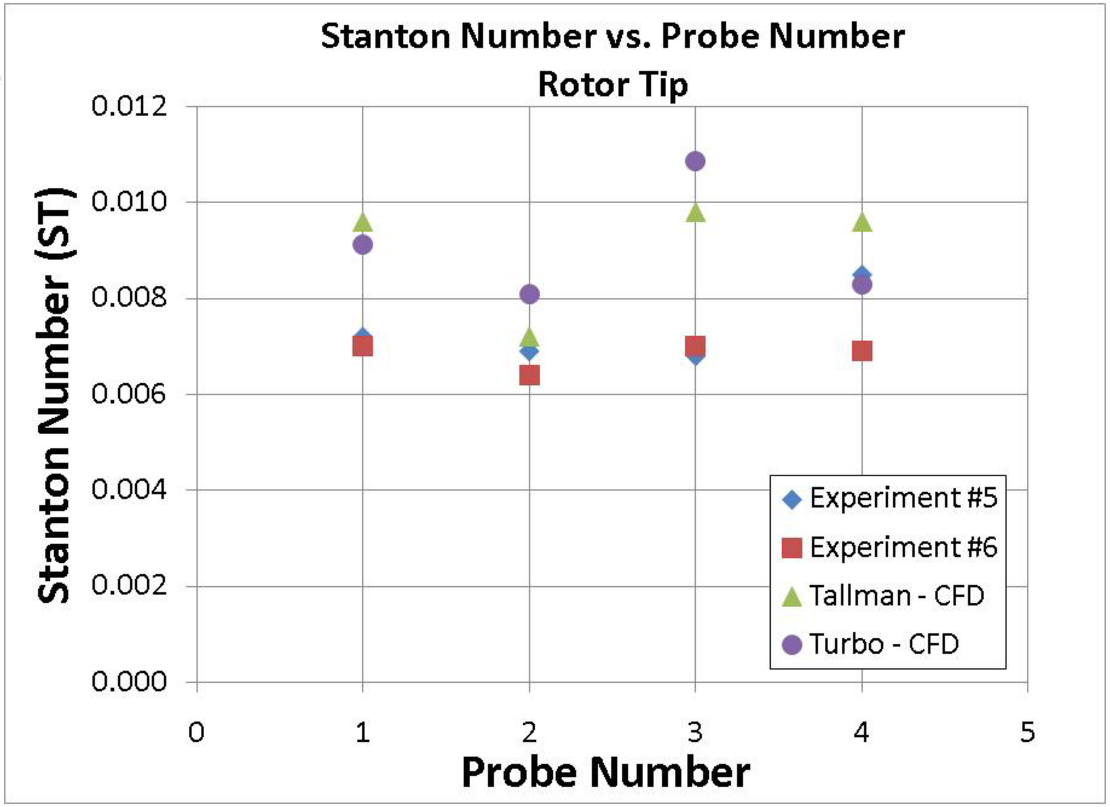


Rotor Tip Heat Transfer – Steady

TURBO predictions

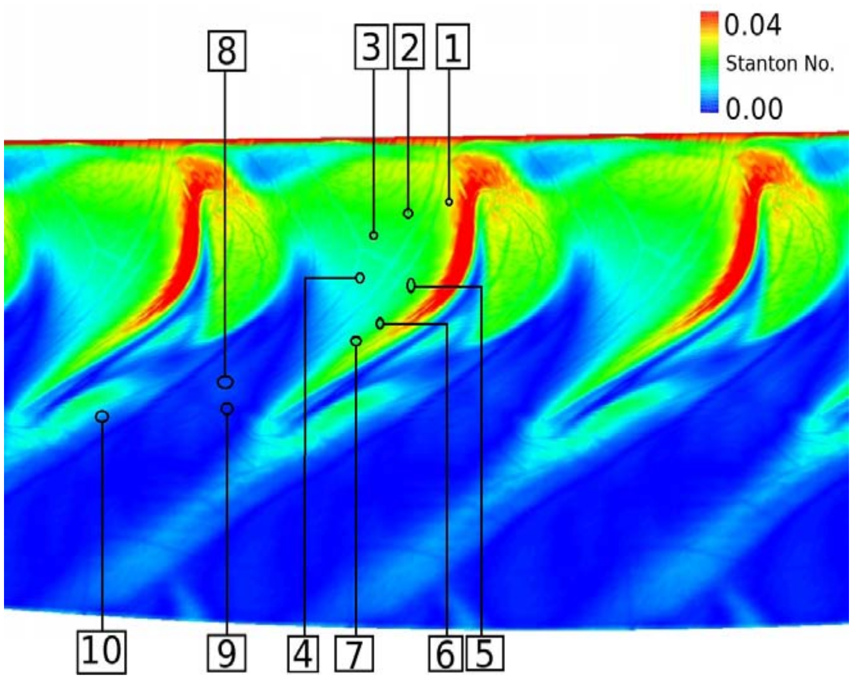


Stanton No. Comparisons

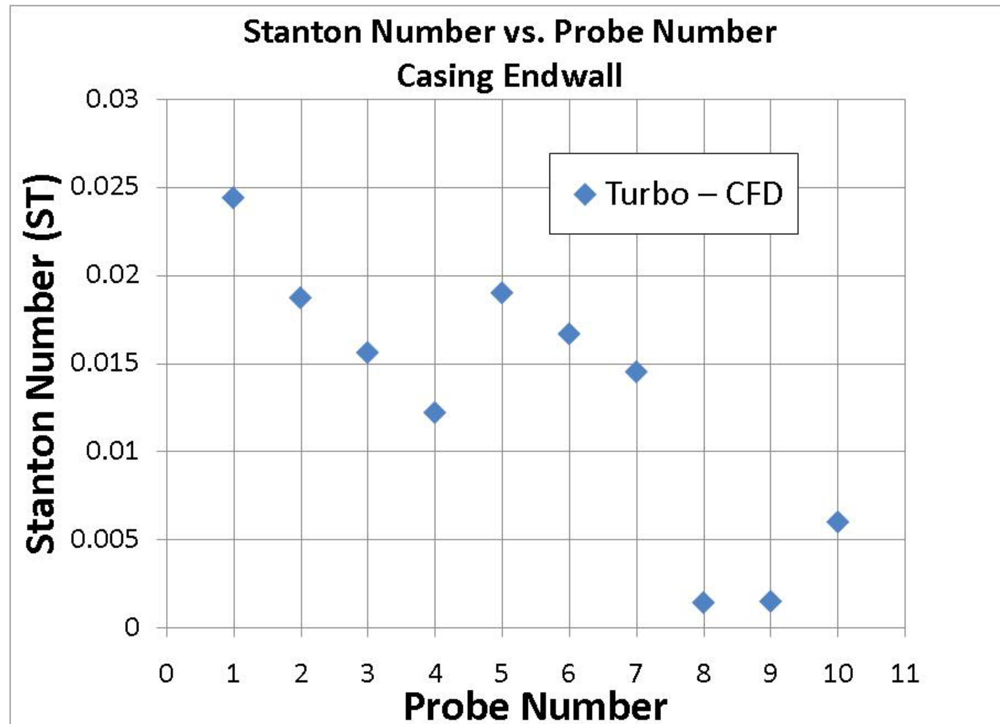


Rotor Casing Surface Heat Transfer - Steady

TURBO predictions



No data available for comparison



Statistics – Steady

Results	TURBO vs. Tacoma	TURBO vs. Experimental
Vane Surface Pressure	Good	Good
Vane Surface Heat Transfer	Good	Good
Blade Surface Pressure	Good	Good
Blade Surface Heat Transfer	Fair	16.3% difference (max: 25%)
Rotor Hub Surface Heat Transfer	13.4% difference	13.1% greater
Rotor Tip Heat Transfer	10.5% difference	15.5% greater

	Iterations	Estimated CPU Time
Stator	30,000	60 Hours
Rotor	40,000	120 Hours