Overview of Workshop Submissions for TUDa-GLR-OpenStage

4th GPPS Turbomachinery CFD Workshop (GPPS 2024)

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Content

- <u>**Description of Test Case**</u>
- Summary of Workshop Submissions
- RANS Grid Convergence Results
- RANS Validation Results
- RANS Verification Results
- Conclusions and Future Plan

Technology Readiness Level Classification

TRL 1
Basic Principles Observed and Reported

TRL 2
Potential Application Validated

TRL 3
Proof-of-Concept Demonstrated

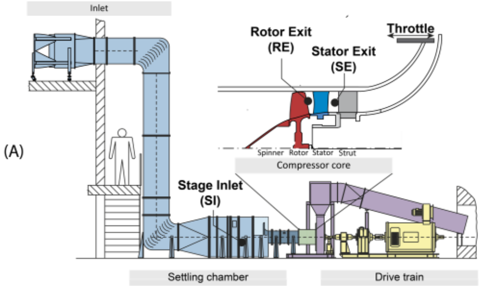
TRL 4 - 5
Component Test Facilities & Validation

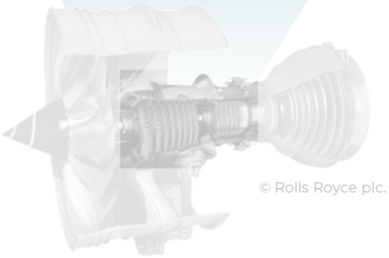
- Good accessibility for instrumentation
- Isolated investigation
- Industrially relevant environment
- Focus on understanding the underlying phenomena

TRL 6 - 7
System Prototype Demonstration in Operation Environment

TRL 8 - 9
System Test, Launch & Operations

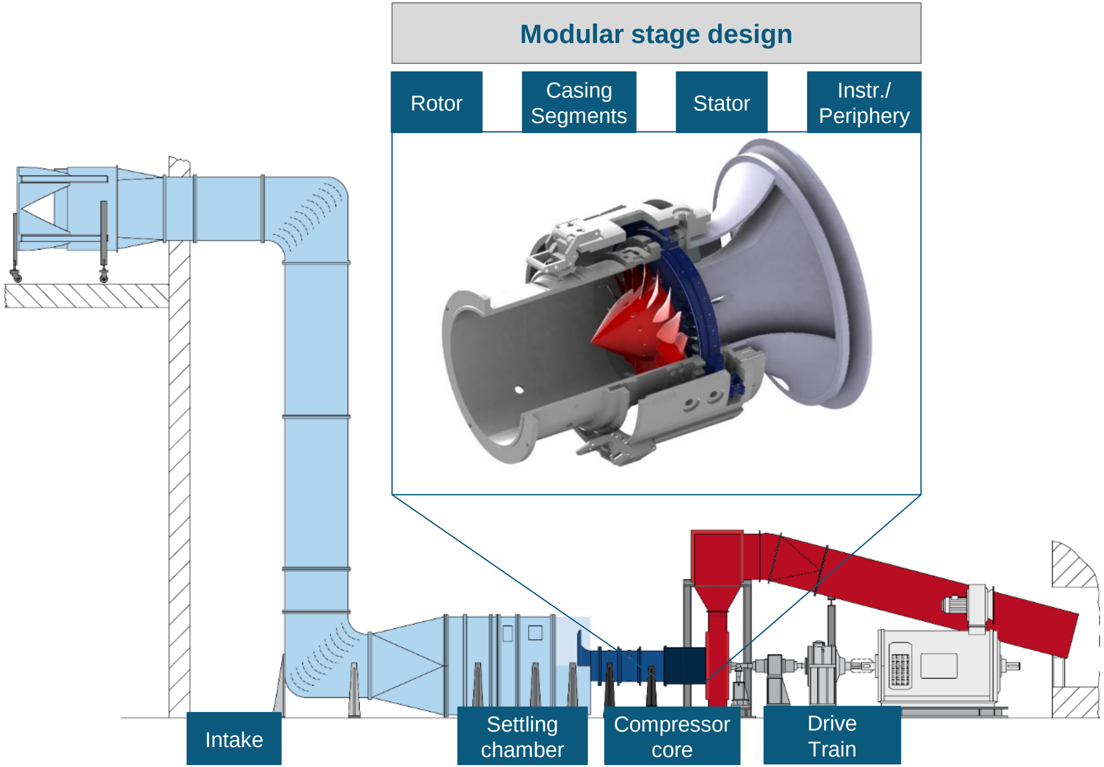
Transonic Compressor TU DARMSTADT





Klausmann, F., Franke, D., Foret, J., and Schiffer, H. (2022). Transonic compressor Darmstadt - Open test case Introduction of the TUDa open test case. *Journal of the Global Power and Propulsion Society*, 6, pp.318-329. https://doi.org/10.33737/jgpps/156120

Facility Design



Single-stage or 1.5-stage axial compressor setups (representative for a HPC front stage)

Capacity	
In /out flow	axial-axial
Electr. Power	800 kW
Max. Torque	350 Nm
Max. speed	20 500 rpm
Max. rotor diameter	0.38 m
Hub to tip ratio	~ 0.5
Rel. Ma-Number @ tip	~ 1.4

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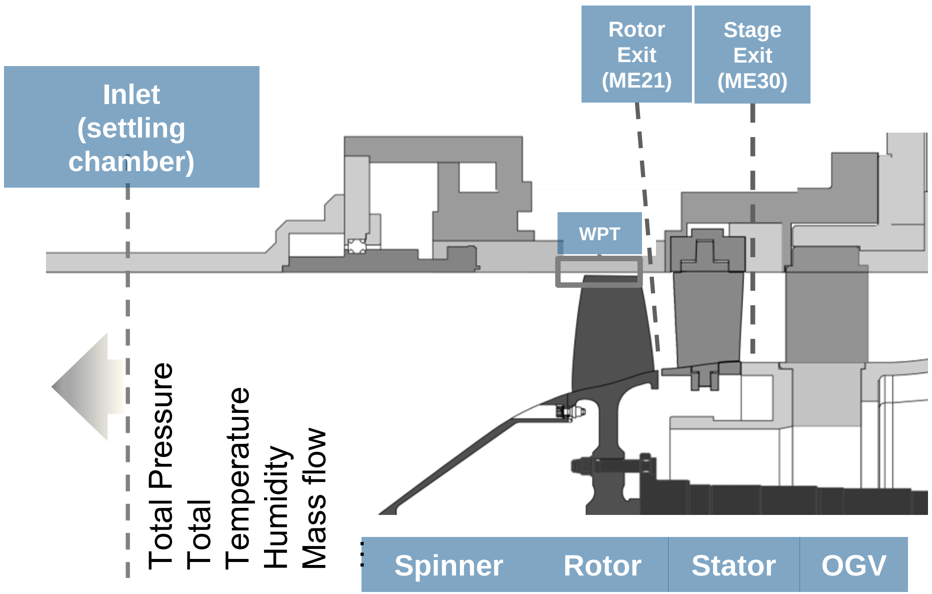
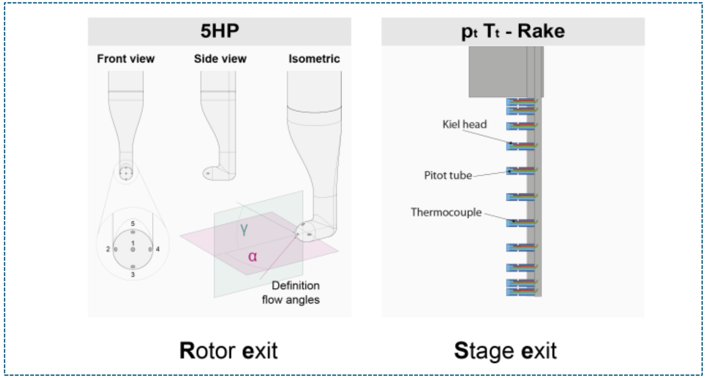
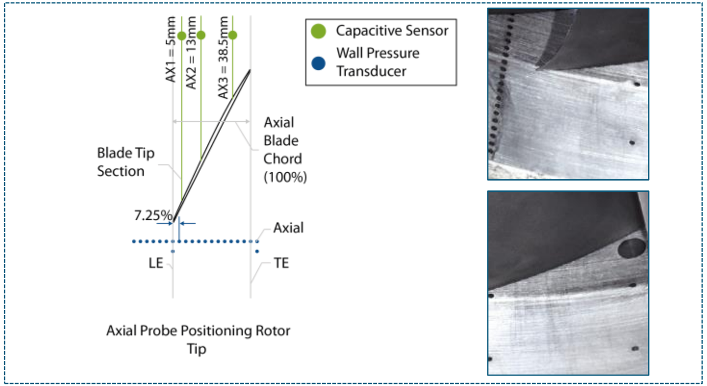
Instrumentation – Compressor Core







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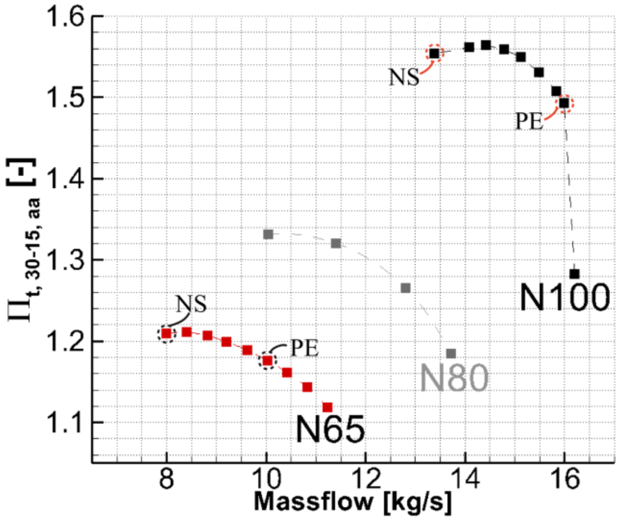
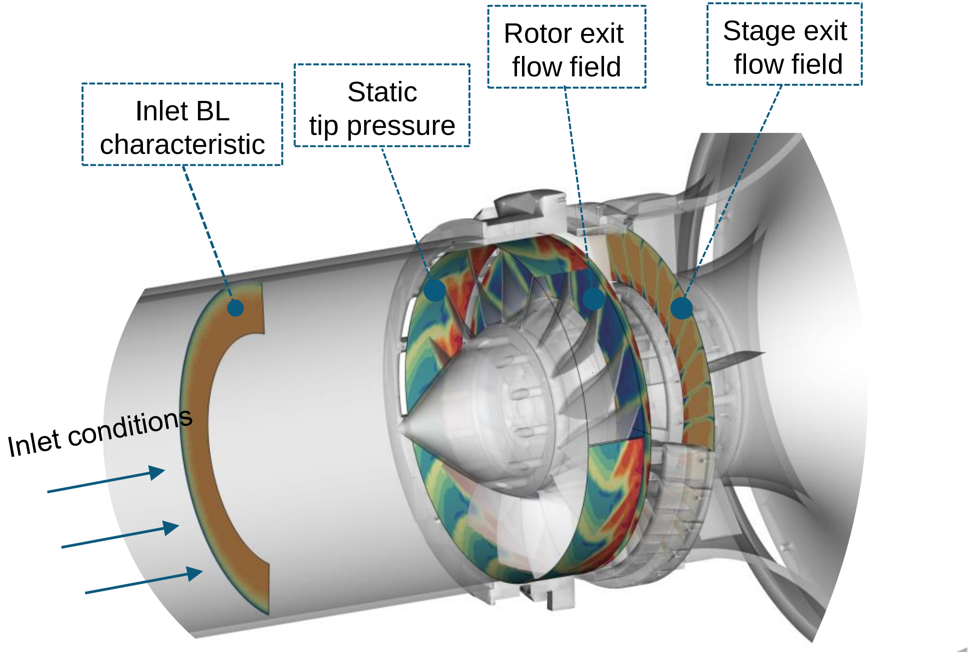
Included Mean Flow Data





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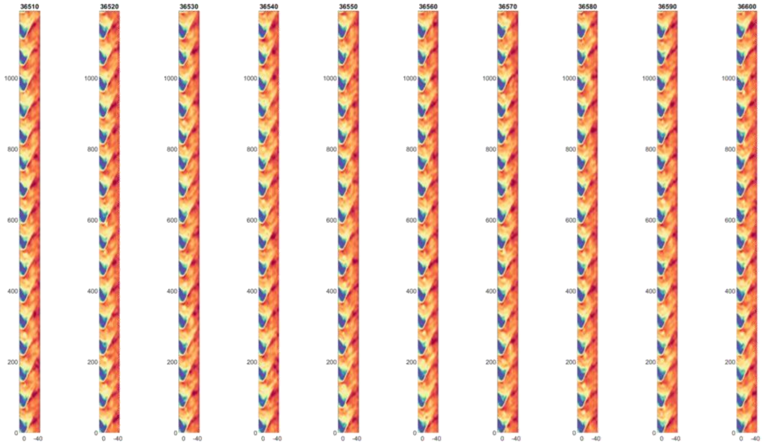
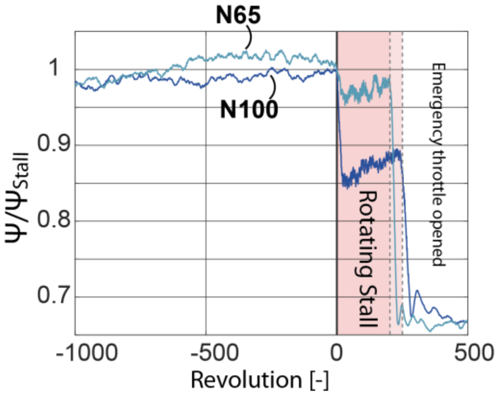
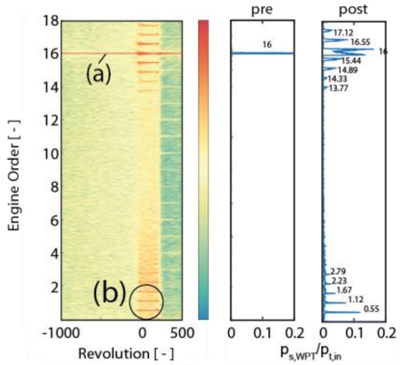
Included Unsteady Data



Static tip pressure during stall inception

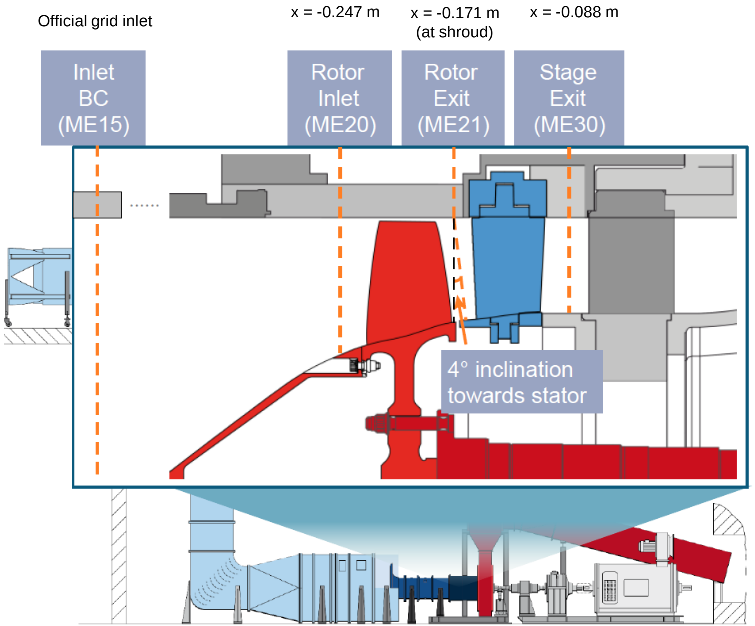


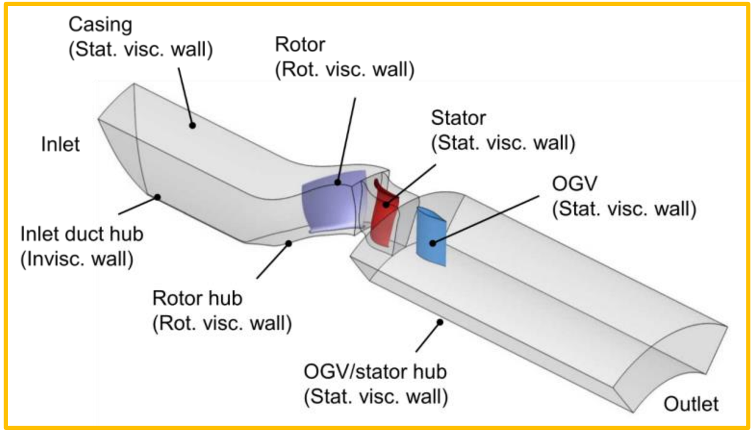


TECHNISCHE UNIVERSITÄT DARMSTADT IMPERIAL

Klausmann, F., Franke, D., Foret, J., and Schiffer, H. (2022). Transonic compressor Darmstadt - Open test case Introduction of the TUDa open test case. *Journal of the Global Power and Propulsion Society*, 6, pp.318-329. https://doi.org/10.33737/jgpps/156120

Numerical Model





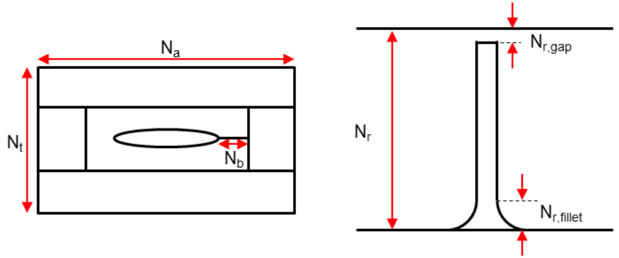
Differences between CFD model and EXP

- The axial-to-radial duct is simplified as an axial duct.
- Changes of the inlet profile are not considered.
- Changes of blade tip gap size are not considered.

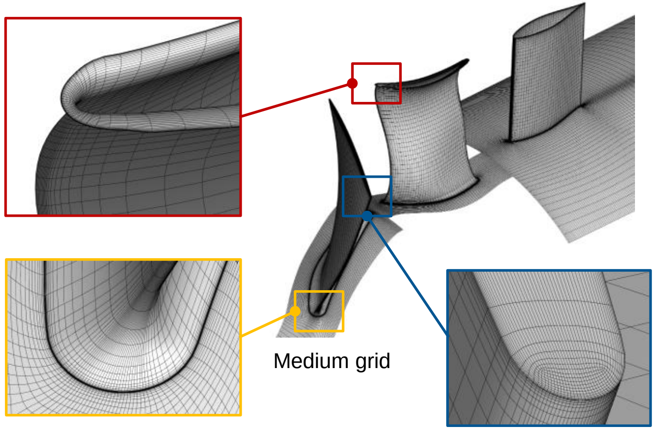
Official Grids Ver. 1 (1st Workshop)

Major features of official grids

- All grid cells are hexahedron.
- Five sets of grids (uniformly refined) in structured/unstructured .cgns format and .trb format.
- Boundary layers are refined with an average $y^+<3$.
- Tip gap and fillets are considered.



	Grid name	UltraCoarse	Coarse	Medium	Fine	UltraFine
Rotor	Total radial grid point	37	53	81	121	181
	Tip gap radial grid point	9	13	21	33	49
	Hub fillet radial grid point	9	13	17	29	45
	Total tangential grid point	29	41	65	93	145
	Total axial grid point	41	61	97	141	213
	Boundary layer grid point	9	13	21	29	45
	Tip gap O-grid point	5	9	13	21	29
	Total grid point (million)	0.12	0.28	1.08	3.36	11.77
Stator	Total radial grid point	41	65	93	137	201
	Tip/hub fillet radial grid point	9	13	21	29	49
	Total tangential grid point	17	29	41	69	101
	Total axial grid point	37	53	85	129	189
	Boundary layer grid point	9	13	21	29	45
	Tip gap O-grid point	5	9	13	21	29
	Total grid point (million)	0.04	0.16	0.53	1.80	5.81
OGV	Total radial grid point	-	-	77	-	-
	Total tangential grid point	-	-	81	-	-
	Total axial grid point	-	-	77	-	-
	Boundary layer grid point	-	-	17	-	-
	Total grid point (million)	-	-	0.85	-	-



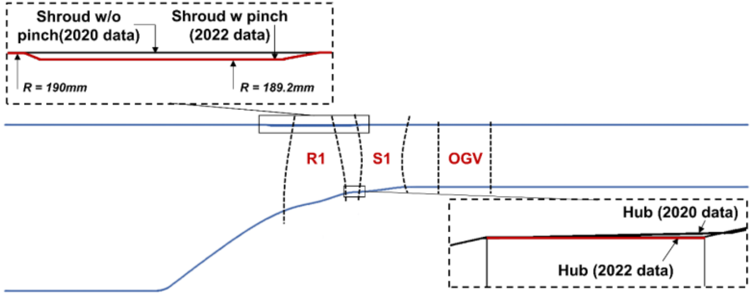
Official Grids Ver. 2 (2nd Workshop)

Major updates on geometry

- All grids based on more realistic hub/casing shapes
- An optional grid (MediumCDS) includes realistic inlet bulb/cone

Major updates on grid quality

- Improved orthogonality via better fillet topology
- Rotor-stator and stator-OGV interfaces set to the measurement planes for easier postprocess



Grid name	UltraCoarse	Coarse	Medium	Fine	UltraFine	MediumCDS
Rotor grid point (million)	0.17	0.33	1.07	3.31	11.49	1.55
Stator grid point (million)	0.05	0.16	0.52	1.67	5.26	0.92
OGV grid point (million)	0.93	0.93	0.93	0.93	0.93	1.25

Quantities of Interest

Track 1: steady RANS

- CFD_Setup_Form.docx
- characteristics.csv
- profile_ME21.csv
- profile_ME30.csv

Track 2: unsteady RANS

- CFD_Setup_Form.docx
- stall_inception_description.docx
- probe_ME21_tip.csv
- probe_ME21_midspan.csv
- probe_casing_midchord.csv
- probe_casing_LE.csv

Track 3: scale-resolving simulation

- CFD_Setup_Form.docx
- characteristics.csv
- profile_ME21.csv
- profile_ME30.csv
- probe_ME21_tip.csv
- probe_ME21_midspan.csv
- probe_casing_midchord.csv
- probe_casing_LE.csv

Post-Process Quality Control

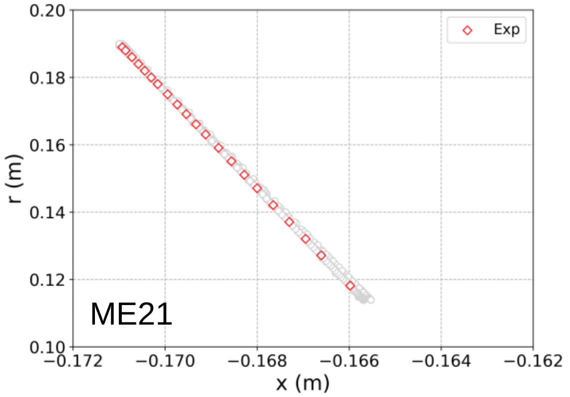
- A sanity check was performed for each submission to reduce human-induced error
- Checking items include:

① if the performance quantities and radial profile quantities were post-processed in the same way as the experiment (e.g., same average method);

② if the profiles were extracted at the same location of the experiment;

③ if the simulation operating points are sufficiently close to the measured points (e.g., Δm<0.1 kg/s)

- About 30%-50% submissions failed the sanity check at first, but quickly passed within 2 rounds of communications.
- All data presented have passed the sanity check.



Example check of ME21 profile location

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Submission Statistics

* Stat summarized as of 4th CFD Workshop

78 characteristic curves submitted by 19 authors from 13 institutes

- 70 curves at 100% speed, 8 curves at 65% speed
- 5 universities: BUAA, Imperial, SJTU, Tsinghua, NWPU
- 6 companies: ADS, AECC, Cadence, IHI, Rankyee, Siemens
- 2 research institute: CARDC, Inria

17 CFD solvers

- 7 commercial solvers: CFX, Dimaxer, Fine/Turbo, Fluent, Leo, STAR-CCM+, Turbostream
- 1 open-source solver: SU2
- 9 in-house solvers: AeroX, ASPAC, HADES, HGAE, MAP, TRANS, TurboXD, UPACS, Wolf

>200 attendees during the past workshop events

Numerical Schemes

* Stat summarized as of 2nd CFD Workshop

- Grid usage: 58% official, 42% in-house
- Turbulence model: 60% SA, 40% SST
- Wall functions: 25% uses wall function
- Advection scheme: all submission are ≥ 2nd order accurate in space
- Inlet BC: 63% official .bc, 28% from measured data, 9% uniform ISA
- Verification study on NASA 2D flat plate: only 24% performed

* For more details, please refer to the summary paper or find the relevant CFD setup form in the data set (to be released)

ID	Org.	Solver (Version)	Type	Grid ID	Turb. model	Convect.	R-S model	Wall func.	In. BC
1	SJTU	CFX (20.1)	C	O1	SA-noft2 [21]	HR	MP	Yes	O, U5
2	SJTU	CFX (20.1)	C	O1	SST-2003 [22]	HR	MP	Yes	O, O
3	SJTU	FineTurbo (14.1)	C	O1	SST [23][a]	Roe	MP	No	O, O
4	SJTU	FineTurbo (14.1)	C	O1	SST [23][a]	JST	MP	No	O, O
5	SJTU	FineTurbo (14.1)	C	O1 (F)	SA-fv3-noft2 [21, 24][a]	JST	MP	No	O, O
6	SJTU	FineTurbo (14.1)	C	O1 (F)	SA-fv3-RC-noft2 [21, 24, 25][a]	JST	MP	No	O, O
7	SJTU	FineTurbo (14.1)	C	O1 (F)	EARSMko2012-S [26][a]	JST	MP	No	O, O
8	IC	HADES (1.3)	I	O1	SA-noft2 [21][a]	JST	1D Giles	Yes	O, O
9	THU	SU2 (7.1.0)	O	O1	SA-R-noft2 [21, 27][b]	JST	MP	No	O, O
10	THU	SU2 (7.1.0)	O	O1	SST [23]	JST	MP	No	O, O
11	CARDC	ASPAC (1.0)	I	O1 (M)	SA [28]	Roe	MP	No	O, O/U1
12	BUAA	HGAE (12.0)	I	O1 (M)	SA [28][a]	Roe	MP	No	O, U2
13	NWPU	Turbostream (2.4)	C	I1	SA [28]	JST	MP	Yes	O, U3
14	NWPU	TurboXD (2.4)	I	I2	SA [28]	JST	1D Giles	Yes	O, U3
15	NWPU	SU2 (7.1.1)	O	I3	SST [23]	JST	MP	No	U, U4
16	BUAA	MAP (6.0)	I	I4	SA-noft2-RC [21, 25][c]	LDFSS	NRMP	No	O, U5
17	BUAA	MAP (6.0)	I	I4	SST-2003-RC [22, 29]	LDFSS	NRMP	No	O, U5
18	AECC	Fluent (19.2)	C	I5	SST-2003-Helicity [22, 30]	PBCS	MP	No	E, O
19	IHI	UPACS Turbo (2.5.5.2)	I	I6	SA [28]	Roe	MP	No	O, U6
20	IHI	UPACS Turbo (2.5.5.2)	I	I6	SA [28]	Roe	NRMP	No	O, U6
21	IHI	UPACS Turbo (2.5.5.2)	I	I6	SA-R-H-QCR2000 [27, 31–33][d]	Roe	NRMP	No	O, U6
22	IC	HADES (1.3)	I	O2	SA-noft2 [21][a]	JST	1D Giles	Yes	E, P
23	IC	HADES (1.3)	I	O2	SA-R-noft2 [21, 27][a]	JST	1D Giles	Yes	E, P
24	IC	HADES (1.3)	I	O2	SA-RC-noft2 [21, 25][a]	JST	1D Giles	Yes	E, P
25	IC	HADES (1.3)	I	O2	SA-PG$_{\omega}$-noft2 [21, 34][a]	JST	1D Giles	Yes	E, P
26	IC	HADES (1.3)	I	O2	SA-QCR2000-noft2 [21, 33][a]	JST	1D Giles	Yes	E, P
27	IC	HADES (1.3)	I	O2	SA-QCR2020-noft2 [21, 35][a]	JST	1D Giles	Yes	E, P
28	SJTU	CFX (20.1)	C	O2 (F)	SST-2003 [22]	HR	MP	Yes	O, O
29	SJTU	CFX (20.1)	C	O2 (F)	EARSMko2005 [36]	HR	MP	Yes	O, O
30	NWPU	FineTurbo (13.2)	C	O2 (F)	SA-fv3-noft2 [21, 24][a]	JST	MP	No	U, N/A
31	Cadence	FineTurbo (17.1)	C	O3	EARSMko2012-S [26][a]	JST	MP	No	E, O
32	Cadence	FineTurbo (17.1)	C	O3	EARSMko2012-S [26][a]	JST	1D Giles	No	E, O
33	Cadence	FineTurbo (17.1)	C	O3	EARSMko2012-S [26][a]	JST	2D Giles	No	E, O
34	Siemens	Turbostream (3.6.3)	C	I7	SA-Helicity-noft2 [21, 31]	JST	MP	Yes	O, N/A
35	ADS	Code Leo (9.0)	C	I8	Wilcox1998 [37]	Ni	NRMP	No	U, N/A

[a] The turbulence model is solved in the relative frame attached to the blade.
[b] The "R" term only switches on in rotating frame.
[c] The vorticity magnitude in the source term is replaced by the strain rate magnitude, and the van Direst near-wall treatment is used.
[d] The coefficients of the "R" term and the "H" term are re-calibrated using the performance characteristics data of a multistage compressor.

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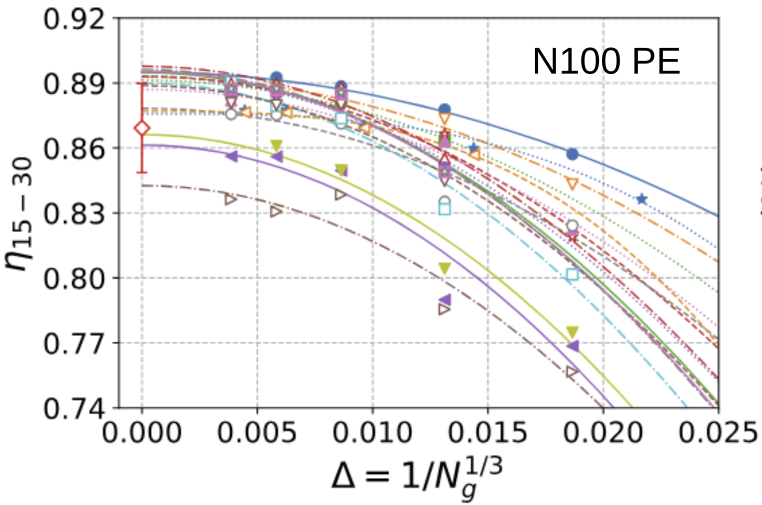
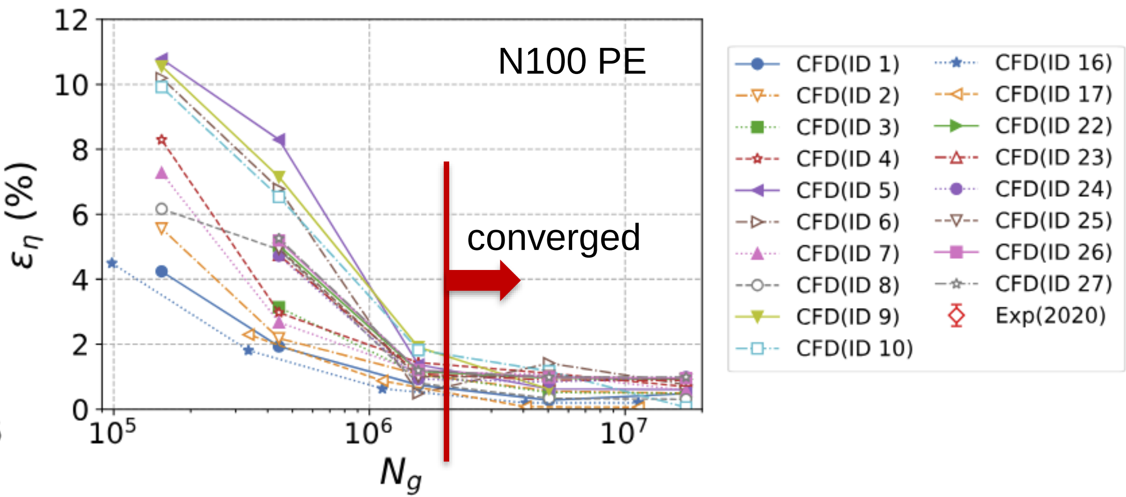
Grid Convergence Results



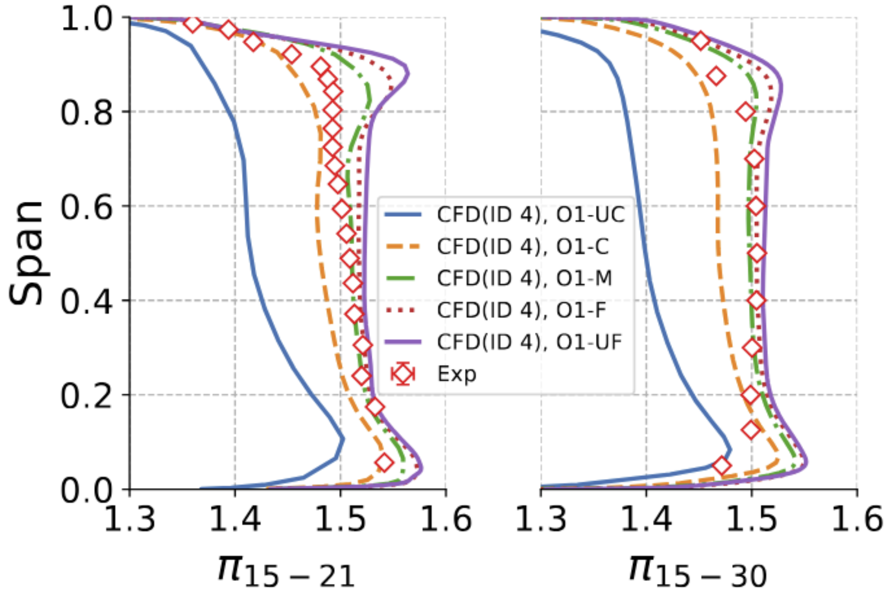


$$q = c\Delta^n + q_{ideal}$$

$$\epsilon_q = \left|\frac{q - q_{ideal}}{q_{ideal}}\right| \times 100\%$$

- Overall performance becomes insensitive to grid density when > 1M grid points per blade passage is used
- Compared to the 1994 ASME IGTI CFD workshop, the recommended number of grid points increases from 0.3M to 1M, mainly due to the boundary layers are resolved in this case

Grid Convergence Results



N100 PE, radial profiles

- Detailed flow fields becomes insensitive to grid density when > 3M grid points per blade passage is used (e.g., O1-F and O1-UF grids)
- Rotor tip still not fully grid converged – local mesh refinement needed

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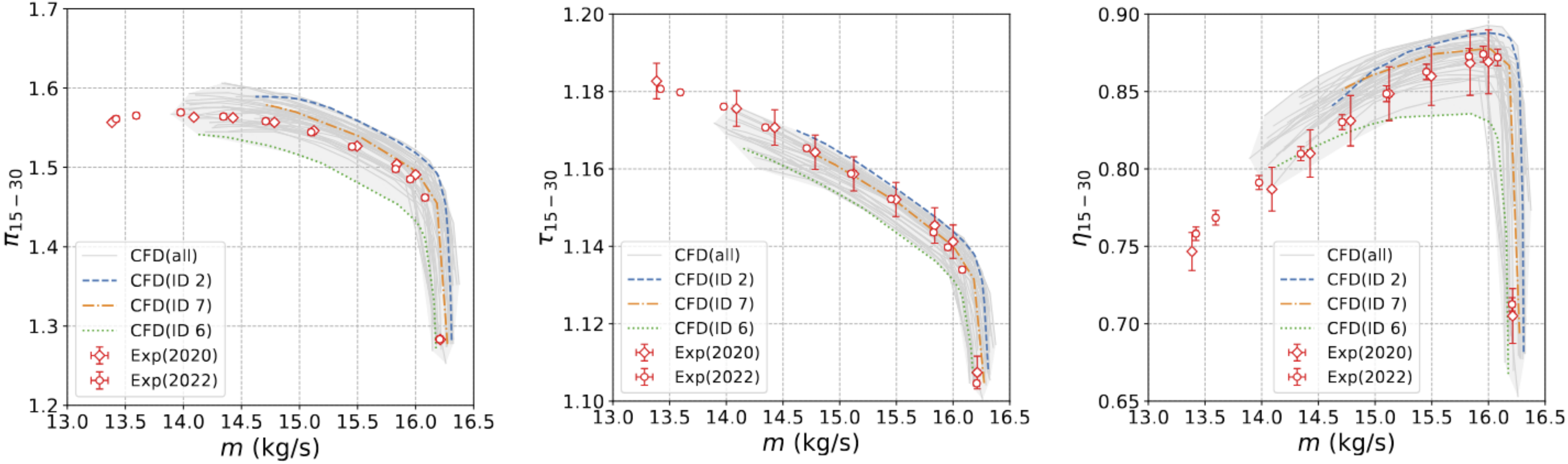
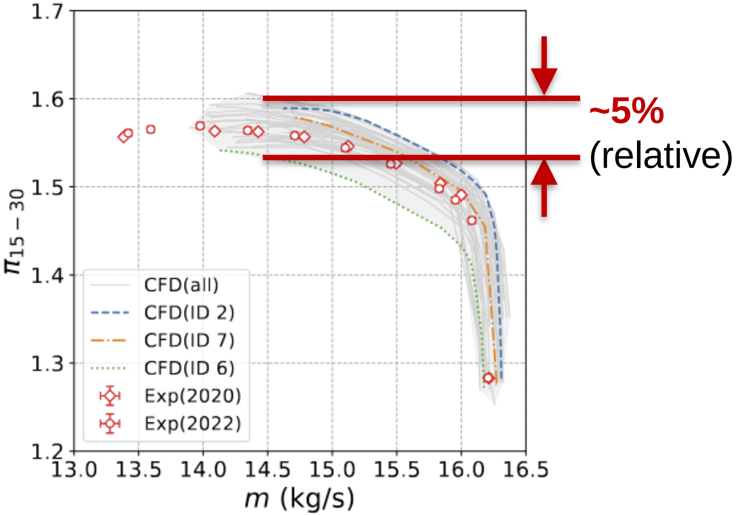
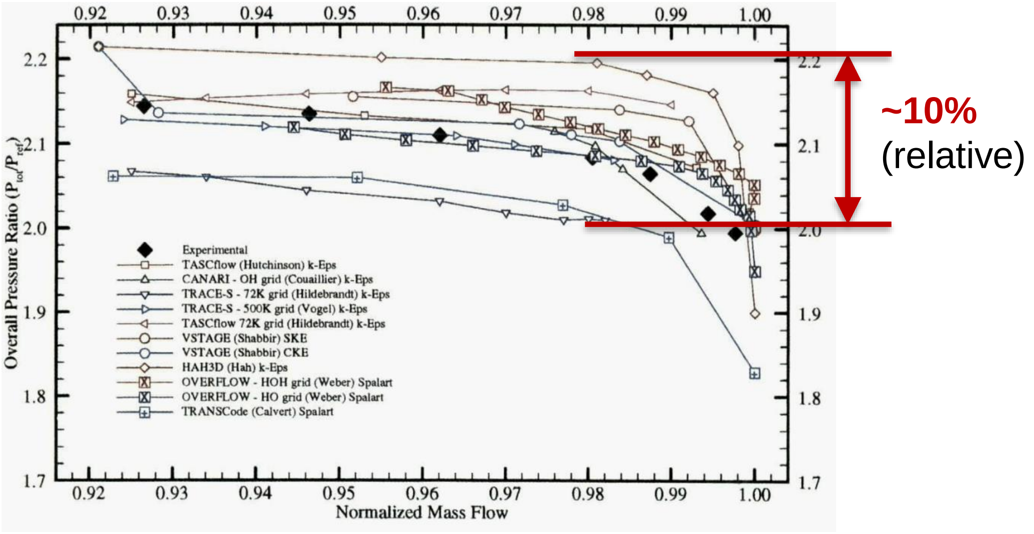
Performance Characteristics



- Measured data well-enveloped by RANS simulation results
- The shapes of the characteristic curves are predicted sufficiently accurate.
- The upper/lower extremities are commercial software results not adhering to its best practice.

Comparison with 1994 Workshop

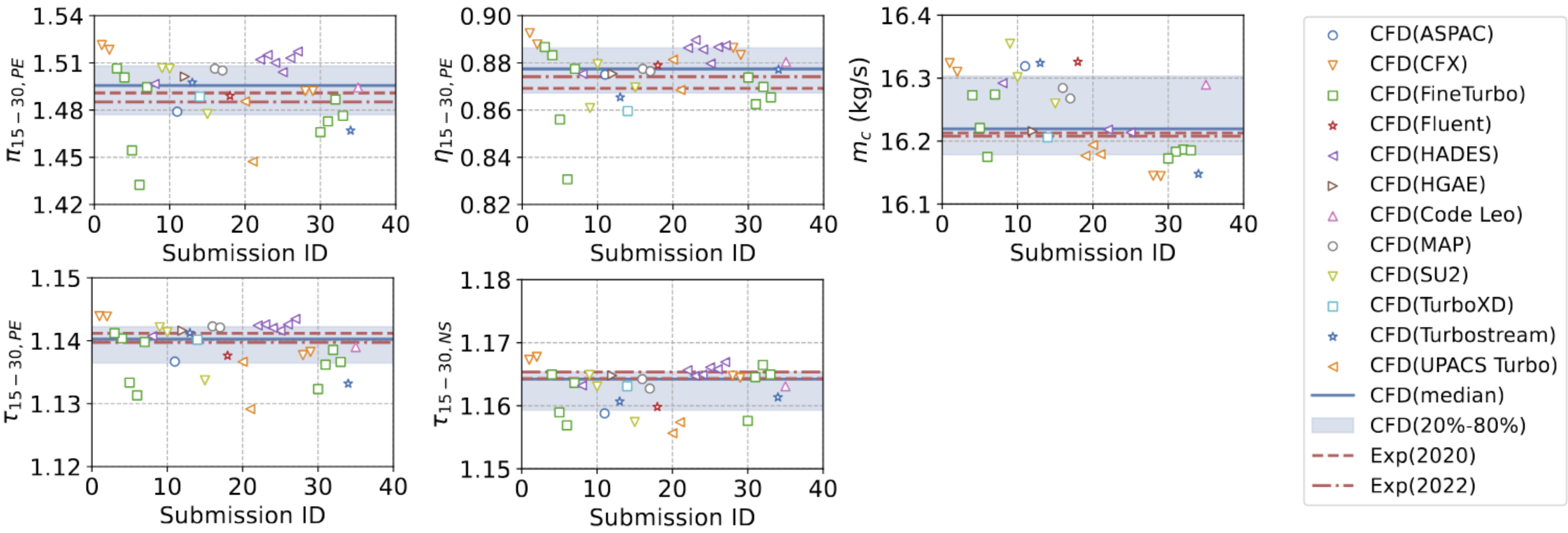




ASME IGTI 1994 Workshop on NASA Rotor 37 (AGARD-AR-355)

- Variation of predictions have been reduced by ~50% over the past 30 years of development.
- Major contributing factor: (1) improved hardware that allows the usage of fine grids; (2) improved CFD solver and mesh generator that allow the modeling of realistic tip clearance geometry; (3) better turbulence model for wall-attached and mild separation flows.

Flow Quantities of Interest Distributions



- RANS solvers predict m_c, τ_t, design Π_t, and design η_{isen} accurately.
- Median prediction errors are 0.06% (rel.), 0.04% (rel.), 0.51% (rel.) and 0.58% (abs.), respectively.

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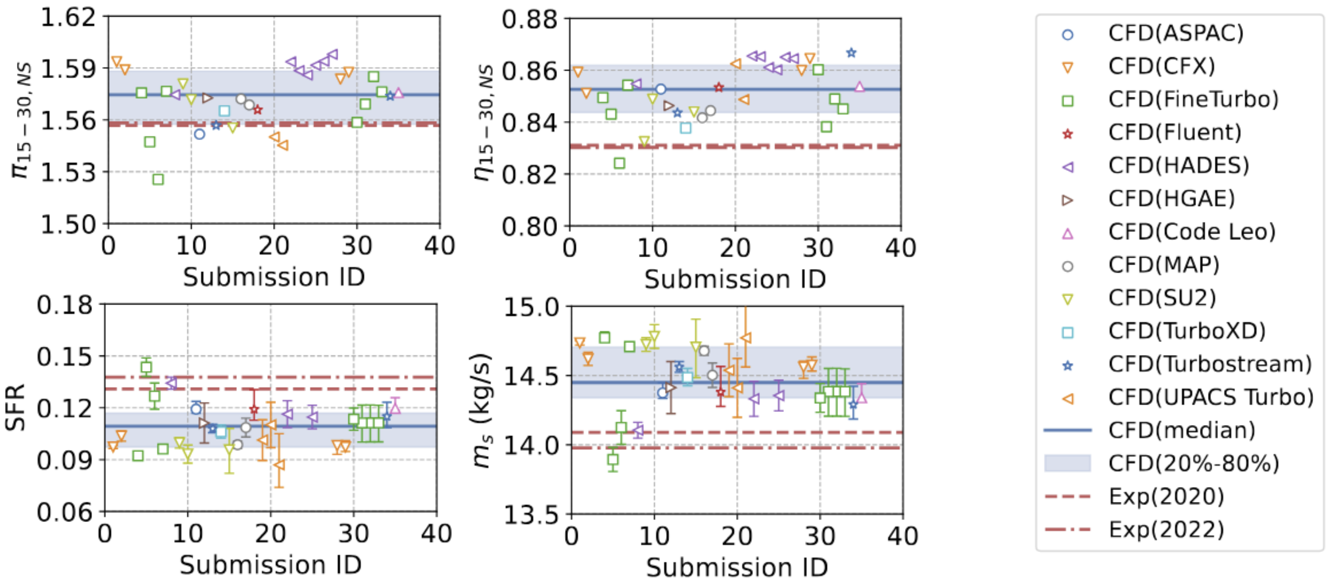
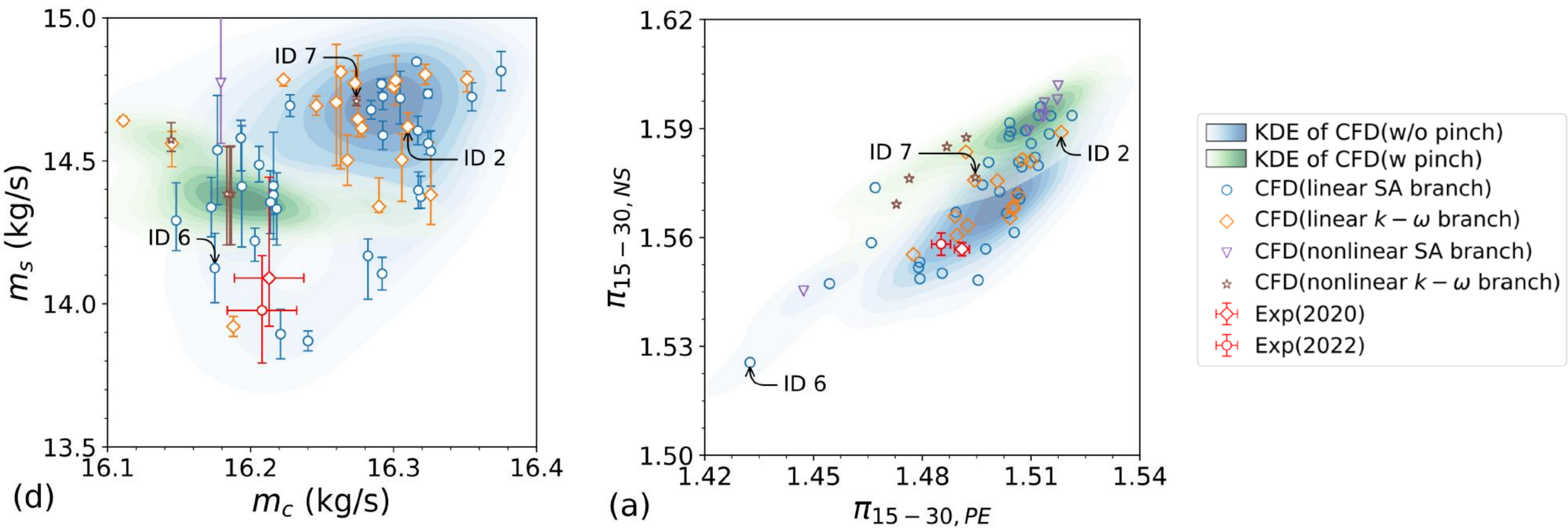
Flow Quantities of Interest Distributions



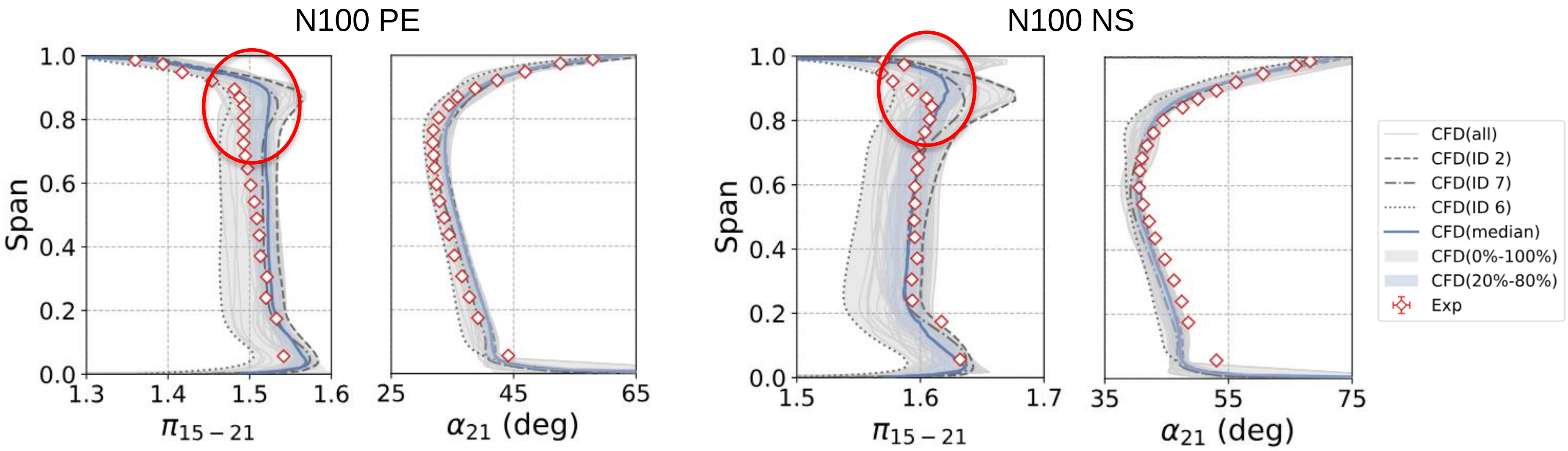
- RANS solvers over-predict m_s, off-design Π_t, and off-design η_{isen}, and under-predict SFR.
- Median prediction errors are 2.96% (rel.), 1.09% (rel.), 2.20% (abs.) and 2.5% (abs.), respectively.

Flow Quantities of Interest Joint Distributions



- Rectifying rotor casing wall with pinch improved prediction of m_s and m_c
- Difficult to conclude one branch of turbulence model is advantageous than another due to large scattering of the results

Rotor Exit Radial Profiles



- Measured data for all QoIs are encompassed by the CFD results.
- A slight over-prediction of π_{15-21} in the upper 40% span at both PE and NS conditions

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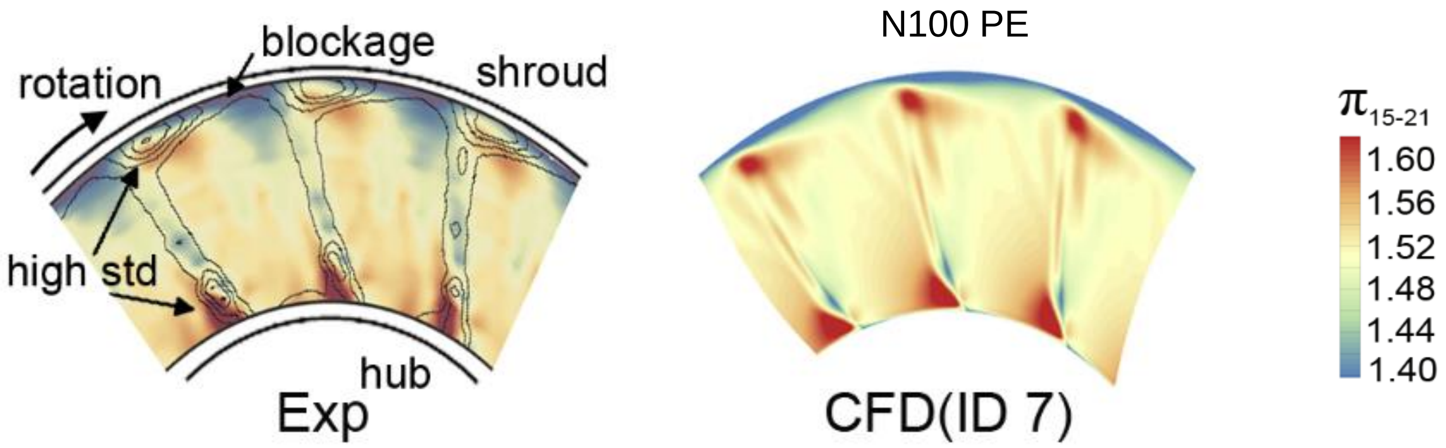
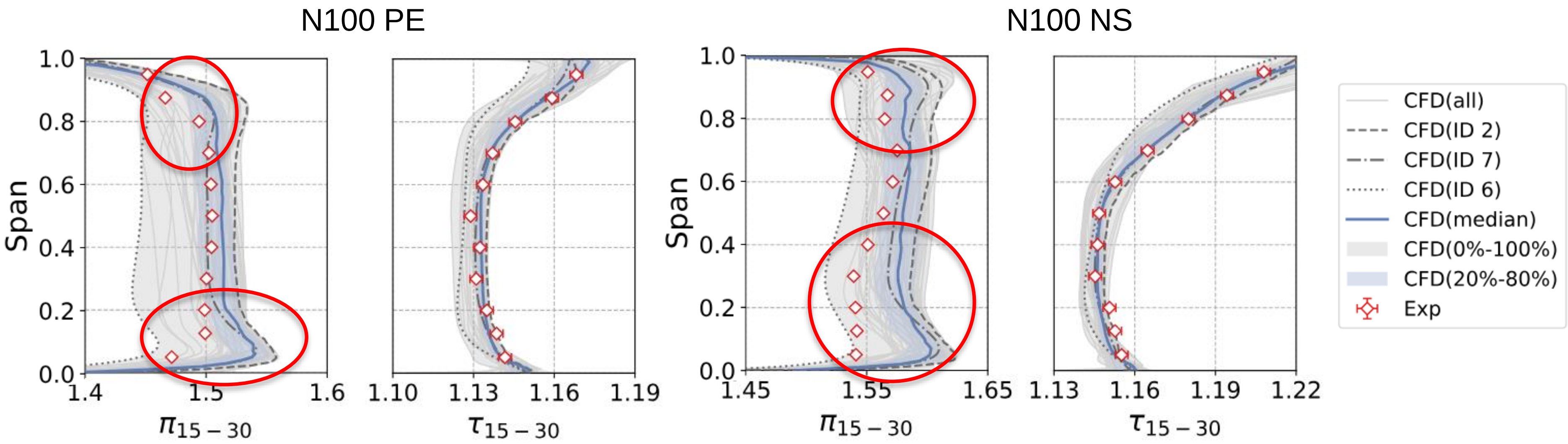
Rotor Exit Contours



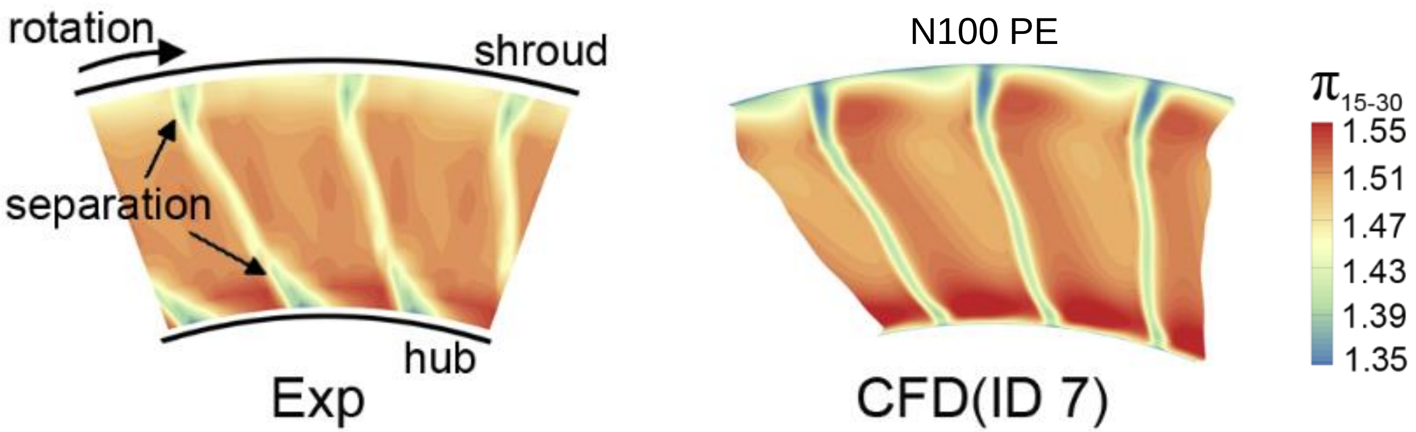
- RANS solver qualitatively reproduced the flow physics
- RANS solver under-predicts the tip blockage size and predicts the blockage location wrong (prediction at casing-PS corner, but measurement at casing-SS corner)
- Such deficiency leads to over-prediction of rotor tip total pressure

Stage Exit Radial Profiles



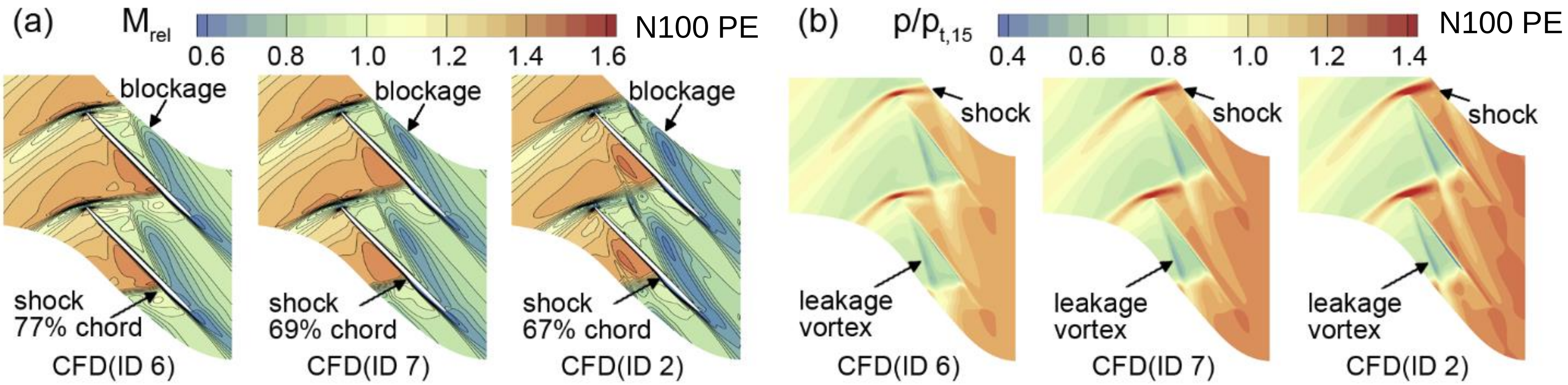
- Measured data for all QoIs are encompassed by the CFD results.
- An over-prediction of $\pi_{15\text{–}30}$ in the upper 20% span at both PE and NS conditions coming from the rotor
- An over-prediction of $\pi_{15\text{–}30}$ in the lower 20% of the span, which becomes more evident at NS than PE

Stator Exit Contours



- RANS solver qualitatively reproduced the flow physics
- RANS solver misses the separation at hub-PS corner, leading to the over-prediction of stator hub total pressure

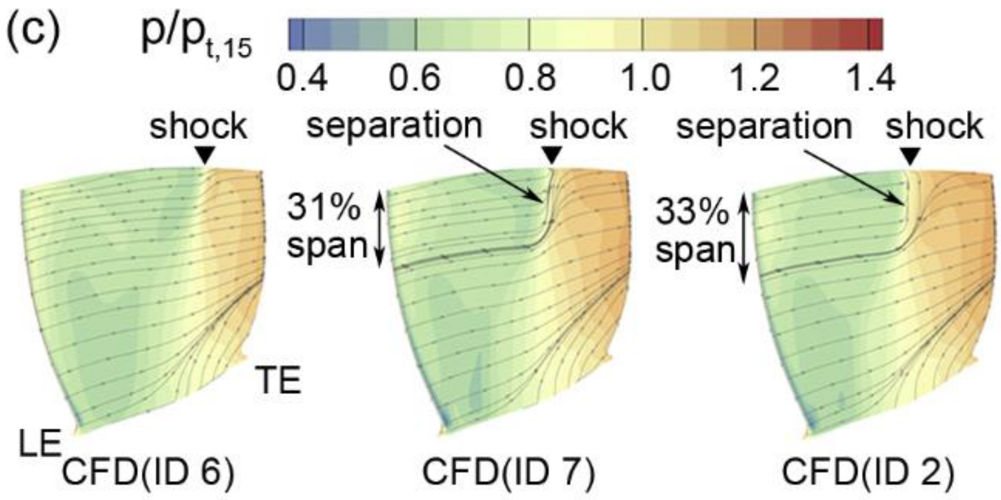
Rotor Tip Constant Radius Contours



- All the predictions capture qualitatively the same flow physics in the rotor tip:

1. A detached shock forms at the rotor leading edge
2. Downstream of the shock front, a blockage zone is formed, which propagates to the shroud-PS corner near the trailing edge.
3. The tip leakage vortex interacts with the shock and break down, which forms the blockage zone

Rotor SS Contours and Streamlines

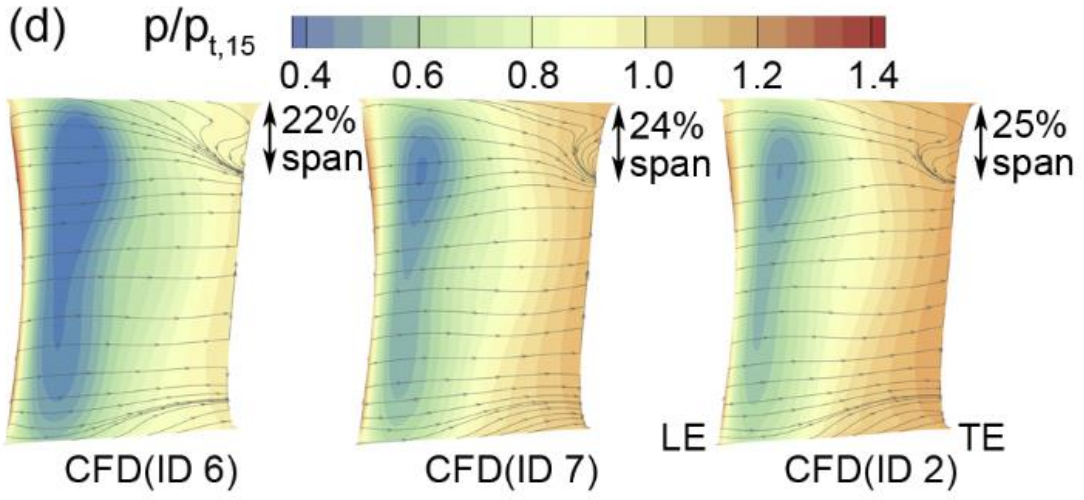


Rotor SS

N100 PE

- All predictions capture qualitatively the same pressure distribution, the formation of a shock in the upper spans and the radial flow migration in the lower spans
- ID 7 and ID 2 also capture a shock-induced separation, but ID 6 misses it

Stator SS Contours and Streamlines

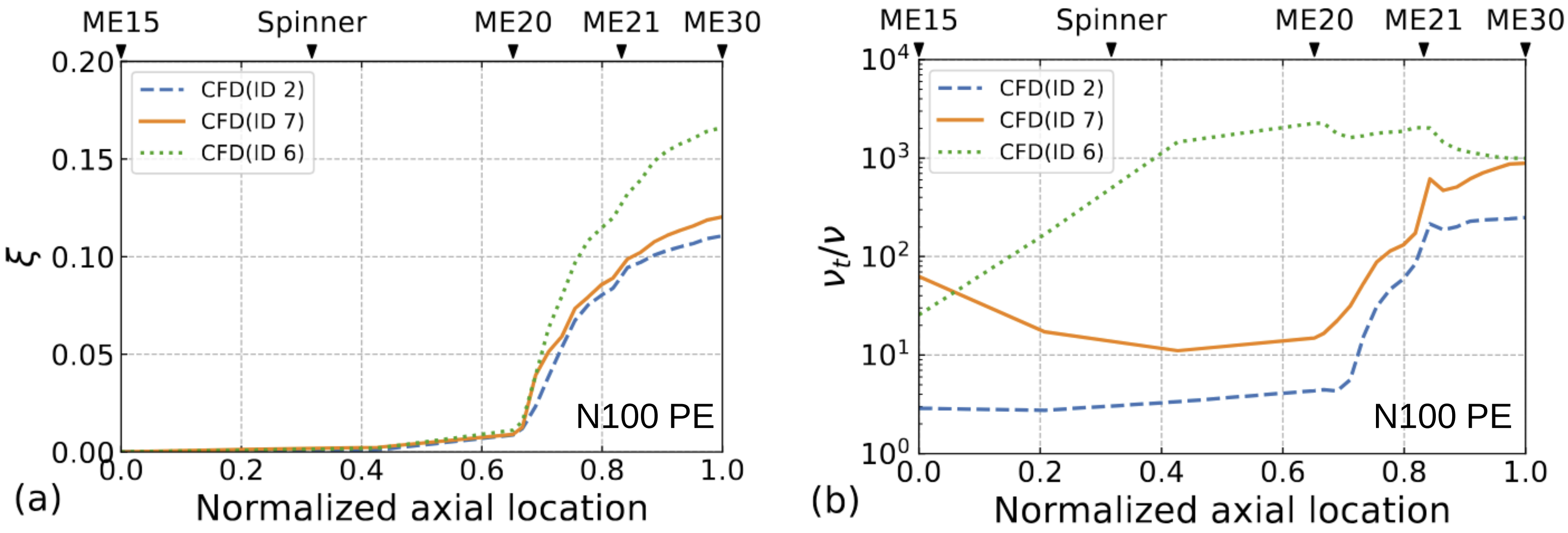


Stator SS

N100 PE

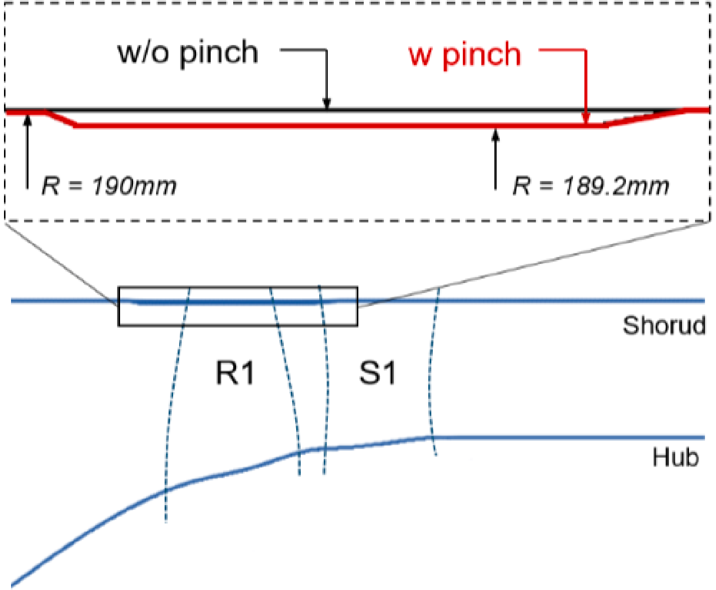
- All prediction results capture qualitatively the same pressure distribution and a trailing edge separation near the shroud.
- Quantitative difference in the predicted affected spans is minor.

Streamwise Profiles

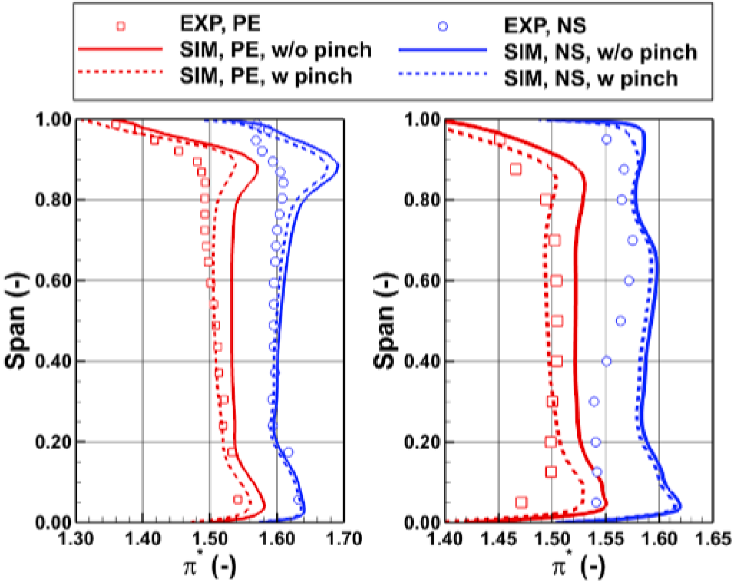


- Difference in entropy loss becomes apparent when flow enters the blade passages
- ID 6 predicts higher skin friction loss due to excessive eddy viscosity production (feature of SA-RC when solved in relative frame)

Effect of Rotor Casing Pinch



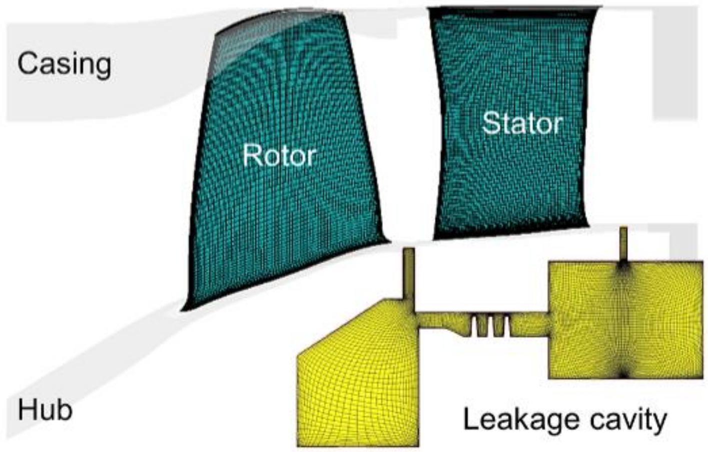
(a) Illustration of rotor casing pinch.

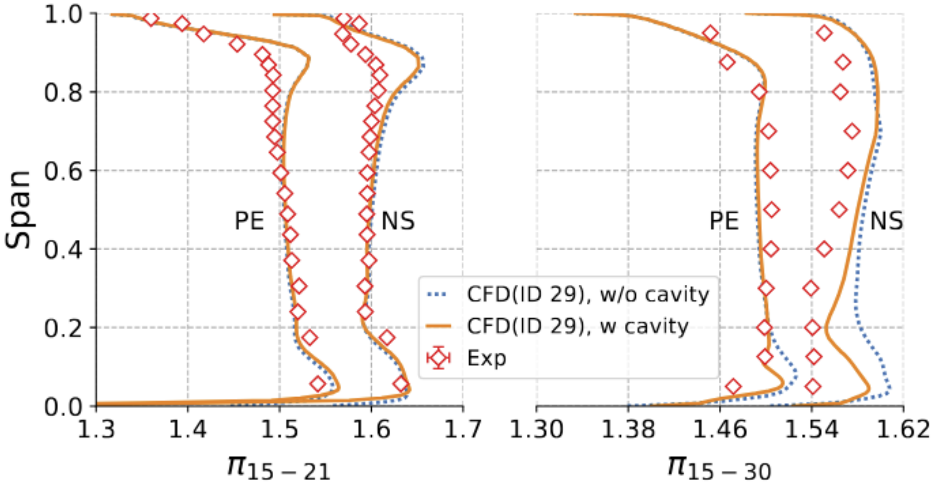


(b) Radial profiles at the rotor exit (left) and the stage exit (right).

- Rectifying geometric error of rotor casing pinch improves prediction accuracy near the rotor tip slightly

Effect of Stator Hub Cavity

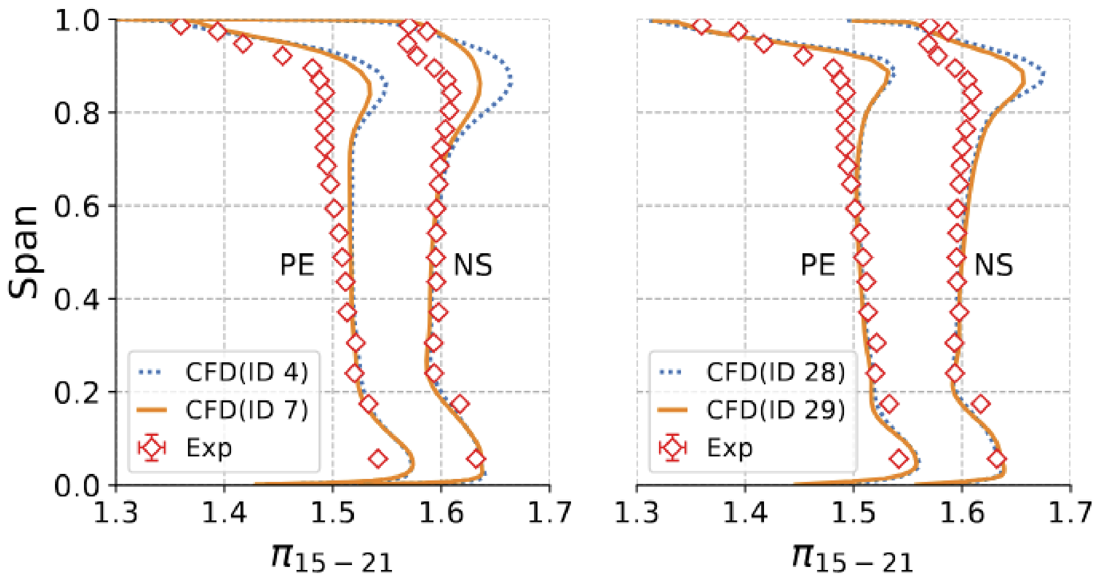




- Rectifying geometric error of stator hub cavity improves prediction accuracy near the stator hub evidently

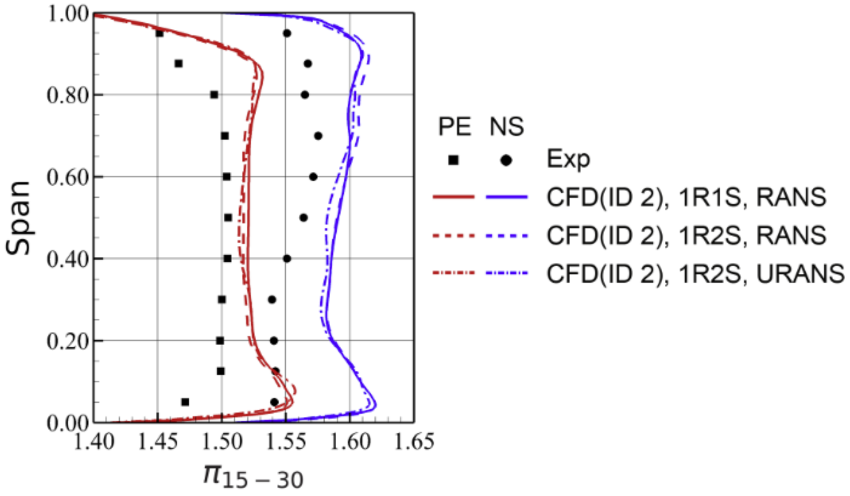
* Note the simulated cavity seal clearance is slightly larger. The original seal geometry is not open to the public due to IP protection.

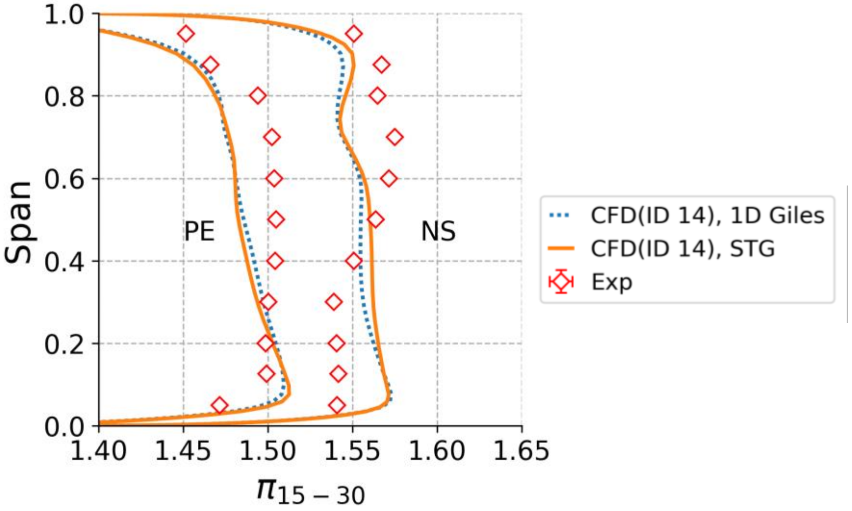
Effect of Turbulence Model



- Nonlinear turbulence models (e.g., EARSM, ID 7 and ID 29) improve prediction accuracy near the rotor tip slightly over conventional linear models (e.g., SST, ID4 and 28)

Effect of Unsteadiness





- Unsteady simulation with sliding planes only show minor difference compared to steady simulation with mixing planes.

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- **RANS Verification Results**
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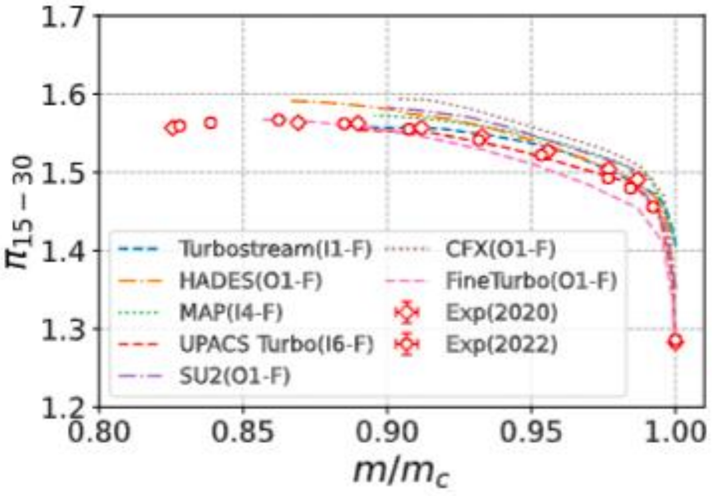
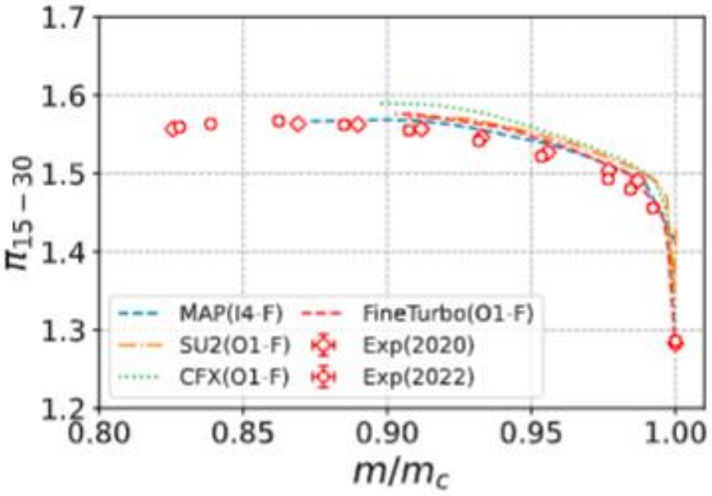
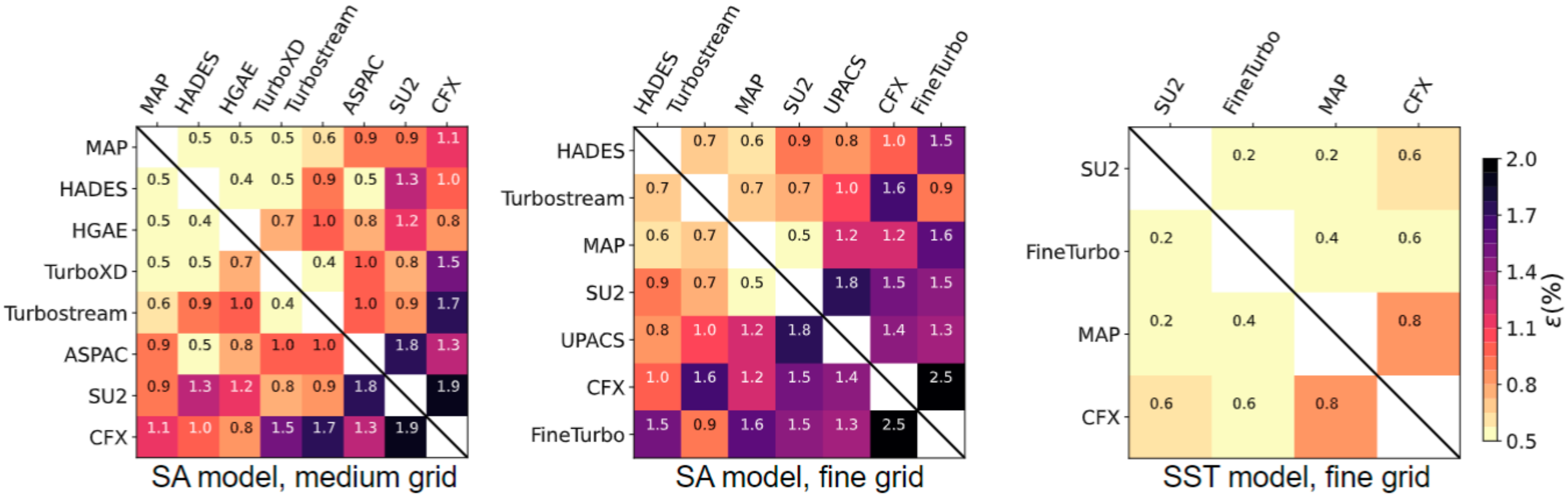
Performance Characteristics





- Using the same geometry and the “standard” turbulence model version of each solver yields different results
- Scattering of the SA model is larger than the SST model

Performance Characteristics



$$\epsilon_{ij} = \frac{1}{n}\sum_{k=1}^{n} \left| \frac{q_i^{(k)} - q_j^{(k)}}{q_{exp}^{(k)}} \right| \times 100\%$$

QoIs: TPR, TTR, efficiency at PE and NS conditions

- The max ϵ_{ij} for the SA-medium, SA-fine and SST-fine results are 1.9%, 2.5% and 0.8%, respectively.
- Within the SA model results, ϵ_{ij} between certain in-house solvers is below 0.8%, indicating a certain level of consistency.

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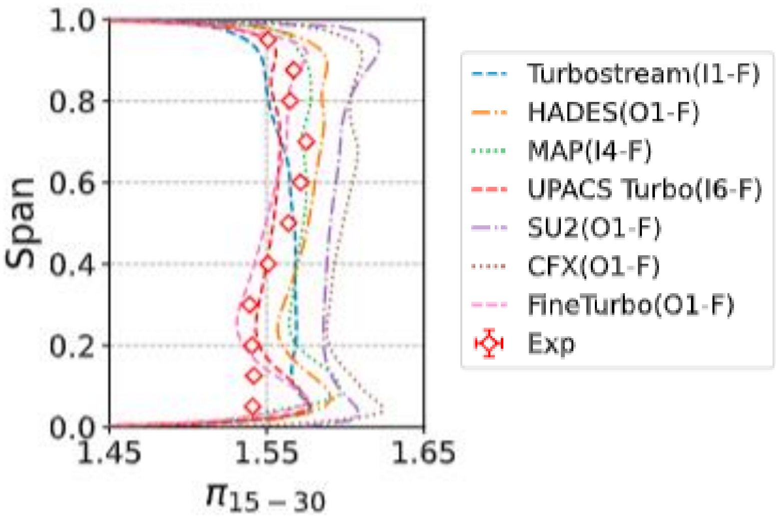
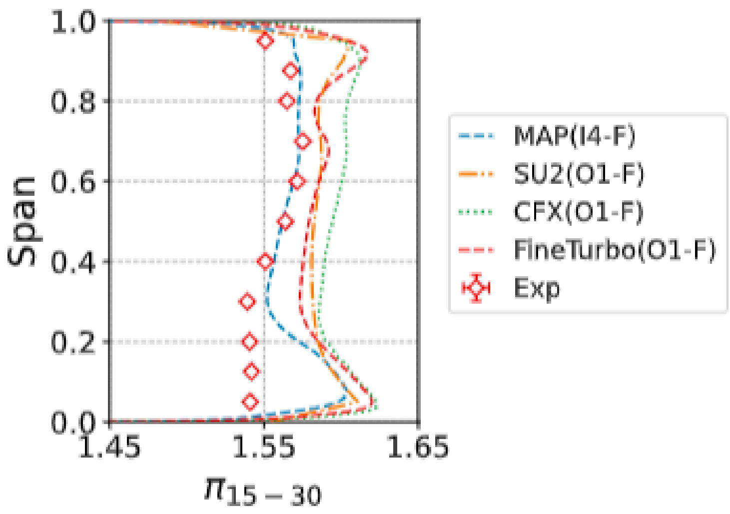
Stage Exit Radial Profiles

SA, N100 NS

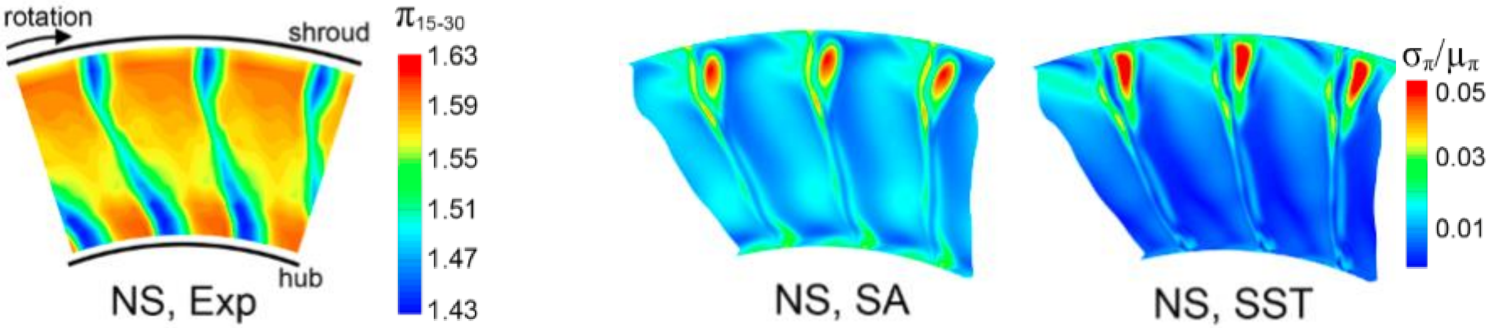


SST, N100 NS



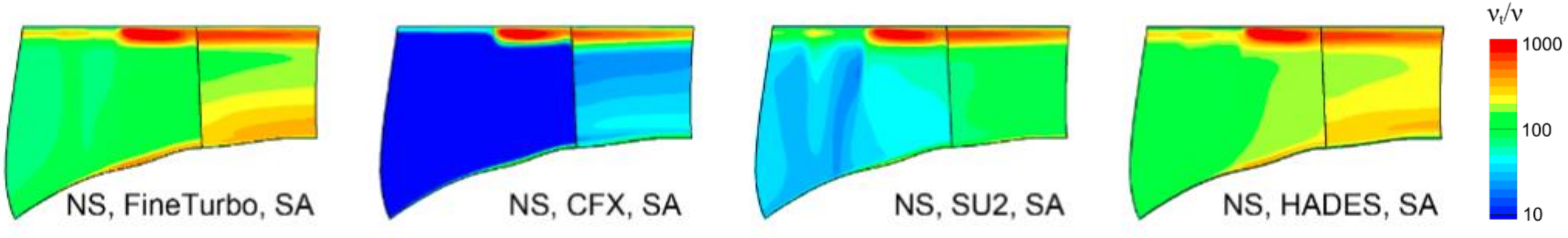
- All results exhibit similar profile shapes, but their magnitudes vary across the entire span (attributed to the difference in boundary layer prediction)
- FineTurbo uses SA-fv3 in rotating frame that tends to over-predict the BL thickness
- CFX uses uses a scalable wall function that tends to under-predicts the BL thickness

Stage Exit Contours



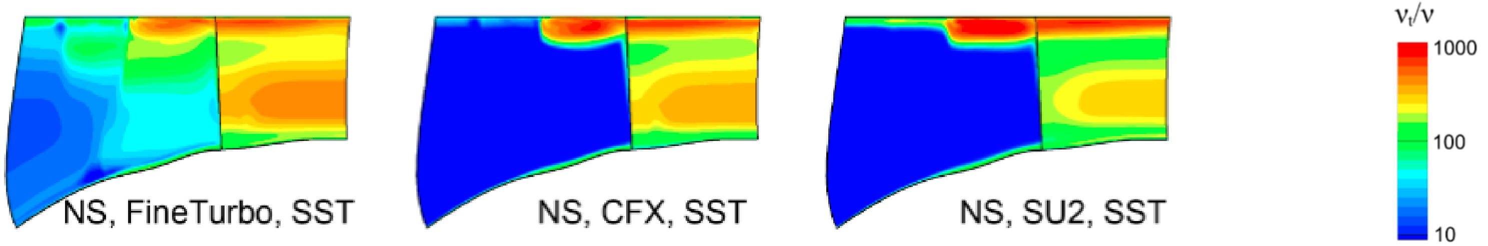
- Most notable variance are found in the stator wake and the stator tip separation regions.
- Variance among the SA results also occurs in the passage

Periodic Surface Contours



- FineTurbo and HADES solve turbulence model in relative frame, both show nonphysical eddy viscosity production in the inlet duct
- SU2 uses higher eddy viscosity at the inlet BC than CFX, hence the difference in freestream eddy viscosity
- The sensitivity of the SA model to the reference frame and the inlet BC leads to the large scattering of the SA-branch results

Periodic Surface Contours



- SST model is less sensitive to the reference frame (e.g., relative frame for FineTurbo and absolute frame for CFX & SU2)
- SST model is less sensitive to the inlet BC as the modelled freestream turbulence cannot sustain long (e.g., small inlet turbulence for CFX, medium inlet turbulence for SU2)
- These features lead to the less scattering of the SST results

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Conclusions

- Contemporary RANS solvers can be sufficiently predictive during the compressor preliminary design phase.

- The majority of the RANS simulation results (excluding coarse-mesh results and extremities) predicted $\mathrm{m_c}$ and τ_t accurately, but they over-predicted Π_t (up to **+1.7%**) and η_{isen} (up to **+2.3%** absolute) and under-predicted **SFR** (down to **-3.7%** absolute).

- The deficiencies of RANS predictions are mainly the over-prediction of total pressure in the **rotor near-shroud region** and the **stator near-hub region**, which can be alleviated via using **nonlinear eddy viscosity turbulence model** and considering **stator hub cavity.**

Conclusions

- The collective of RANS simulation results (excluding coarse-mesh results) exhibited **variations of 5.3% (relative) in Π_t**, which is **halved** compared to 1994 ASME IGIT Workshop due to the past 30 years of development in RANS.
- **The extreme RANS simulation results qualitatively predicted the same flow phenomenon** as the median simulation result (except for one submission missing the shock-induced separation). The quantitative difference comes from the prediction on the location of the shock front, the thickness of the boundary layer, the thickness of the wake, and the size of the rotor tip blockage.
- **Scattering of RANS simulation results can be improved via verification**, e.g., (1) standard turbulence model implementation, especially check reference frame and wall distance calculation; (2) documentation of R-S model and wall functions; (3) open-source turbo solver

Future Plan

Release of official grids ver. 3 and the relevant measurement data

- Including stator hub cavity. New measurement was performed in 2023 with in-house designed seal, whose clearance is slightly larger.
- Release 6 month earlier before next workshop.

Release of workshop numerical database on Github (Imperial)

- Numerical data of all submissions to “Track 1: steady RANS” and basic visualization scripts.
- Release soon after the 4th workshop.

Investigation of rotor tip geometric uncertainty and error (TU Darmstadt)

Future Plan

Open topics for public

- transition model
- UQ of turbulence model
- advanced turbulence models
- adaptive mesh refinement
- scale-resolving simulation
- inlet BC sensitivity
- (anything else improves validation accuracy)

References

1. Klausmann, F., Franke, D., Foret, J., & Schiffer, H. P. (2022). Transonic compressor Darmstadt-Open test case Introduction of the TUDa open test case. Journal of the Global Power and Propulsion Society, 6, 318-329. **Major reference to the open test case and the mean flow measurement data.**
2. Klausmann, F., Spieker, D., & Schiffer, H. P. (2024). Transonic compressor darmstadt open test case–unsteady aerodynamics and stall inception. Journal of the Global Power and Propulsion Society, 8, 52-61. **Major reference to the unsteady measurement data.**
3. He, X., & Klausmann, F., 2024, RANS Capabilities for Transonic Axial Compressor: A Perspective from GPPS CFD Workshop. ASME Journal of Turbomachinery (online). **Major reference to the overall summary of the workshop submissions**.
4. He, X., 2023, On the Consistency of RANS CFD in Predicting Axial Compressor Flows: A Perspective from the GPPS RANS CFD Workshop (Preprint on ResearchGate). **Major reference to the verification of workshop submissions.**
5. He, X., Zhu, M., Xia, K., Fabian, K. S., Teng, J., & Vahdati, M. (2023). Validation and verification of RANS solvers for TUDa-GLR-OpenStage transonic axial compressor. Journal of the Global Power and Propulsion Society, 7, 13-29. **Major reference to the ver. 1 official grids.**
6. Xia, K., He, X., Zhu, M., Klausmann, F. S., Teng, J., & Vahdati, M. (2023). Endwall geometric uncertainty and error on the performance of TUDA-GLR-OpenStage transonic axial compressor. Journal of the Global Power and Propulsion Society, 7, 113-126. **Major reference to the ver. 2 official grids.**

Overview of Workshop Submissions for TUDa-GLR-OpenStage

4th GPPS Turbomachinery CFD Workshop (GPPS 2024)

Questions & Answers