DOE NETL: 24 September 2024

Thermal Management of Zero-to-Near-Zero CO_2 Emission Gas Turbines

Tom I-P. Shih
School of Aeronautics and Astronautics, Purdue University

Mark Bryden
Ames National Laboratory, U.S. Dept. of Energy

Richard Dalton and John Crane
National Energy Technology Laboratory, U.S. Dept. of Energy

Acknowledgement: NETL: Doug Straub, Justin Weber, Matthew Searle
Purdue: Jack Beuchler, Eric Chen, Brandon Hay, Dylan Hsieh, Jay Kim, James Peck, Adwiteey Shishodia

Our nation's goal to reach 100% carbon-free electricity by 2035 opens many challenges and opportunities for gas turbines.

There are many pathways to transition from what we have today
to one that is 100% carbon free!

For the gas-turbine hot section:

- Need to continue pushing the limits of
    - all technologies: combustion (RDE), aerothermal, materials, control
    - all fuels and working fluid: NG, NG + H_2, H_2, ammonia, ammonia + H_2, …; sCO_2

  for **reliable operation**, increased **efficiency**, and increased **service life**.

- **On GT aerothermal**, the need – for any fuel or working fluid – continues to be
    - Reducing aerodynamic loss for **efficiency**.
    - Reducing cooling flow for **efficiency** and **service life**.

Challenges and Opportunities for Aerothermal: NG → NG + H_2 → H_2

RDC: thermal management
sCO2: efficient HX

$H_2 \approx CH_4 /3$ in energy density

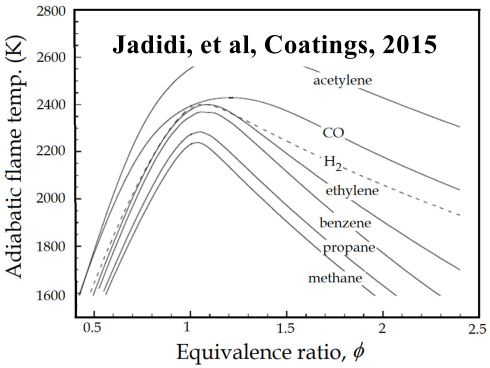
higher volumetric flow rate to get same work output

- more H_2O
- H_2O more efficient than CO_2 on infrared radiation

higher gas radiation

H_2 has higher adiabatic flame temperature

higher temperature in hot-gas path



Increased Thermal load

Other Challenges:
- cost of H_2 manufacture
- infrastructure to transport and store H_2.

Need new designs, which REQUIRE
- deep understanding of the fundamentals.
- better, faster, cheaper D&A tools.

This is the focus of our research!

Objective:

Advance thermal management of gas turbines that enable near-zero to zero CO_2 emissions.

Approach:

1 Assess and encapsulate the literature/knowledge base.

2 Assess and develop tools.

3 Advance fundamentals.

4 Advance applications.

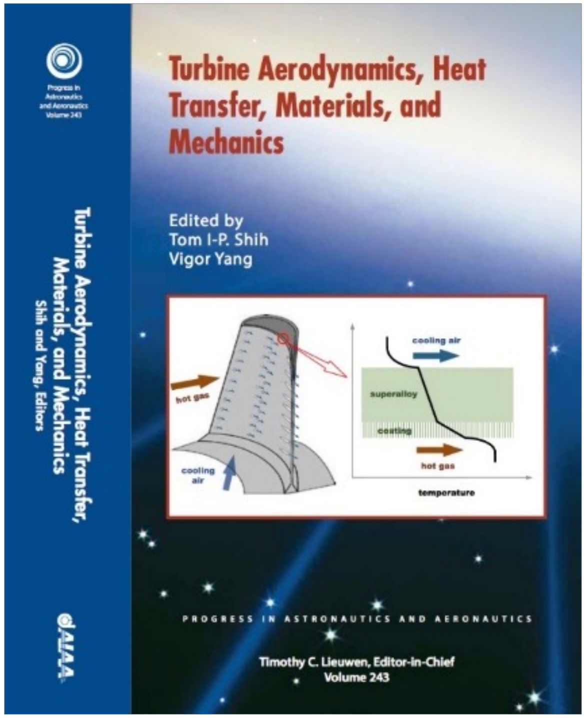
4 Work and coordinate with NETL on the research.

Assess & Encapsulate the Literature

Turbine Aerodynamics, Heat Transfer, Materials, and Mechanics, 2014.

This is the first book that integrates design, aerothermal, mechanics, materials, and failure modes for the turbine component.

Gas Turbine Compressors and Fans: Fundamentals, Design, and Analysis, 2024 or 2025


Progress in Astronautics and Aeronautics Volume 243

Turbine Aerodynamics, Heat Transfer, Materials, and Mechanics
Shih and Yang, Editors

AIAA

Turbine Aerodynamics, Heat Transfer, Materials, and Mechanics

Edited by
Tom I-P. Shih
Vigor Yang

PROGRESS IN ASTRONAUTICS AND AERONAUTICS

Timothy C. Lieuwen, Editor-in-Chief
Volume 243

Table of Content

PART I: The Compressor and Fan Systems

Forward: Alan Epstein (MIT, P&W), Frank Haselbac (AirBus)

Chapter 1: Introduction – Mark Turner (NASA; previously, GE and U. of Cincinnati)
  1.1 Intro to Gas Turbines
  1.2 Intro to compressors and Fans
  1.3 Challenges and Opportunities

Chapter 2: Design-Build-Test Process - Steve Wellborn (Rolls-Royce)
  2.1 Preliminaries
  2.2 Design considerations
  2.3 Aerodynamic Design Process
  2.4 Multidisciplinary Design Process
  2.5 Manufacture
  2.6 Measurements and Testing
  2.7 Health Monitoring and MRO
  2.8 Cost

Steve Wellborn
Tom Shih
Vigor Yang

PART II: Design and Analysis

Chapter 3: Preliminary Design and Analysis – Mark Turner (NASA)

Chapter 4: Aerodynamic Design of Fan Rotors for Ultra-High-Bypass Ratio Turbofan Engines – Ernersto Benini (U. of Padova) and Aspi Wadia (GE)

Chapter 5: Computational Fluid Dynamics for Turbomachinery - Feng Liu & Yalu Zhu(UC Irvine)

Chapter 6: Computational Solid Mechanics and Fluid-Structure Interactions - Wei Zhao (Oklahoma State U.), Sameer Mulani (U. Alabama), Rakesh Kapania (Virginia Tech), and Mani Sadeghi (Pratt & Whitney)

PART III: Physical Processes in Compressors and Fans

Chapter 7: Physical Processes in Fans and Compressors - John Bolger (Rolls-Royce)

Chapter 8: Aerodynamic Noise and Its Control - Xiaofeng Sun and Xiaoyu Wang (Beihang University)

Chapter 9: Seals - Robert Krewinkel (Graz U. of Technology), James Scobie (U. Bath), Luis San Anders (Texas A&M), Mahmut F. Aksit (Sabanci U.), , John C. Blanton (Classic Engineering), and Raymond E. Chupp (REC Consulting)

Chapter 10 Aeromechanics - Matt Montgomery (PW), Bob Kileb (Duke; previously, GE & NASA), and Ken Hall (Duke)

Chapter 11: Corrosion, Erosion, Deposition, and Ground Effect-Sand Ingestion – Stephan Staudacher and Christian Koch (Stuttgart)

Chapter 12: Icing - Eric Loth (Virginia)

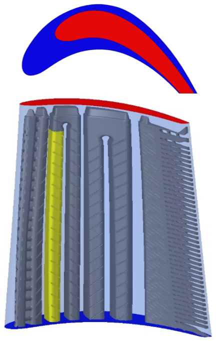
Recent and Current Efforts

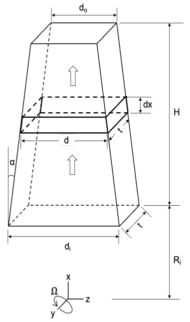
Tools

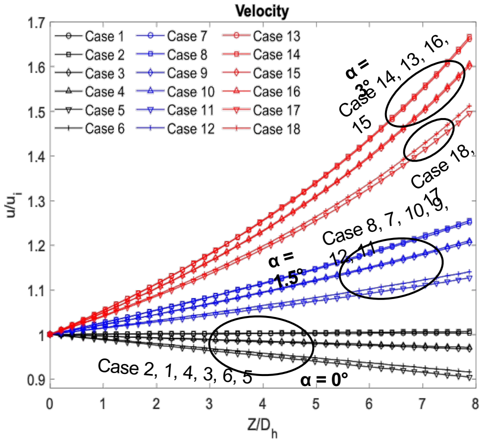
- Hybrid LES-RANS methods (2 papers in IJNMF in 2021 and 2022)
- ROM for tapered cooling ducts in 1st stage turbine (2024 IGTI).
- ROM for conjugate HT in conical cooling ducts with tip leakage in 2nd stage turbine.
- Physics-based ROM for internal cooling of vane & blade w/ 3-D effects.
- Physics-based ROM for internal cooling of RDC
- ROM + Optimization + machine learning for design

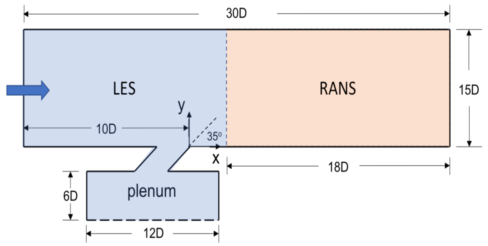
Fundamentals

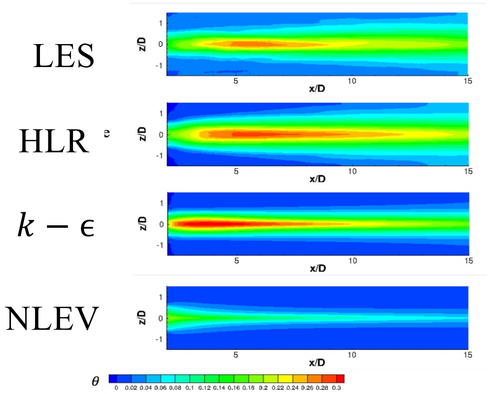
Applications







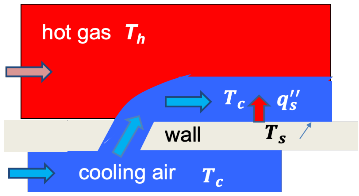


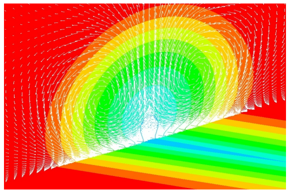


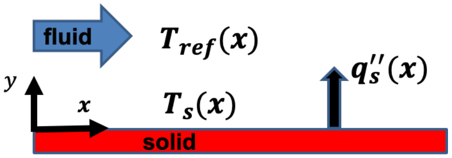
The total number of cells reduced by 35% when compared to the LES. Cost was reduced by 57%.

Max errors in ρ, V, and T relative to steady RANS are 4.9%, 7.1%, 0.9%, 4.7% for a ribbed duct.

Recent and Current Efforts





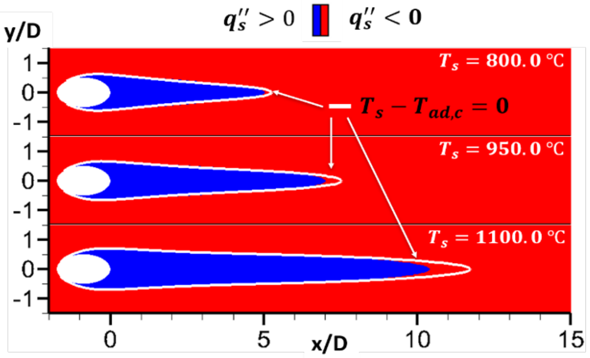


$$q''_s = h(T_s - T_{ref})$$

Tools

Fundamentals

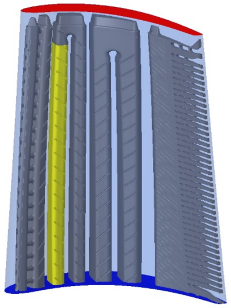
- Revisit $T_{adiabatic}$ on its physical meaning & how to measure/compute (directly to journals in 2024, 2025)
- Revisit film cooling dimensionless parameters (2024 IGTI → accepted JTM)

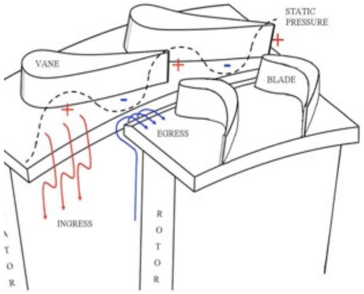


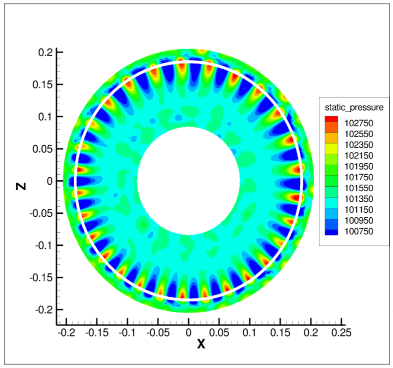
IGTI 2020

Applications

- Internal cooling w and w/o rotation and taper (2024 IGTI → JTM)
- Internal cooling of RDC walls.
- Transition duct from RDC to turbine
- New film-cooling holes: downstream VG with cross flow; Y-shaped hole (Doug Straub & Justin Weber)
- New film-cooling design paradigms from machine learning (w/ Doug Straub & Justin Weber)
- Biot no. analogy to study TBC in sCO2 turbine cooling (w/ Matthew Searle)
- Rotationally & externally-induced rim-seal ingress (2papers in Energies in 2023).
- **Blade-tip leakage in a 1.5 stage turbine via RANS and LES (2025 IGTI, …)**







Hybrid LES-RANS and RANS Study of Tip Leakage Flow in a 1.5 Stage Power-Generation Gas Turbine under Engine-Relevant Conditions

Purdue:	**Adwiteey Shashodia and Tom I-P. Shih**
DoE Ames Lab:	**Mark Bryden**
DoE NETL:	**John Crane**

Acknowledgement: Jay Kim

LES-RANS of Tip-Leakage Flow in a 1.5 Stage Turbine

- Introduction
- Literature Review
- Objective
- Problem Description
- Problem Formulation
- Numerical Method of Solution
- Verification and Validation
- Results
- Summary and Conclusions

In gas turbine, there is a gap between the rotating blades and the shroud.

- ≈ 1 to 2% of blade span during cold start
- hot gas flows across this gap

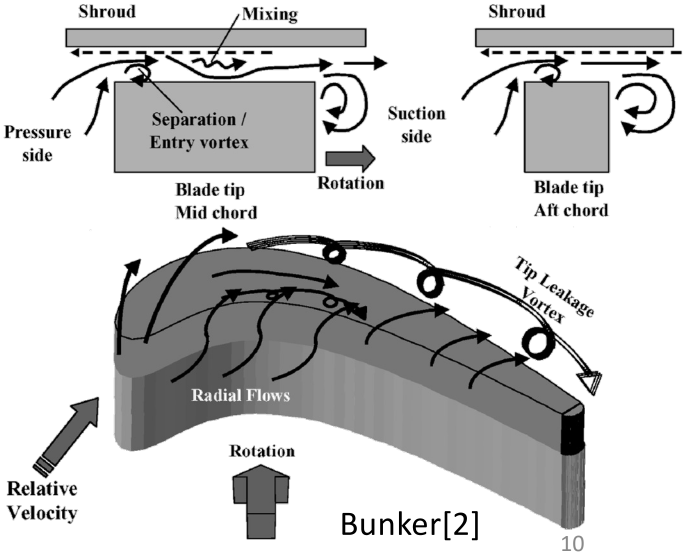
Lavagnoli et al.

Siemens

Tip-leakage flow (TLF) accounts for 1/3 of total turbine stage efficiency loss(Booth, 1985).

Thus, want to **reduce TLF.**

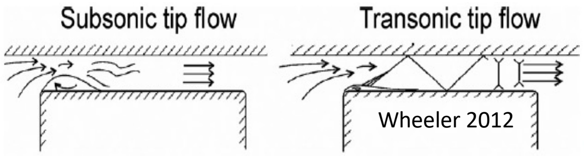
1% decrease in tip gap/span can improve stage efficiency by 2%(Yoon, 2013 & Maesschalck, 2014).



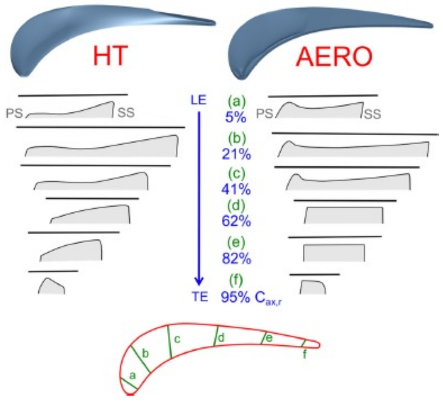
Bunker[2]

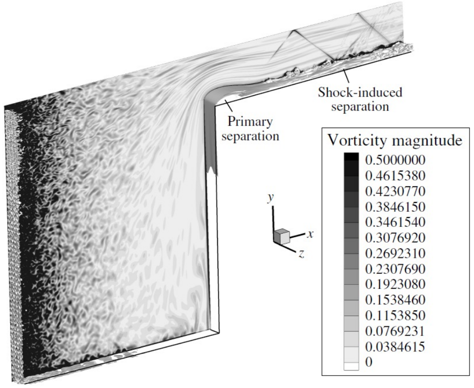
Previous Work

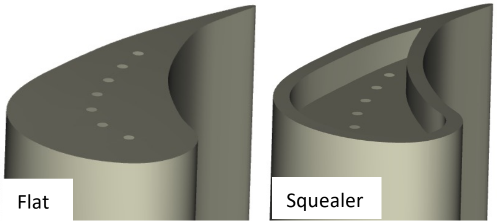
Parameters Studied	Range	Experiment/ CFD
Exit Mach Number	Subsonic, Supersonic	Wheeler et al. (2009 & 2012); Zhang & He (2011); Zhang et al. (2011)
Tip Gap size	0.5 to 2% blade span	Yoon et al. (2014) ; Zhang et al. (2011); Maesschalck et al.(2014); Rahman et al. (2013)
Rotor RPM	1200 to 12000 RPM	Rezasoltani et al. (2015); Rahman et al. (2013)
Tip Design	flat, many variations of squealer, contoured	Mischo et al. (2008); Mischo et al. (2008); Maesschalck et al. (2014 &2016); Zhang & He (2013)
Film-Cooling Design	blade tip, blade's PS, shroud	Rezasoltani et al. (2015); Tamunobere and Acharya (2016); Andreoli V et al. (2019)

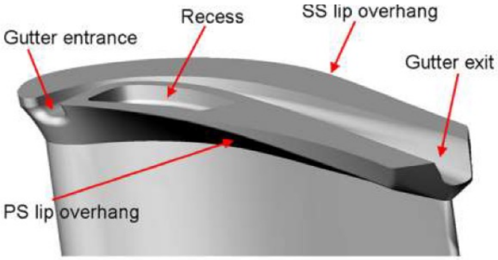


Maesschalck, et al (2014)









O'Dowd et al (2011)

Gaps in the Literature

CFD:

- No LES or hybrid LES-RANS studies to date on the details of the flow in the tip gap including the effects of stator, stator-rotor interaction, and downstream stator.

Benchmark data:

- No time and spatially resolved turbulence and heat transfer data that could be used to improve RANS models and develop reduced order models.
- Changing load with constant RPM – varying mass flow rate

Lab vs Engine-Relevant Conditions:

- No experimental data at engine conditions due to high temperatures. Most experiments are conducted under scaled down operating conditions with simplified blade geometries.

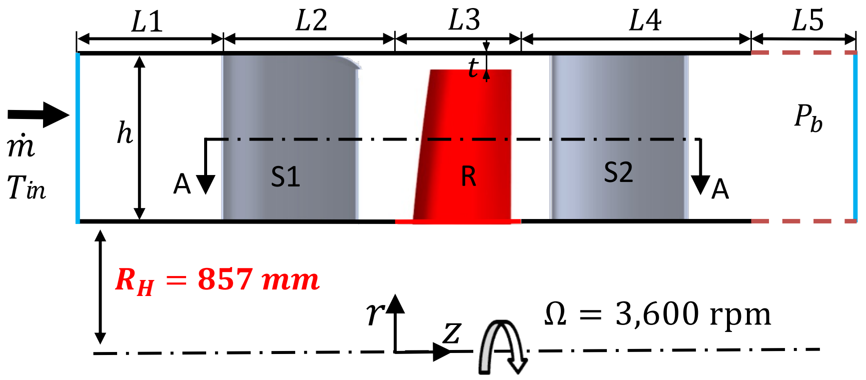
Objectives

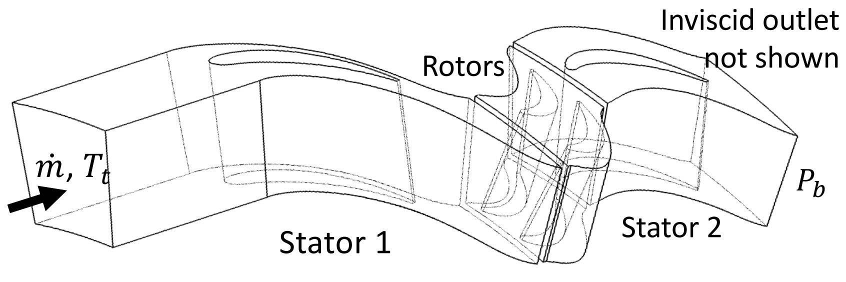
Use **hybrid LES-RANS** to study the flow and heat transfer about the blade tips in a **1.5 stage** power-generation gas turbine **at engine relevant conditions**.

Examine where RANS fails to predict in the 1.5 stage turbine fails and where it succeeds in predicting the flow and performance parameters relative to LES-RANS.

Examine effects of loading with engine speed fixed on flow and heat transfer mass flow rate by using RANS.

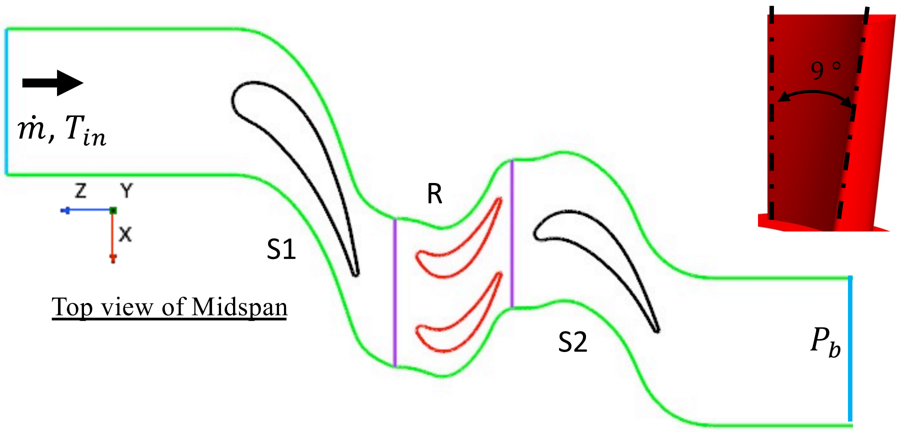
Problem Description: Hybrid LES-RANS





$\dot{m}$ (kg/s) + velocity profile	324 (design), 376 (115%), 250 (75%)
T_{in} (K)	1700
P_b (kPa)	700

$$\boxed{Re_{D_H} = 1.786\times10^{6}}$$



Problem Description: RANS

Electric–power generation GT with twist but no taper on blade.

Added an upstream duct to get “fully developed” flow upstream,]m of stator (length = 20C$_{s1,ax}$).

Assumptions Invoked

ASSUMPTION INVOKED IN THIS CFD STUDY

- "Fully-developed" flow at inflow boundary. Did not consider the large-scale turbulent structure that exit the combustor.
- Adiabatic wall. Vanes, blades, and endwalls do not have internal or film-cooling and no conjugate heat transfer.
- No trailing-edge film cooling. Thus, get vortex shedding in addition to Kevin-Helmholtz instability.
- Did not account for hot-gas path cross-sectional area changes.
- Did not consider endwall and vane/blade contouring.
- Accounted for twist in the blade, but not its taper.

Problem Formulation & Numerical Method: Hybrid LES-RANS

- **Problem Formulation**
  - Inertial frame for stators and non-inertial frame for rotor
  - Favre-averaged “3D, unsteady” continuity, compressible Navier-Stokes, and total energy for RANS part of IDDES
  - Filtered “3D, unsteady” continuity, compressible Navier-Stokes, and total energy for LES part of IDDES
  - RANS to/from LES via IDDES

  closed by
  - thermally perfect gas
  - temperature-dependent transport properties
    - Sutherland’s model for viscosity and thermal conductivity
    - Specific heat, $c_p(T) = 1.1529 \cdot 10^3 - 9.5080 \cdot 10^{-1} T + 2.2003 \cdot 10^{-3} T^2 - 1.8939 \cdot 10^{-6} T^3 + 7.4571 \cdot 10^{-10} T^4 - 1.1197 \cdot 10^{-13} T^5$
    - Prandtl number, $Pr(T) = c_p(T) \times \mu / k(T)$
  - LES - RANS: Modified Shear-Stress-Transport (SST) model (wall functions not used)

  BCs: specify $\dot{m}$ (with velocity profile), T, and turbulent quantities at inflow; p_b at outflow
- **Code**
  - cell-centered finite volume code, SIEMENS STAR-CCM+ V.2206 (double precision)
- **Numerical Method**
  - fully coupled implicit algorithm
  - 2nd order Roe upwind for inviscid fluxes
  - algebraic multigrid with V-cycle to accelerate convergence at each time step (20 to 30 iterations)

Problem Formulation & Numerical Method: RANS

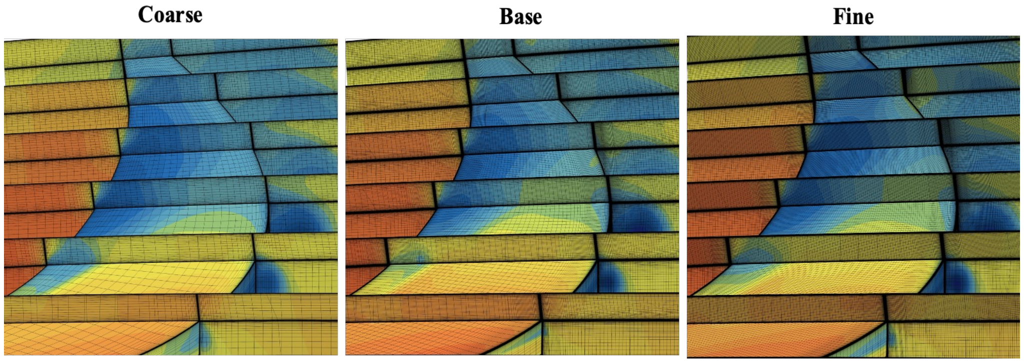
- **Problem Formulation**
  - Inertial frame for stators and non-inertial frame for rotor
  - Favre-averaged continuity, compressible Navier-Stokes, and total energy

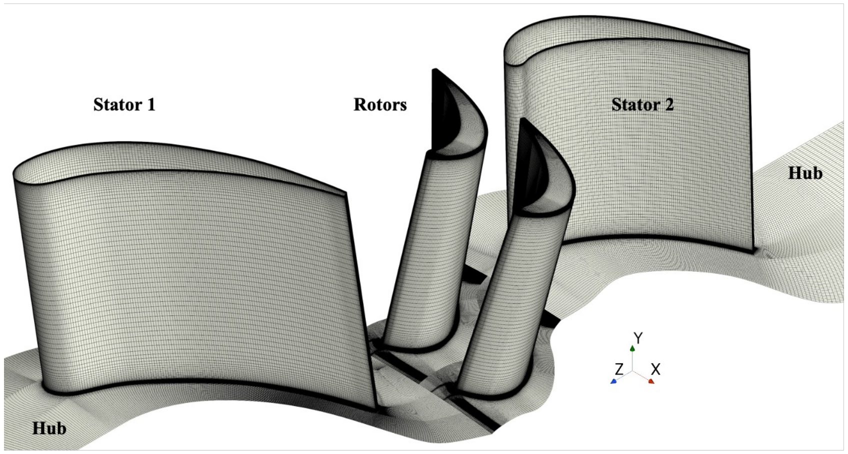
  closed by
  - thermally perfect gas
  - temperature-dependent transport properties
    - Sutherland's model for viscosity and thermal conductivity
    - Specific heat, $c_p(T) = 1.1529\cdot10^{3} - 9.5080\cdot10^{-1}T + 2.2003\cdot10^{-3}T^{2} - 1.8939\cdot10^{-6}T^{3} + 7.4571\cdot10^{-10}T^{4} - 1.1197\cdot10^{-13}T^{5}$
    - Prandtl number, $Pr(T) = c_p(T) \times \mu / k(T)$
  - Shear-Stress-Transport (SST) model (wall functions not used)

  BCs:
  - specify $\dot{m}$ (with uniform velocity profile), T, and turbulent quantities at inflow; p_b at outflow
  - mixing plane at rotor-stator interface
- **Code**
  - cell-centered finite volume code, SIEMENS STAR-CCM+ V.2206 (double precision)
- **Numerical Method**
  - fully coupled implicit algorithm
  - 2nd order Roe upwind for inviscid fluxes
  - algebraic multigrid with V-cycle to accelerate convergence to steady state

V&V: Grid-Sensitivity Study

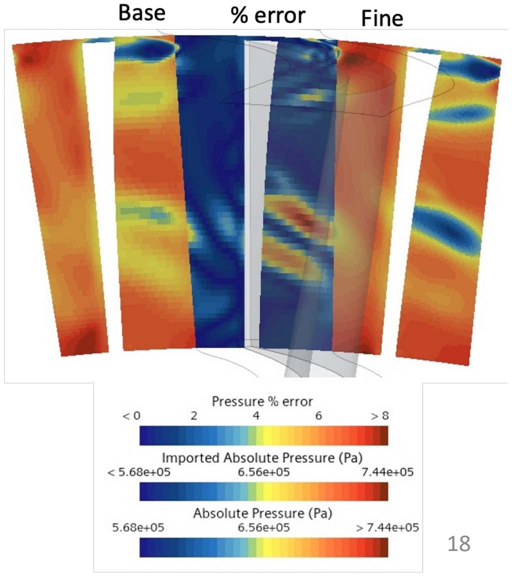
Domain	**Coarse** $r \times \theta \times z$ (O-grid) total	**Baseline** $r \times \theta \times z$ (O-grid) total	**Fine** $r \times \theta \times z$ (O-grid) total
Inlet Duct	60×40×75 **0.18 mil**	140×75×150 **1.57 mil**	200×100×180 **3.6 mil**
Stator 1 (10 deg)	75×75×150 (25) **1.1 mil**	150×145×275 (50) **7.7 mil**	225×240×390 (80) **39.45 mil**
Rotor (5 deg)	130×65×165 (30) **1.6 mil**	225×130×335 (55) **15.65 mil**	345×240×540 (70) **63.51 mil**
Stator 2 (10 deg)	80×50×150 (25) **0.84 M**	150×100×265 (50) **5.59 M**	210×145×285 (65) **11.83 M**
TOTAL RANS	**3.8 M**	**31 M**	**106 M**



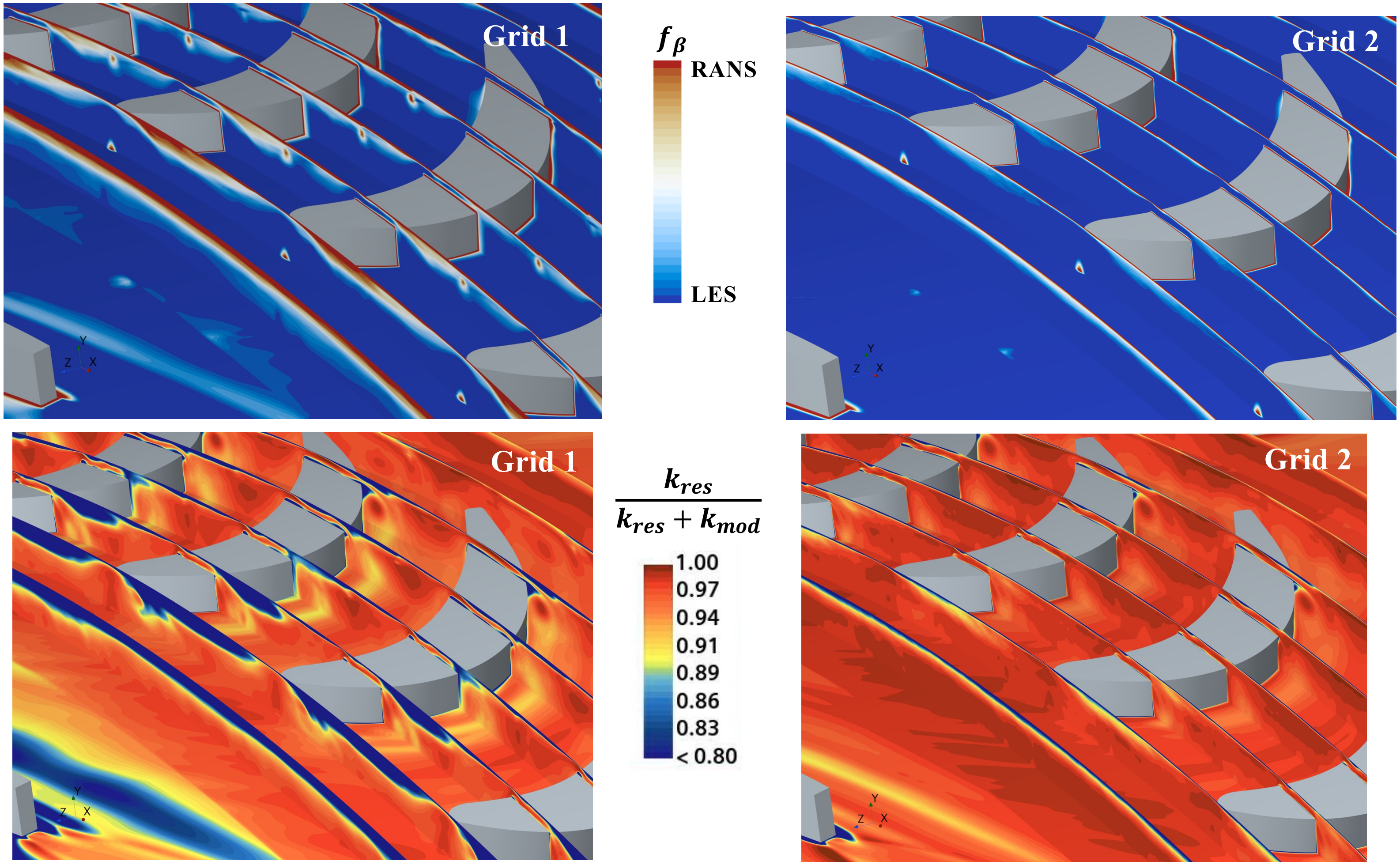


45, 75, and 125 in the radial direction inside the tip gap.

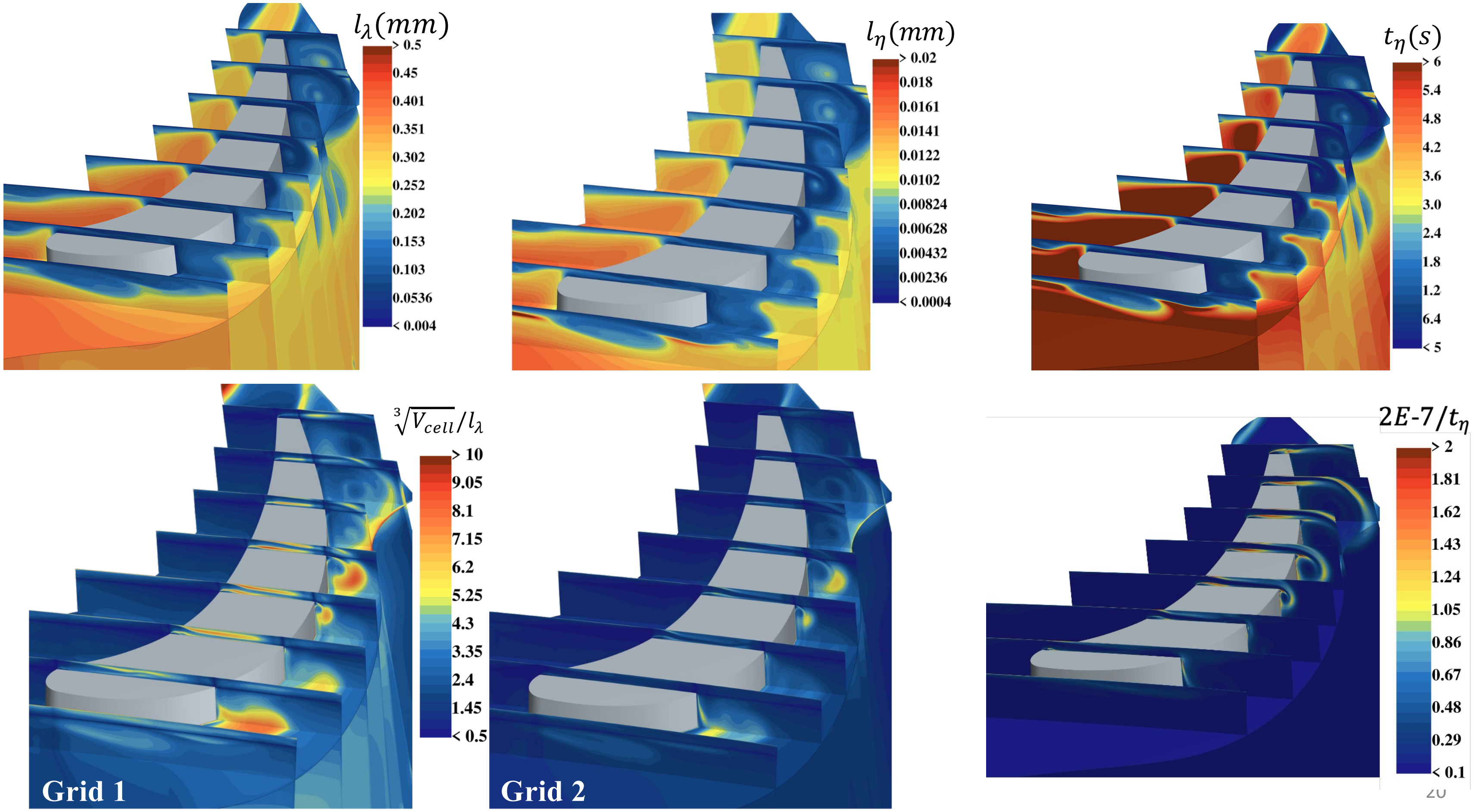
1st cell next to wall: $y^+ < 1$



Verification: Blade–Tip Region

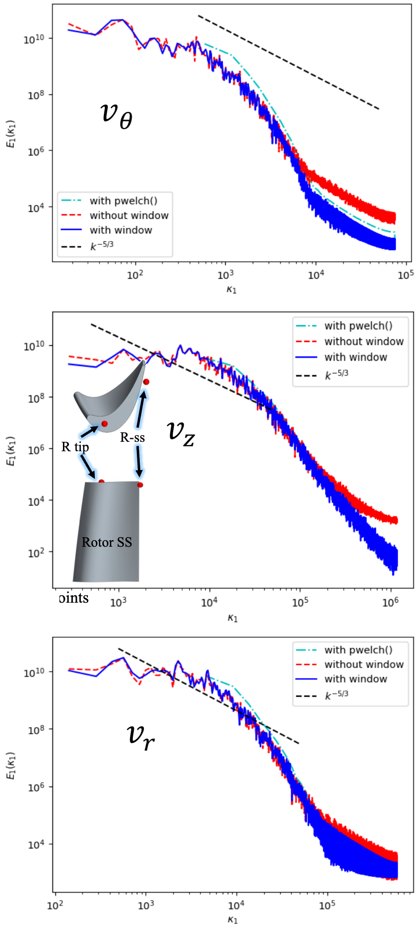


V&V: Grid- and Time-step Sensitivity Study

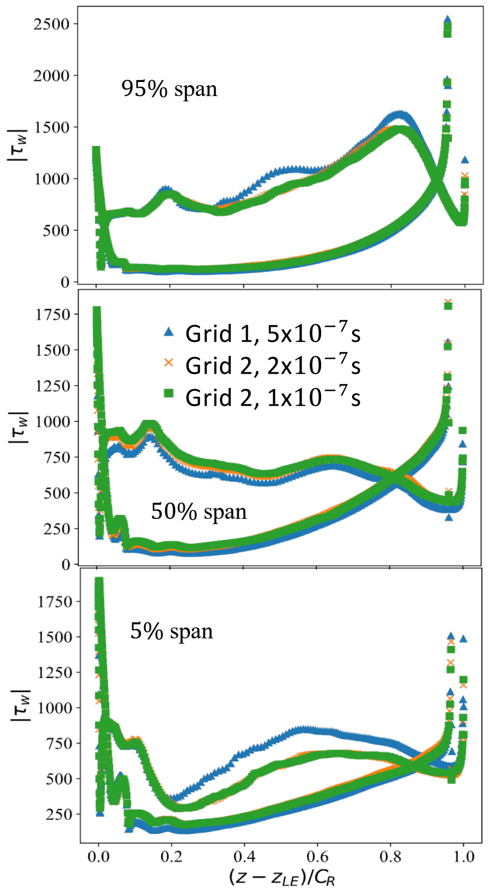


Verification

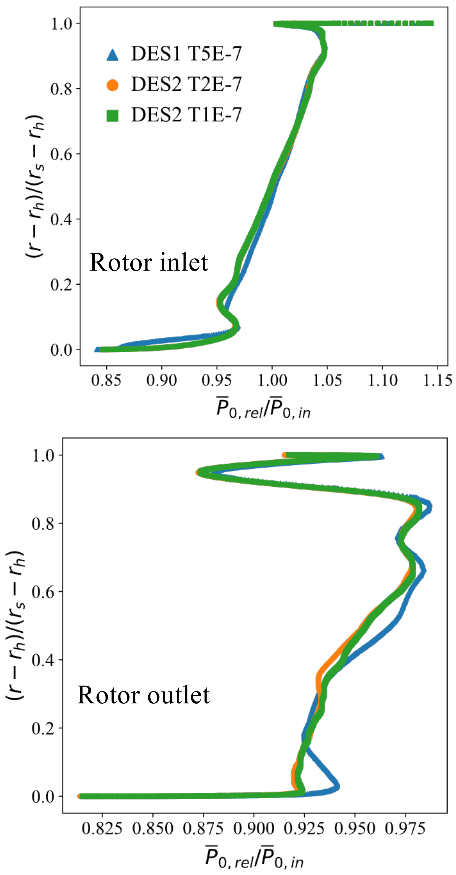
Rotor Suction side



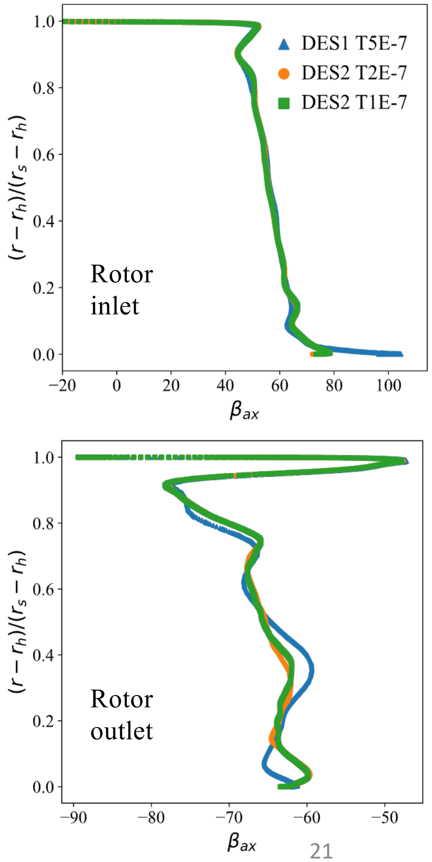
wall shear stress



relative total pressure ratio



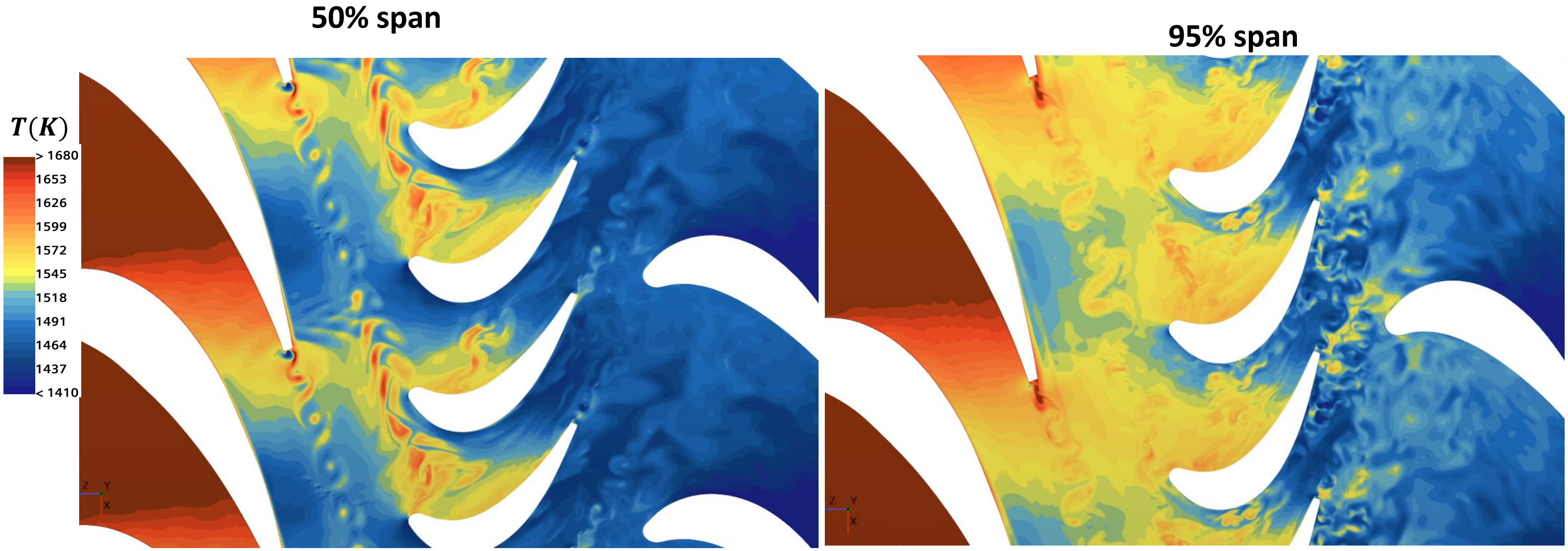
flow angle



LES-RANS of Tip-Leakage Flow in a 1.5 Stage Turbine

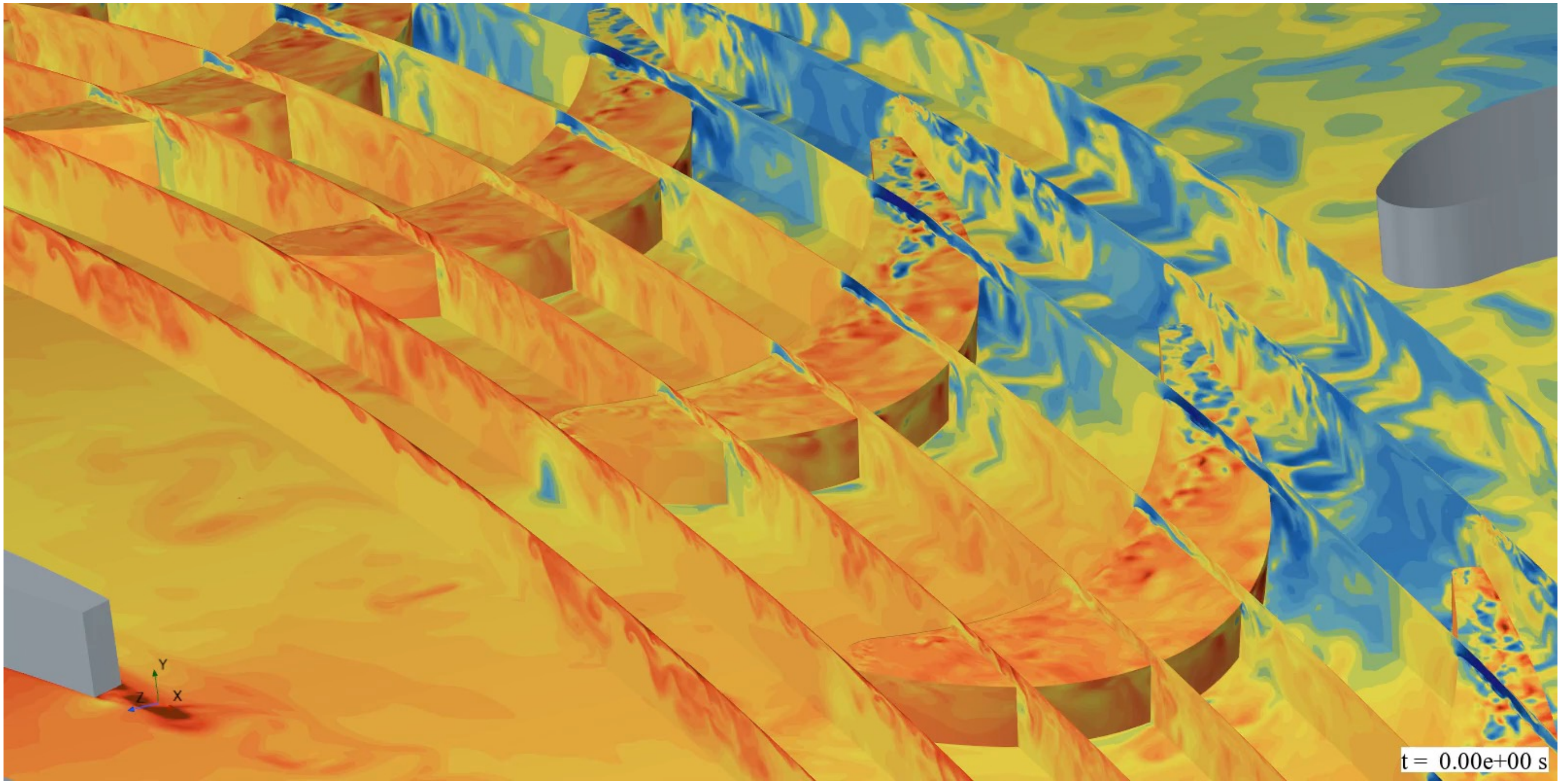
- Introduction
- Literature Review
- Objective
- Problem Description
- Problem Formulation
- Numerical Method of Solution
- Verification and Validation
- **Results**
- Summary and Conclusions

Instantaneous Flow: Temperature

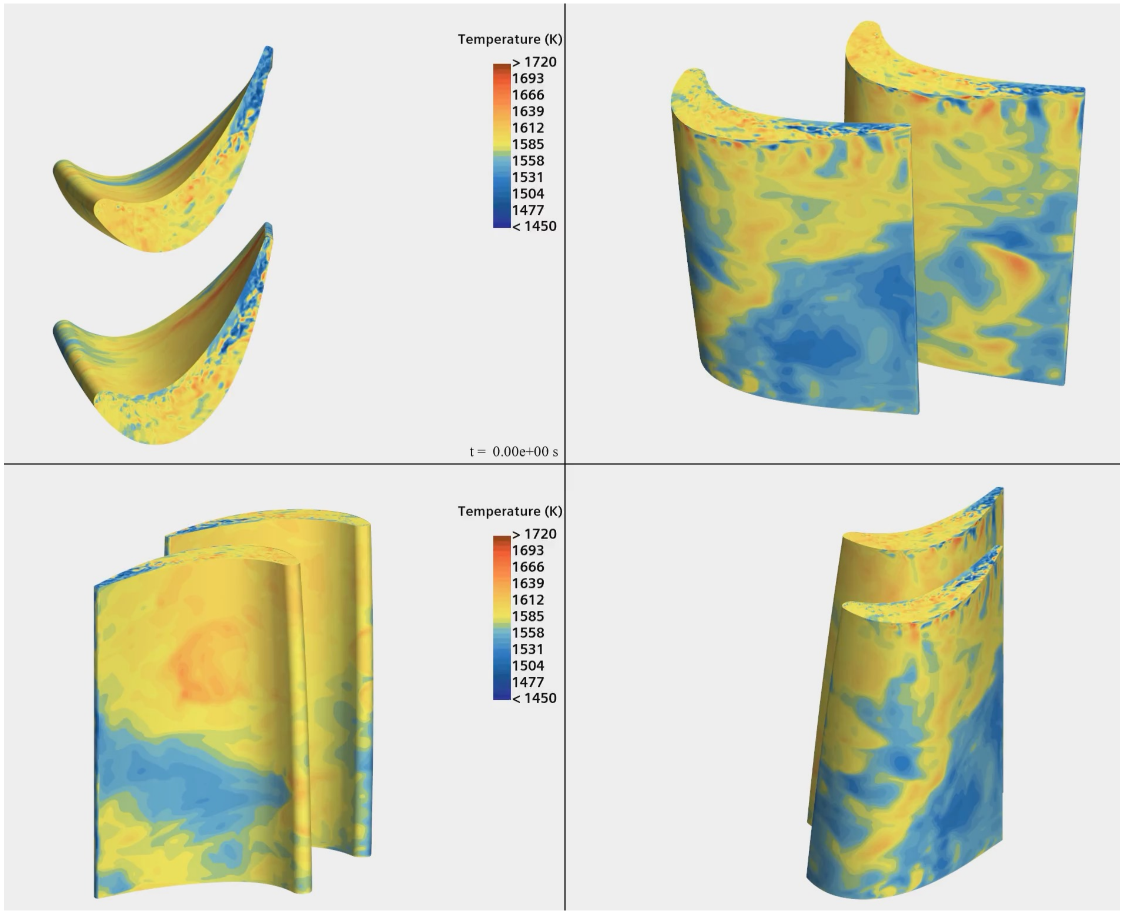


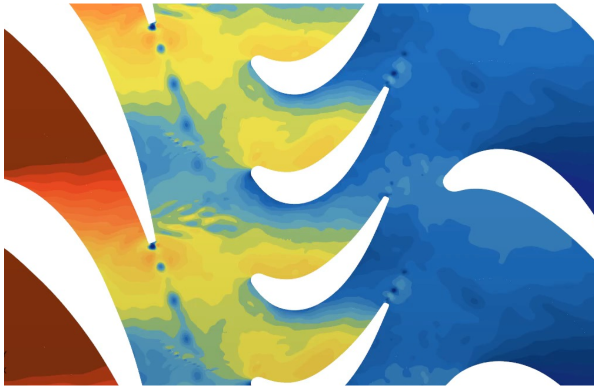
On shedding+Kelvin-Helmholtz at trailing edge, note that there are **no film-cooling from trailing edge**.

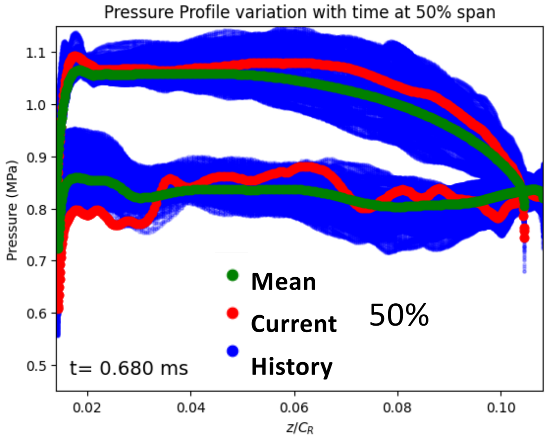
Instantaneous Flow: Temperature

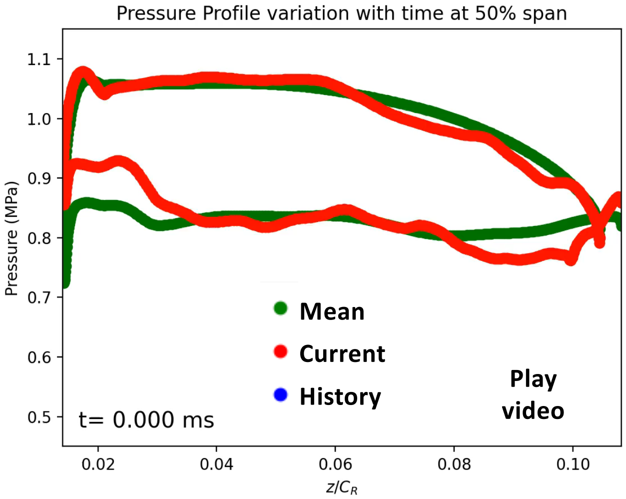


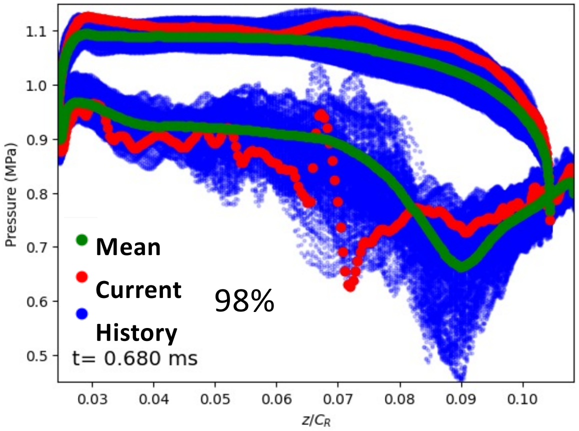
Instantaneous Flow: Temperature

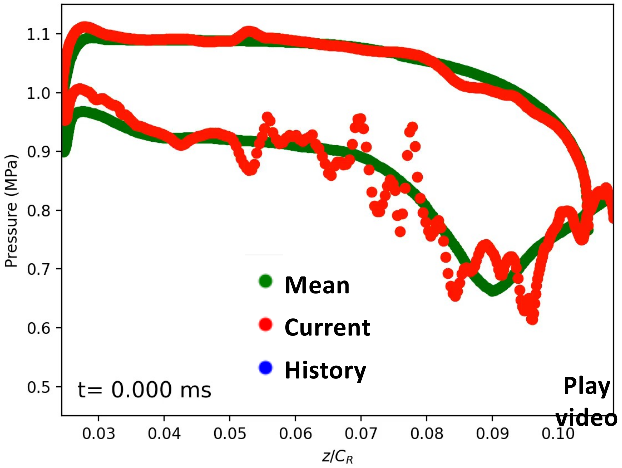




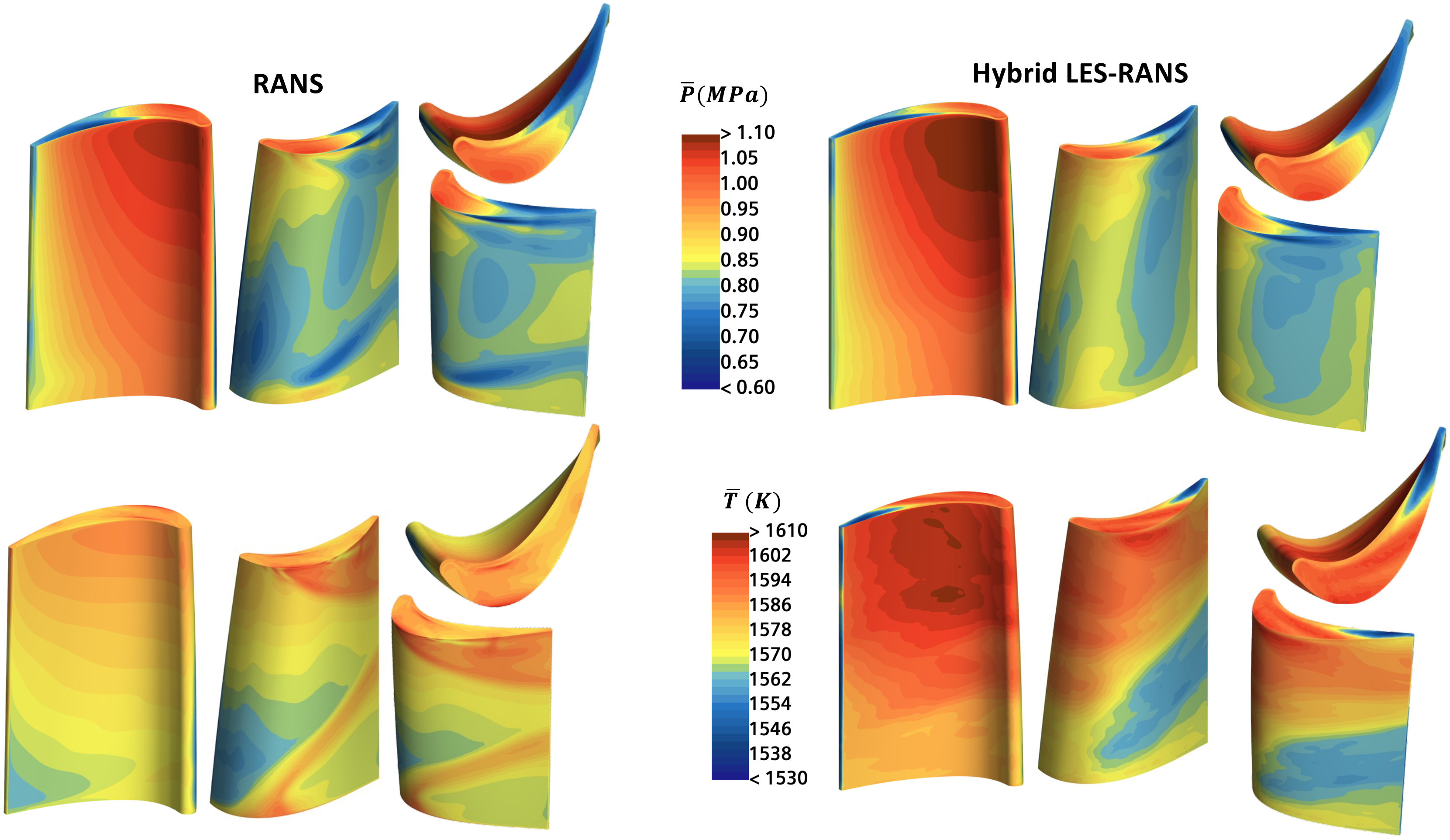

Pressure Profile variation with time at 50% span
Pressure (MPa)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.02
0.04
0.06
0.08
0.10
z/C_R
Mean
Current
History
50%
t= 0.680 ms


Pressure Profile variation with time at 50% span
Pressure (MPa)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.02
0.04
0.06
0.08
0.10
z/C_R
Mean
Current
History
Play video
t= 0.000 ms


Pressure (MPa)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
z/C_R
Mean
Current
History
98%
t= 0.680 ms

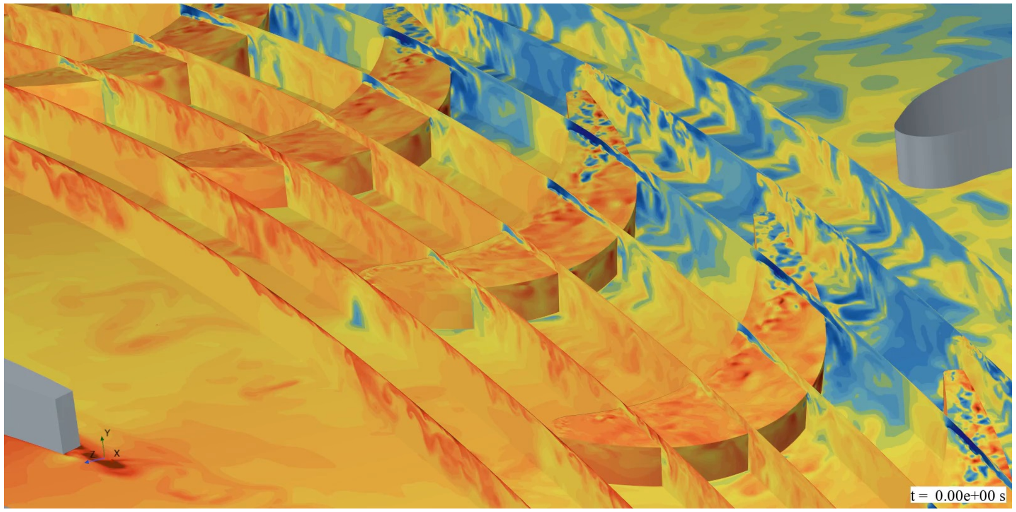

Pressure (MPa)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
z/C_R
Mean
Current
History
t= 0.000 ms
Play video

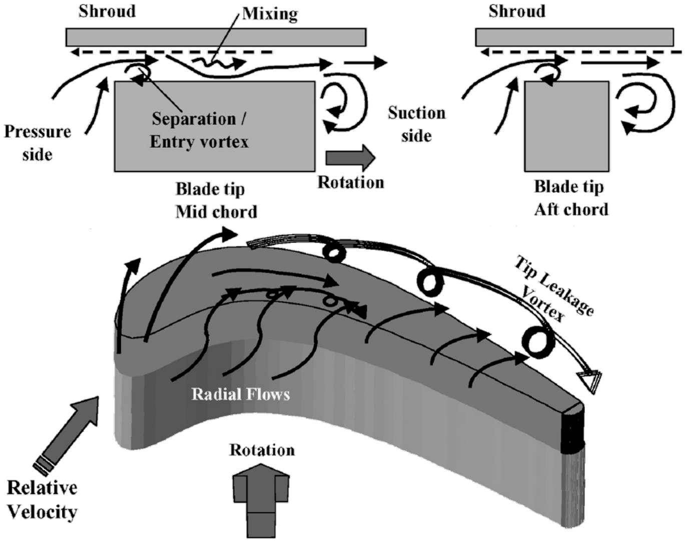
Hybrid LES-RANS vs RANS: P & T on Blade Surface



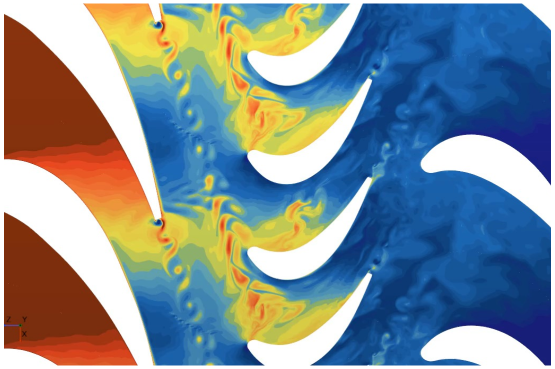
Summary and Conclusions

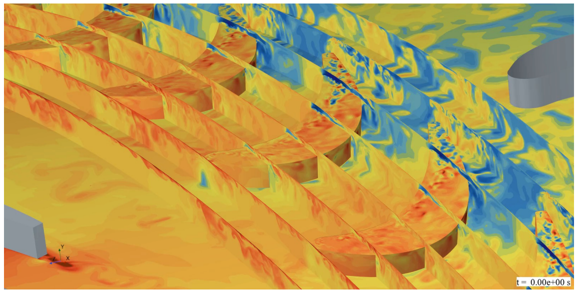
To be presented at the 2025 IGTI!!!





Current Efforts to Meet Our Nation's Goal of Carbon-Free Electric-Power Generation by 2035





Tools

- ROM for conjugate HT in conical cooling ducts with tip leakage in 2nd stage turbine.
- Physics-based ROM for internal cooling of vane & blade w/ 3-D effects.
- Physics-based ROM for internal cooling of RDC
- ROM + Optimization + machine learning for design

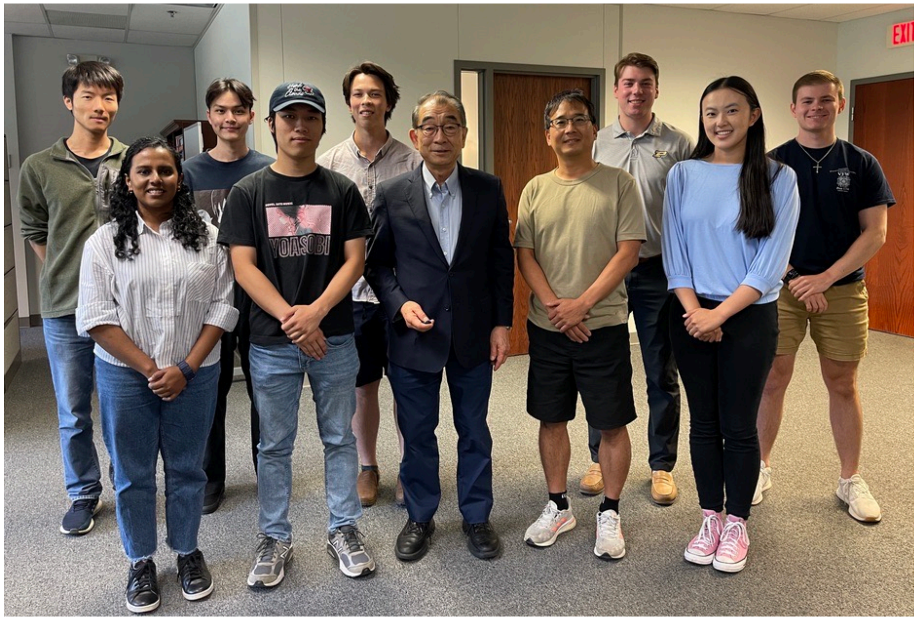
Fundamentals

- Revisit $T_{adiabatic}$ on its physical meaning & how to measure (directly to journals in 2024, 2025)

Applications

- **Tip-leakage flow in 1.5 stage turbine.**
- Internal cooling of RDC walls.
- Transition duct from RDC to turbine
- New film-cooling holes: **downstream VG with cross flow**; **Y-shaped hole** (Doug Straub & Justin Weber)
- New film-cooling design paradigms from machine learning (w/ Doug Straub & Justin Weber)
- Biot no. analogy to study TBC in sCO2 turbine cooling (w/ Matthew Searle)

My current students…



Eric Chen, Abhi Victor, Dylan Hsieh, Jiekun Wu, Robert Gillespy,
Tom Shih, Jay Kim, Jack Buechler, Madeleine Yee, Brandon Hay

Not shown: James Peck, Sharouk Reza, Adwiteey Shishodia