Summary of Submissions

3rd GPPS Turbomachinery CFD Workshop (GPPS 2023)

Xiao He Imperial College London

References:

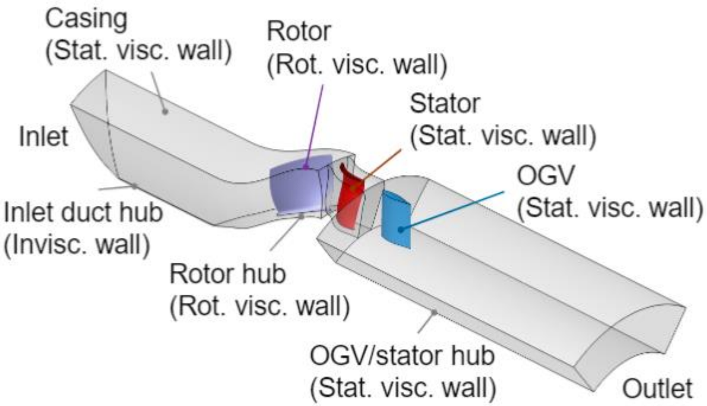
1. He, X., & Klausmann, F. RANS Capabilities for Transonic Axial Compressor: A Perspective from GPPS CFD Workshop. Preprint available on ResearchGate. (2023)

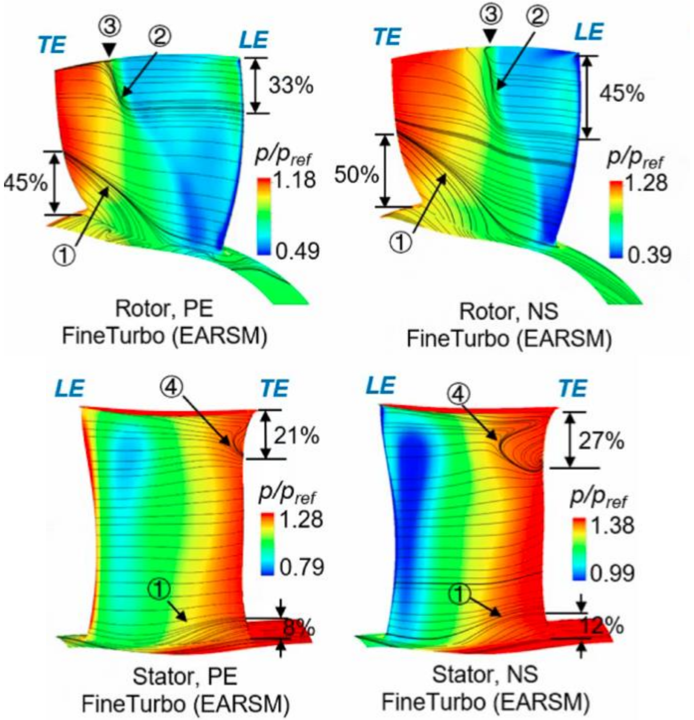
2. He, X. On the Consistency of RANS CFD in Predicting Axial Compressor Flows: A Perspective from the GPPS RANS CFD Workshop. Preprint available on ResearchGate. (2023)

Description of Workshop Test Case

Description of Workshop Test Case

- Numerical model and flow physics





Notation: ① Hub corner separation; ② Shock-induced separation; ③ Shock front; ④ Trailing edge separation

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Submission Statistics of Workshops

Submission Statistics of Workshops

As of GPPS 2022 workshop:

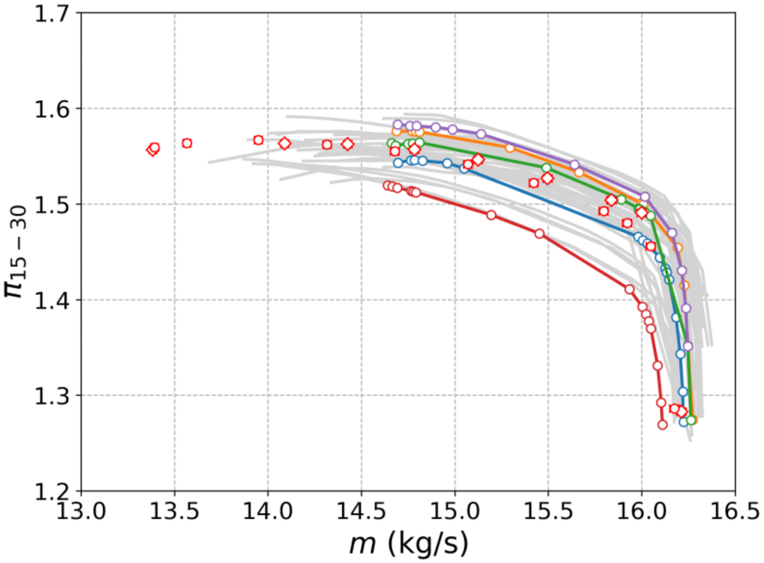
- 14 participants, 5 countries, 11 organizations, 12 solvers
- Turbulence model: mostly SA or SST branch of models
- ≥2nd order accuracy in space
- Inlet BC: mostly using the official inlet.bc file

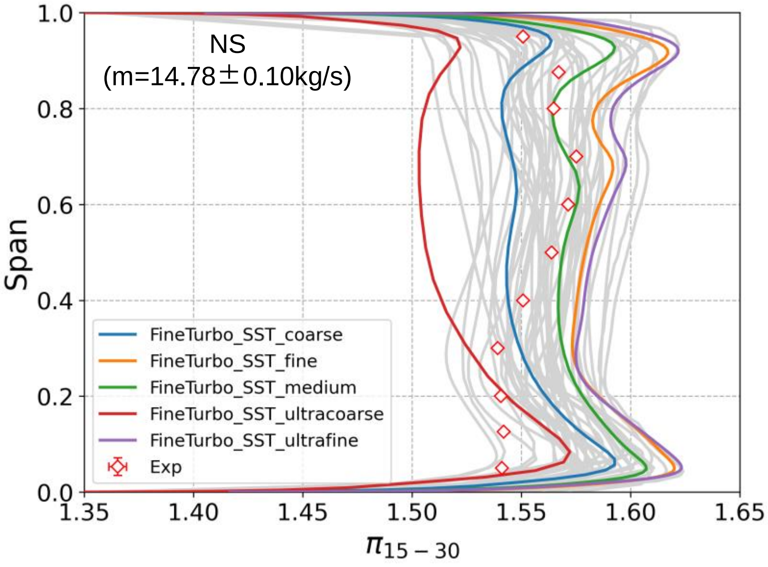
ID	Org.	Solver (Version)	Type	Grid ID	Turb. model	Convect.	R-S model	Wall func.	In. BC
1	SJTU	CFX (20.1)	C	O1	SA-noft2	HR	MP	Yes	O, U5
2	SJTU	CFX (20.1)	C	O1	SST-2003	HR	MP	Yes	O, O
3	SJTU	FineTurbo (14.1)	C	O1	SST[a]	Roe	MP	No	O, O
4	SJTU	FineTurbo (14.1)	C	O1	SST[a]	JST	MP	No	O, O
5	SJTU	FineTurbo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

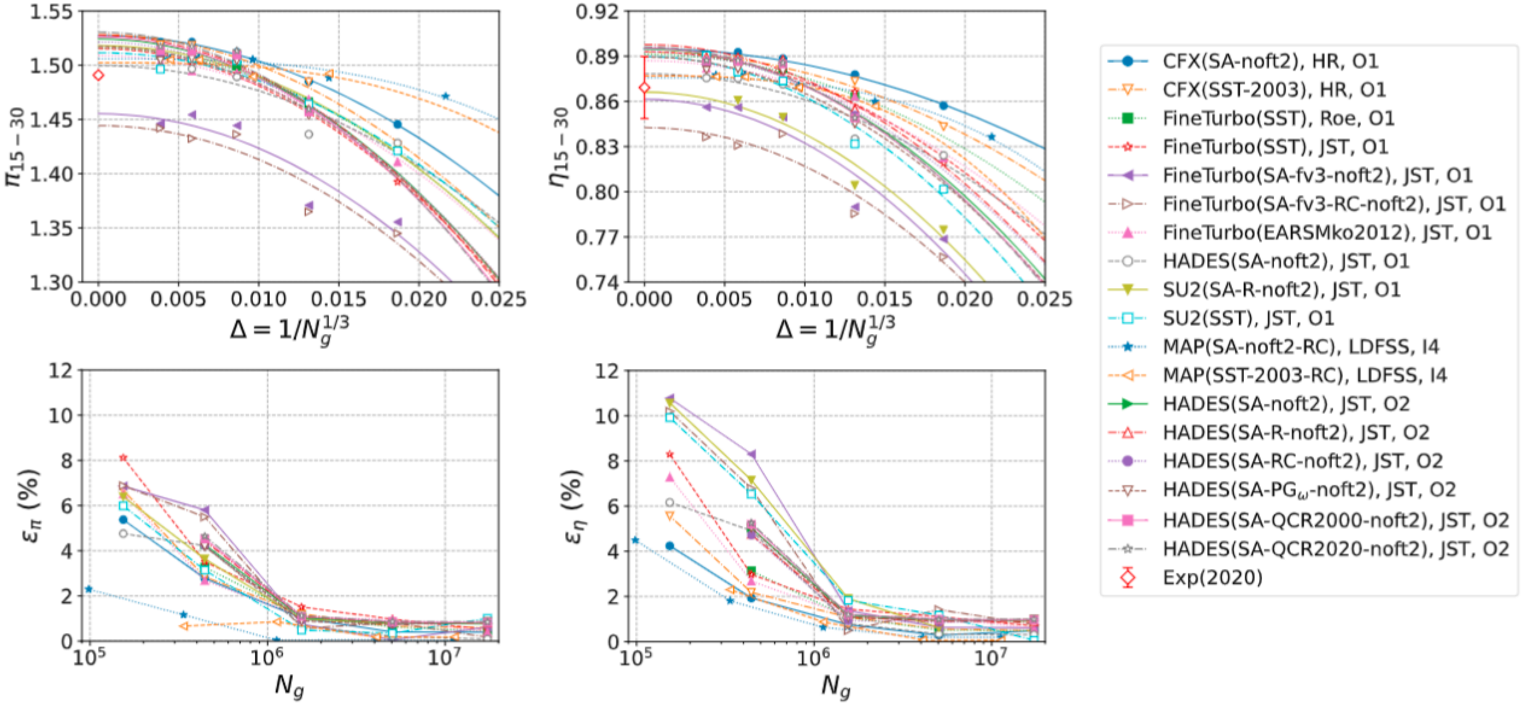
Grid Convergence Results

Grid Convergence Results

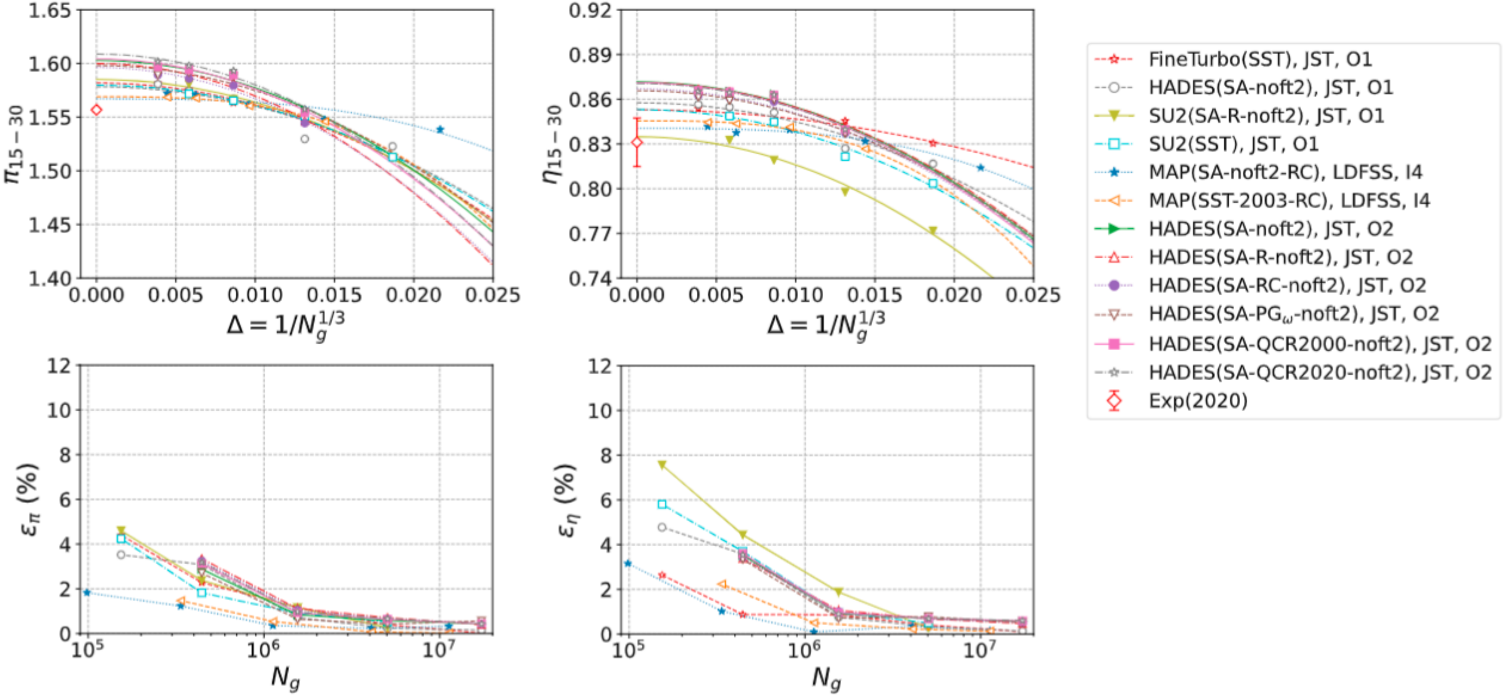




Grid Convergence Results

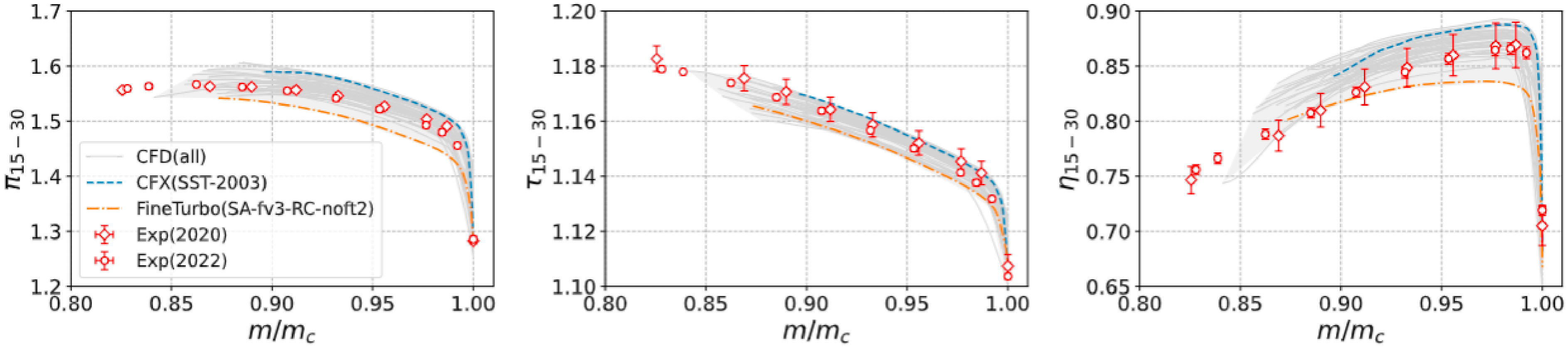


Grid Convergence Results

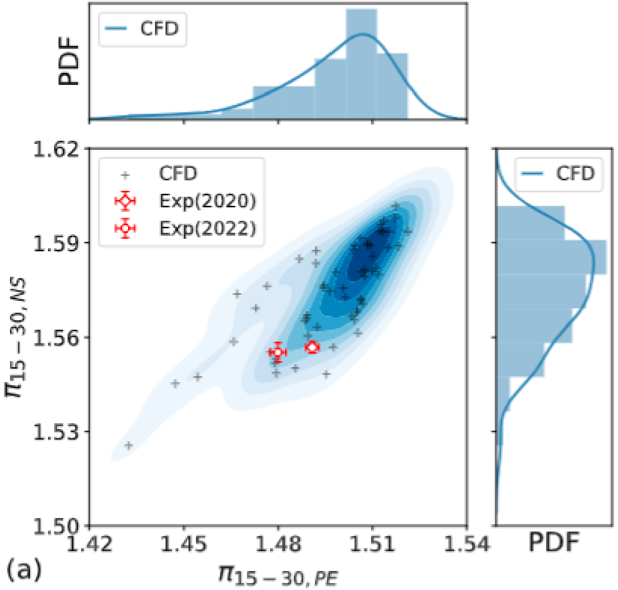


Validation: Experiment versus CFD

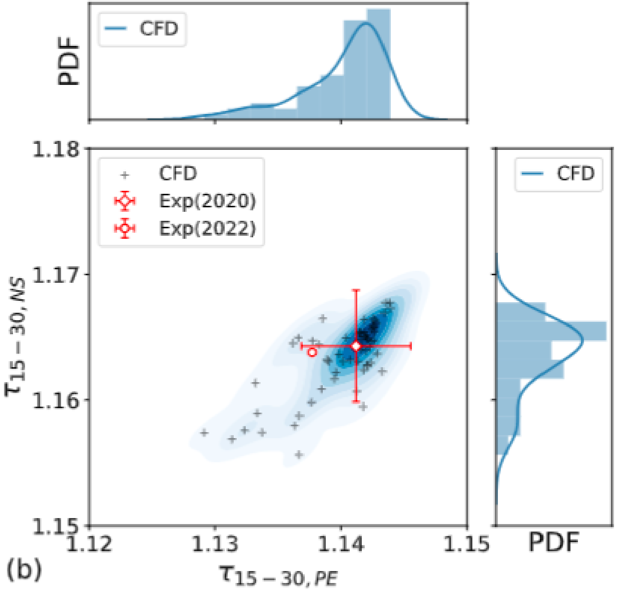
Validation: Performance Characteristics



Validation: Performance Characteristics

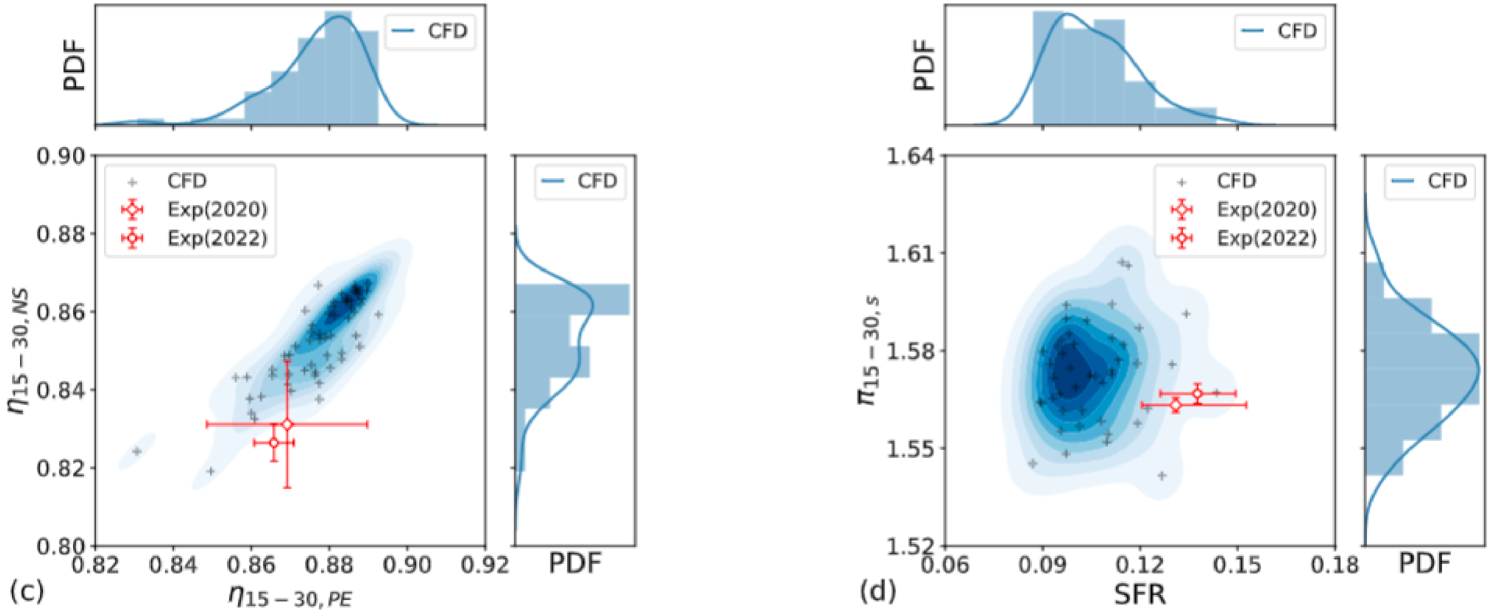


(a)

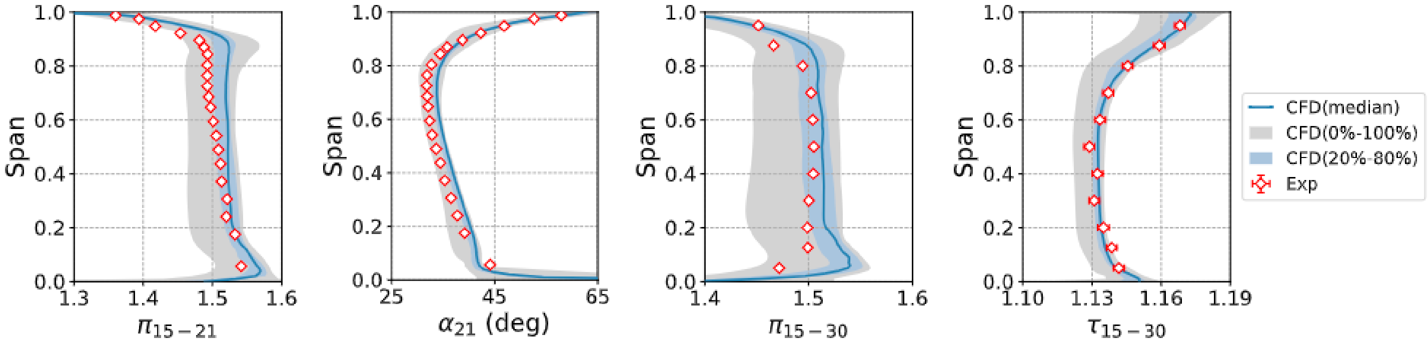


(b)

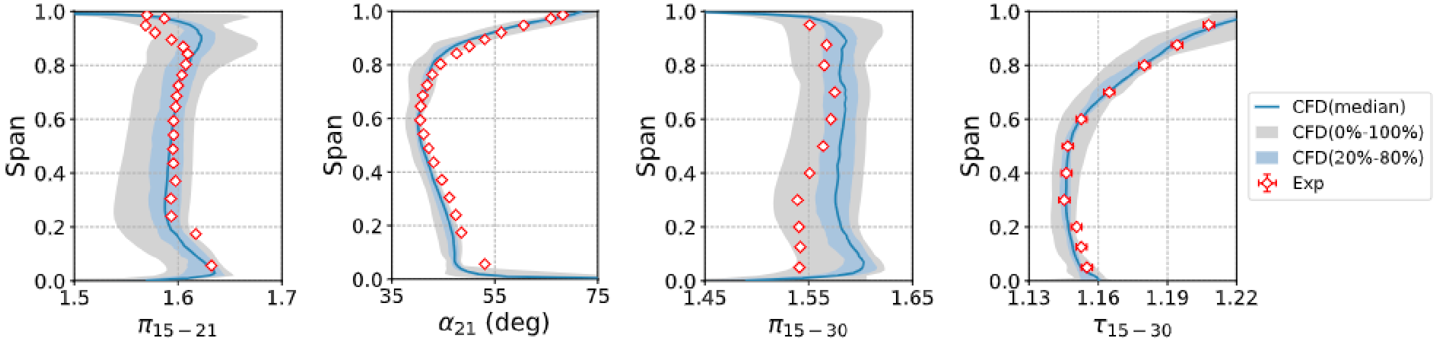
Validation: Performance Characteristics



Validation: Radial Profiles



(a) PE condition, 100% design speed.



(b) NS condition, 100% design speed.

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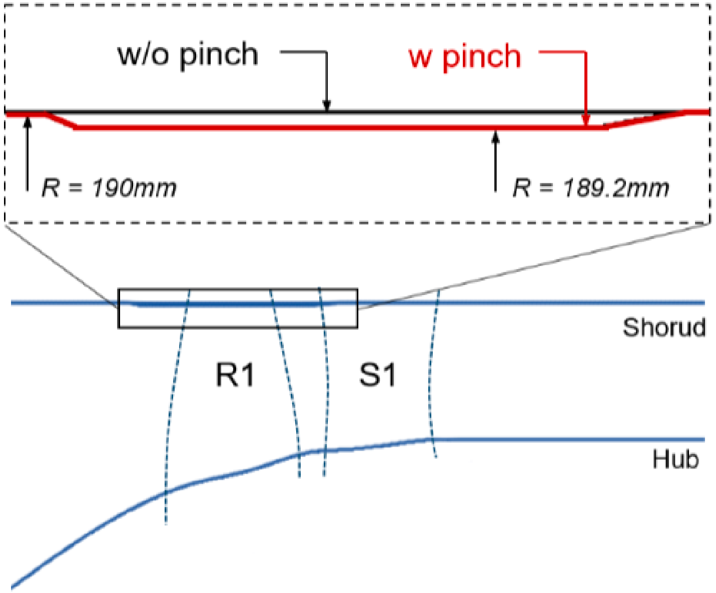
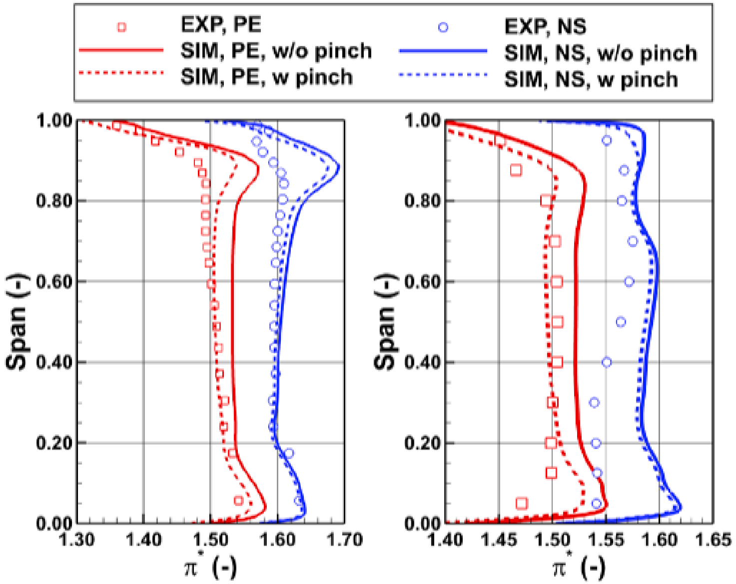
Validation: Investigation of Deficiency

- Geometric error: rotor casing pinch



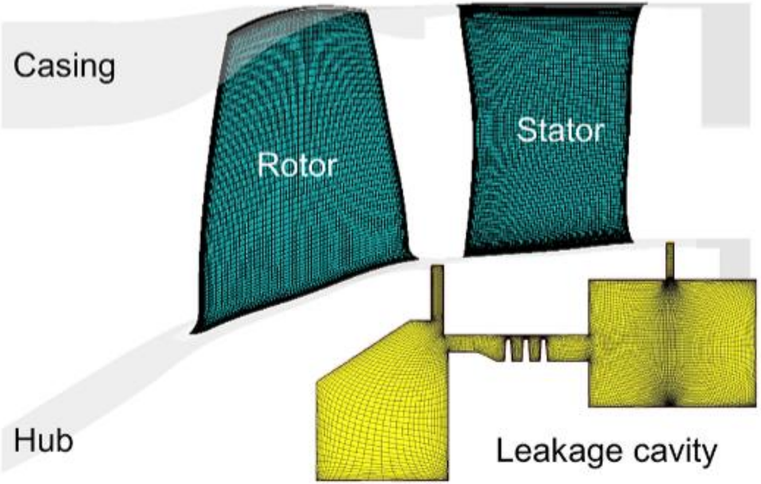
(a) Illustration of rotor casing pinch.



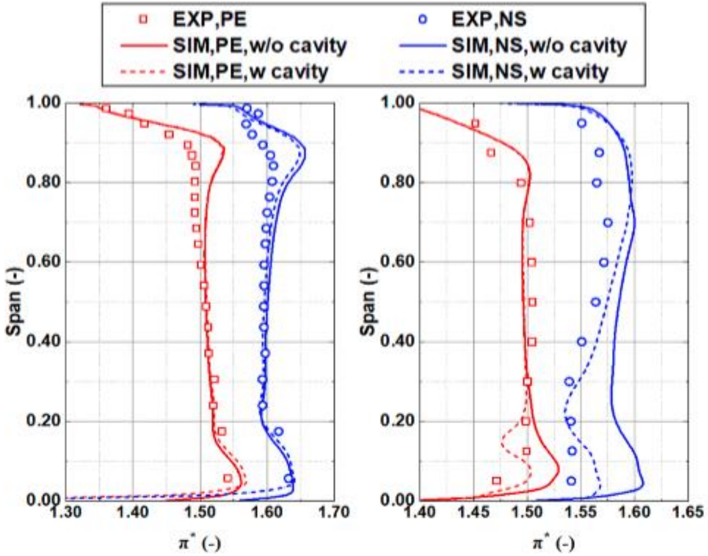
(b) Radial profiles at the rotor exit (left) and the stage exit (right).

Validation: Investigation of Deficiency

- Geometric error: stator hub cavity (major contributor)



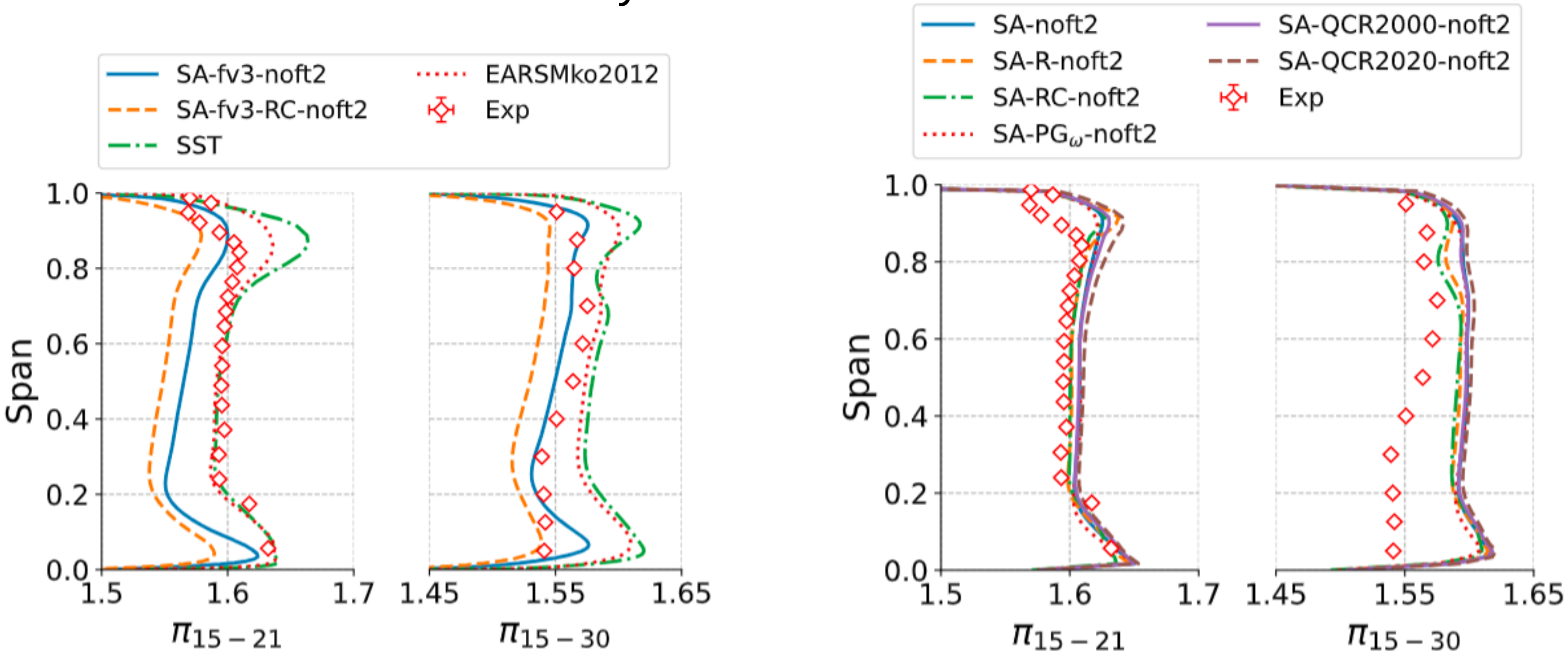
(a) Illustration of stator hub cavity.



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

Validation: Investigation of Deficiency

- Turbulence model deficiency

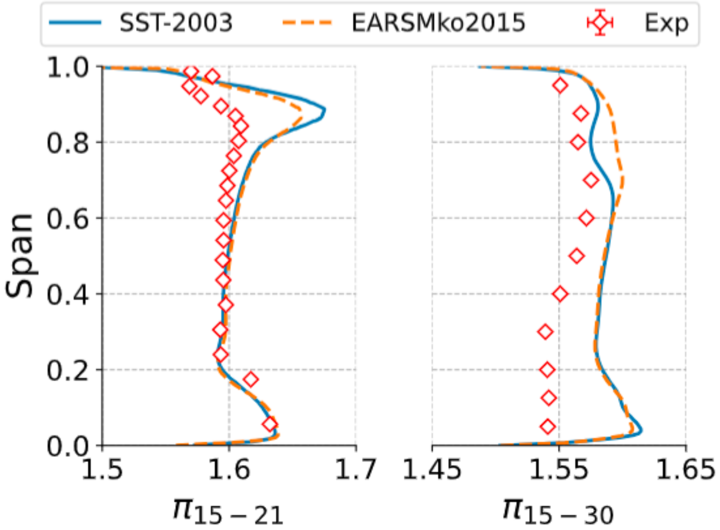


(a) FineTurbo results (submission ID 4 to 7).

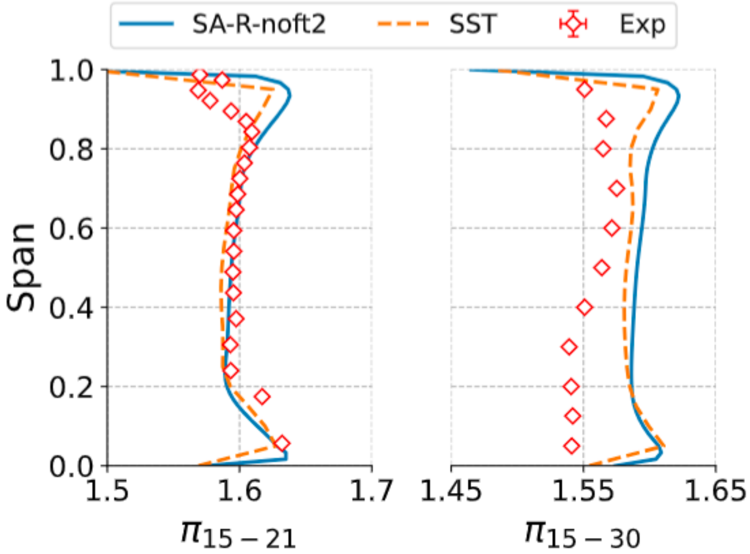
(b) HADES results (submission ID 22 to 27).

Validation: Investigation of Deficiency

- Turbulence model deficiency



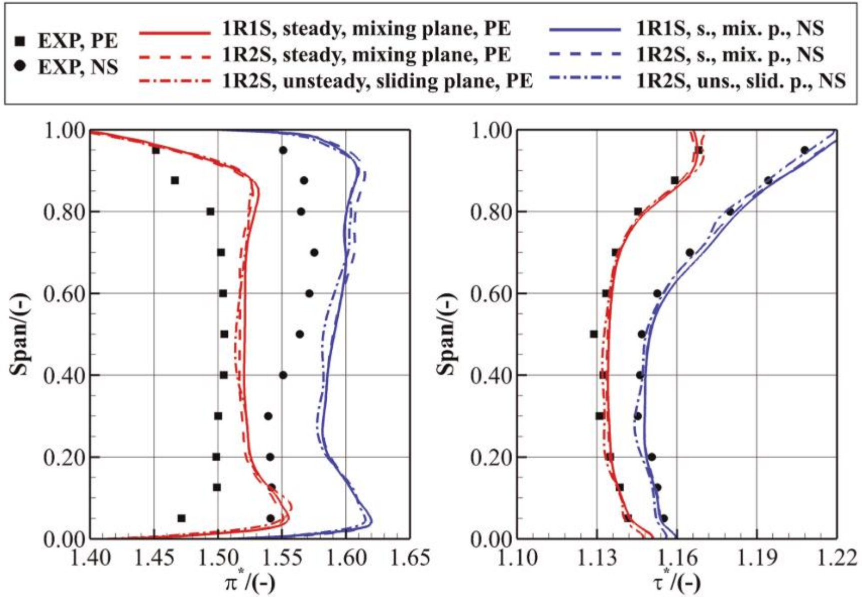
(c) CFX results (submission ID 28, 29).



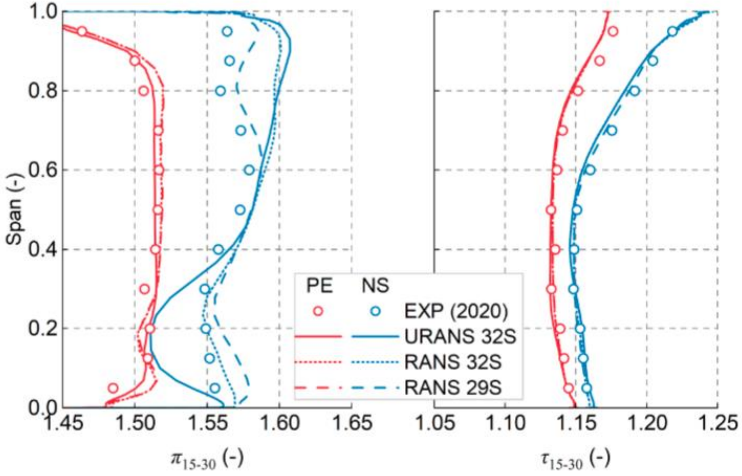
(d) SU2 results (submission ID 9, 10).

Validation: Investigation of Deficiency

- Unsteady effect



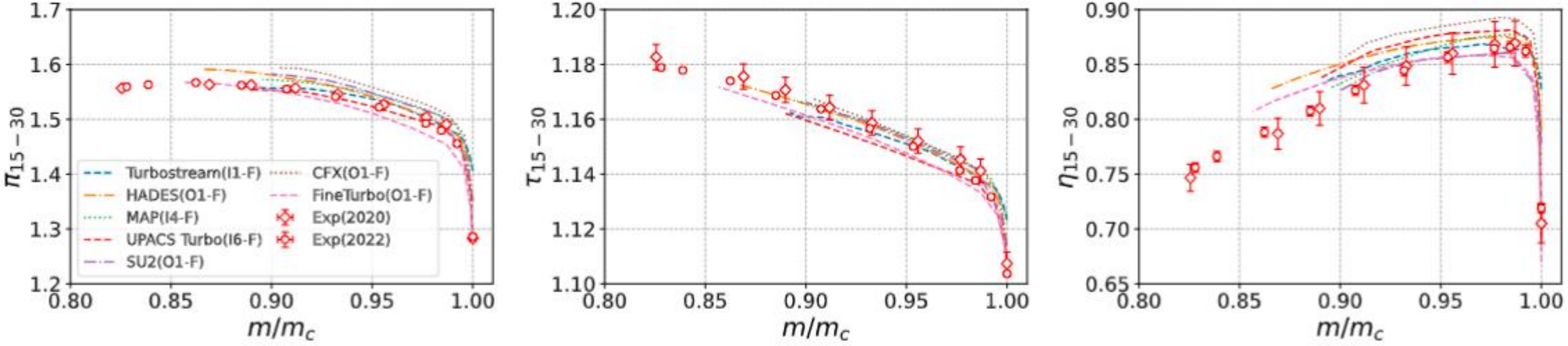
w/o cavity; He et al. (2023), GPPS J



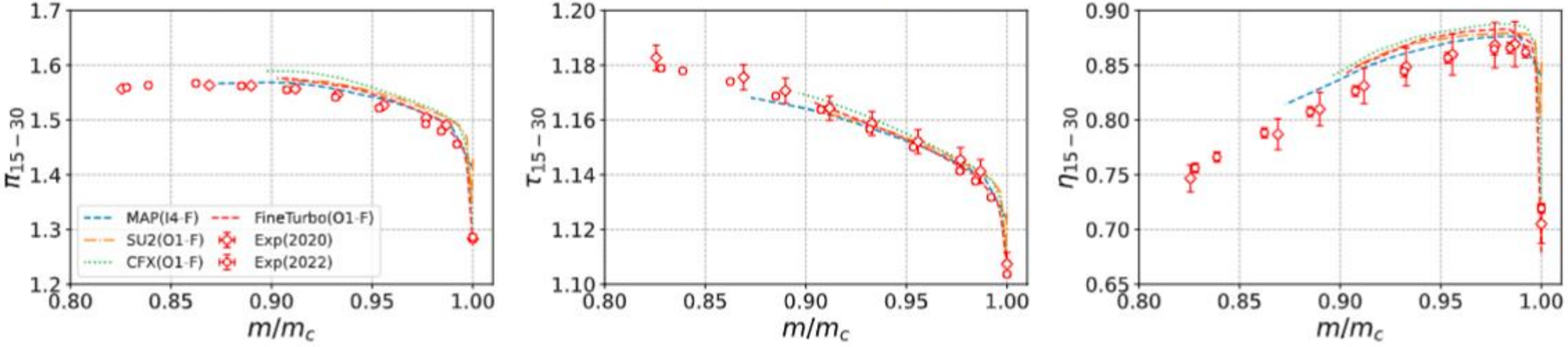
w cavity; Deng et al. (2023), GPPS-TC-2023-0027

GPPS 2021 Geometry Verification: CFD versus CFD

Verification: Performance Characteristics



(a) SA model, fine grid.



(b) SST model, fine grid.

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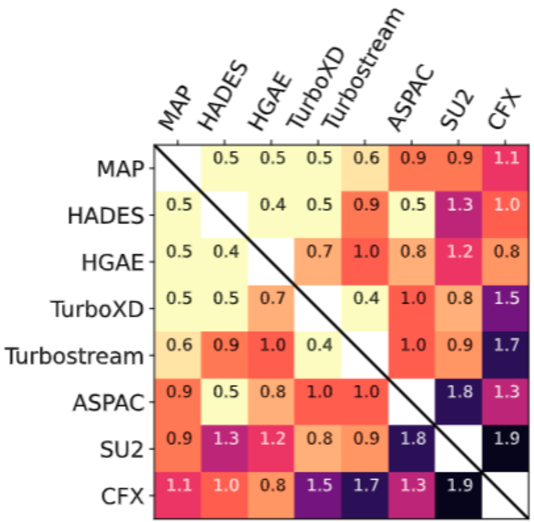
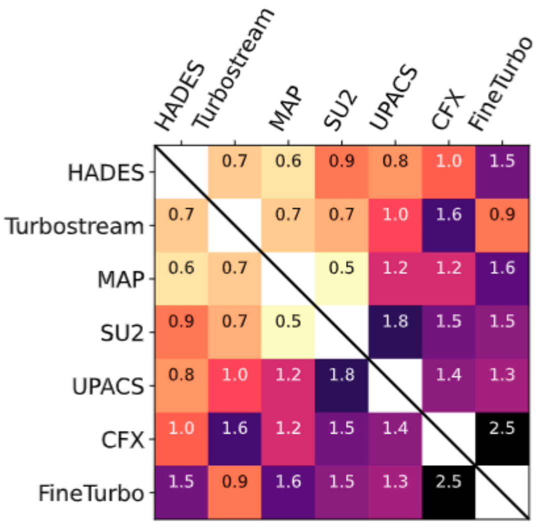
Verification: Performance Characteristics

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

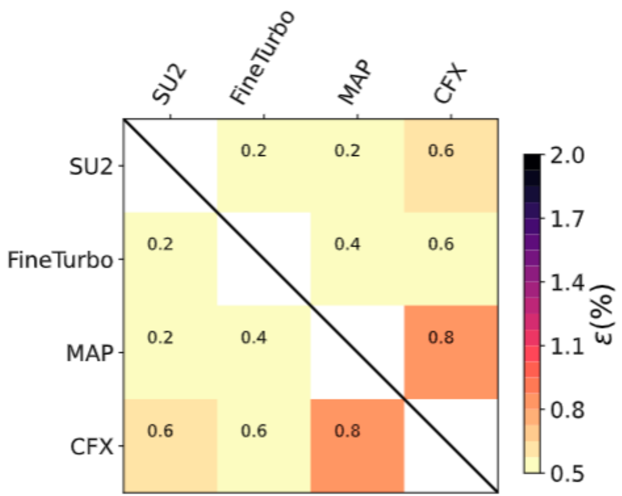
QoIs: TPR, TTR, efficiency at PE and NS conditions



SA model, medium grid

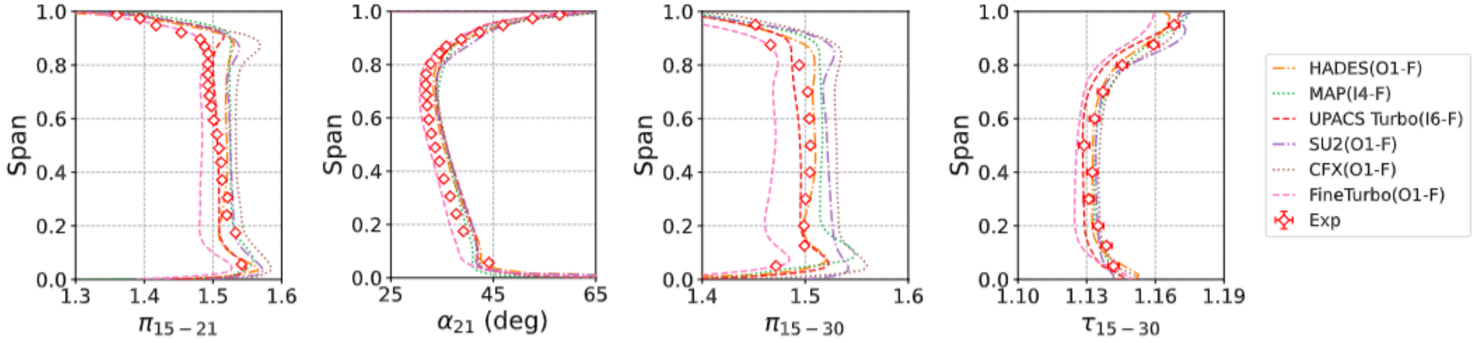


SA model, fine grid

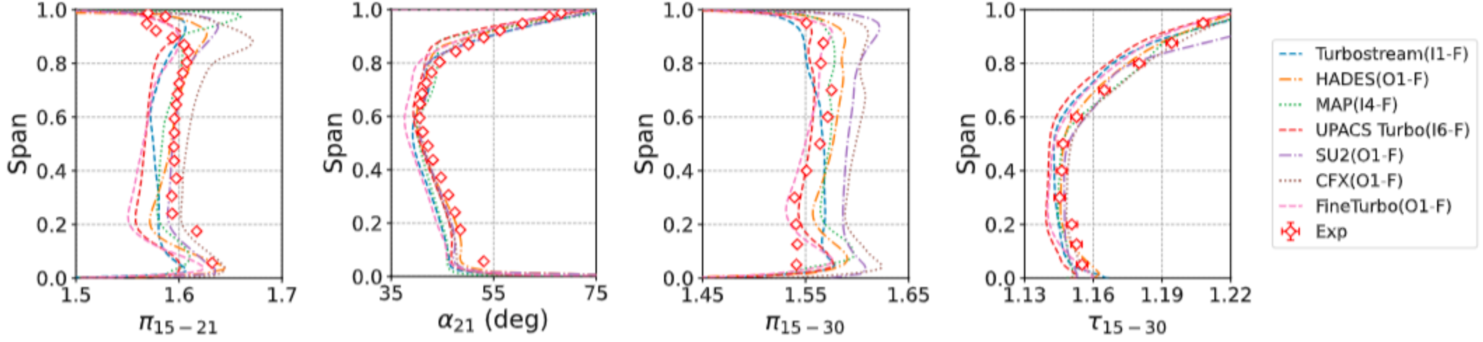


SST model, fine grid

Verification: Radial Profiles

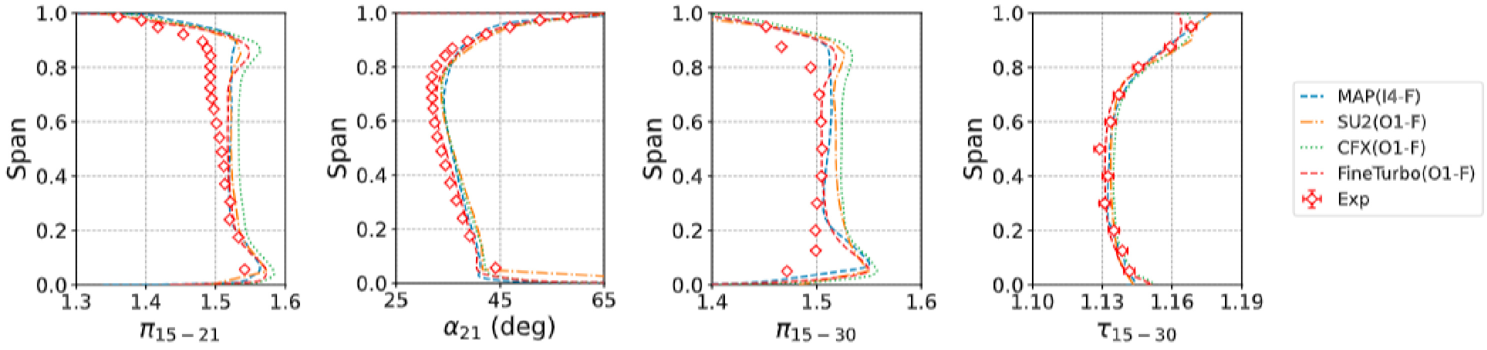


(a) SA model, fine grid, PE condition, 100% design speed.

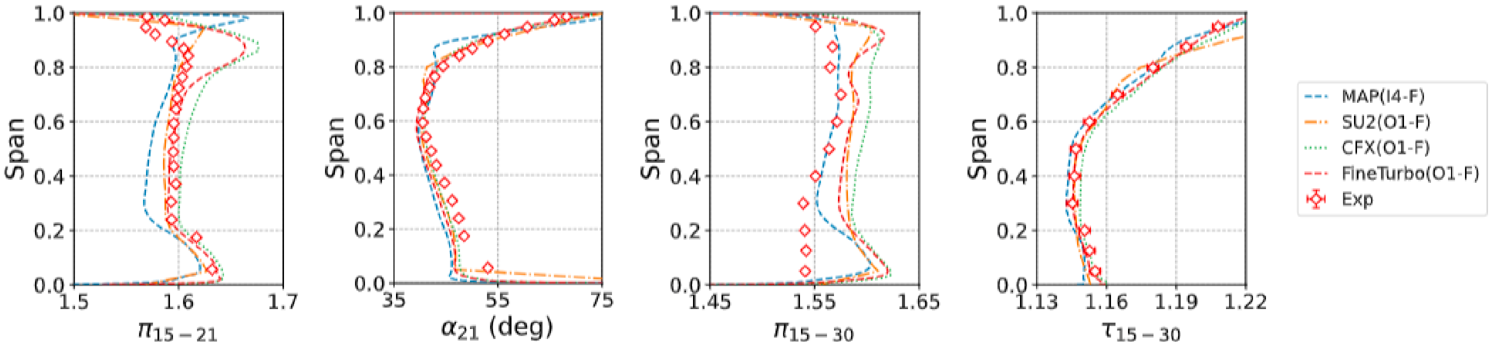


(b) SA model, fine grid, NS condition, 100% design speed.

Verification: Radial Profiles

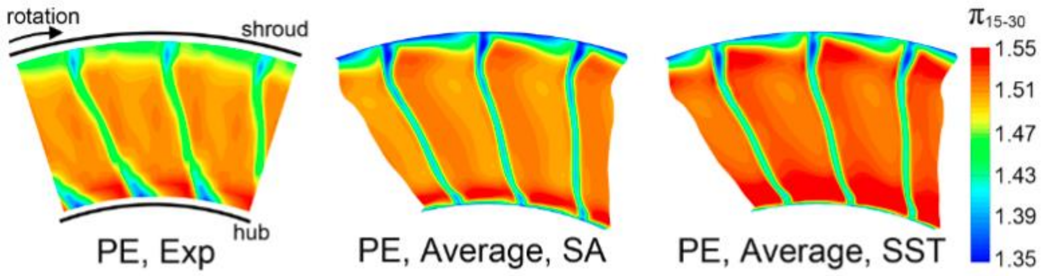


(c) SST model, fine grid, PE condition, 100% design speed.

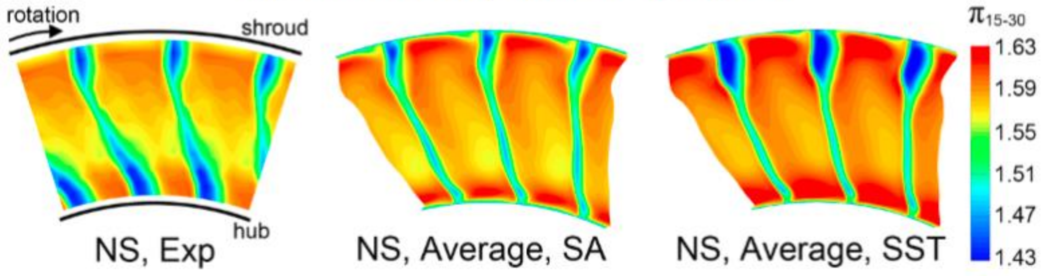


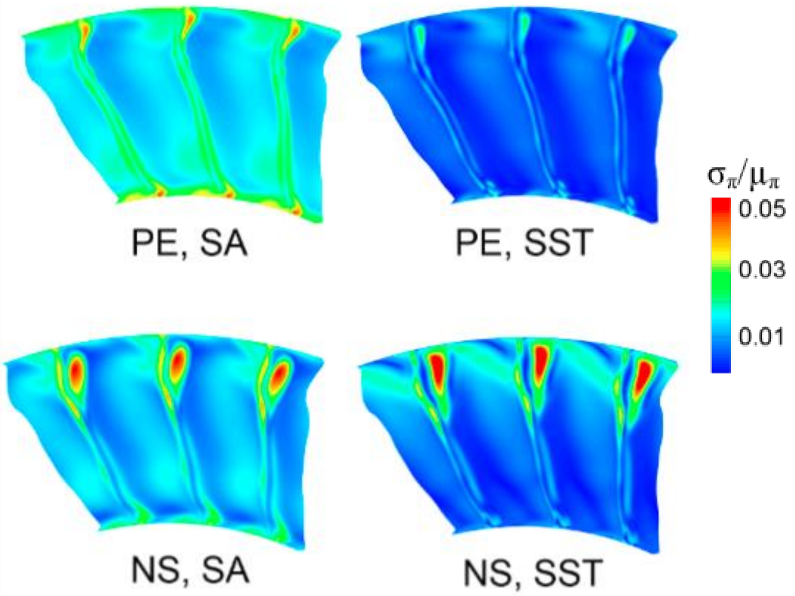
(d) SST model, fine grid, NS condition, 100% design speed.

Verification: Stage Exit Contours

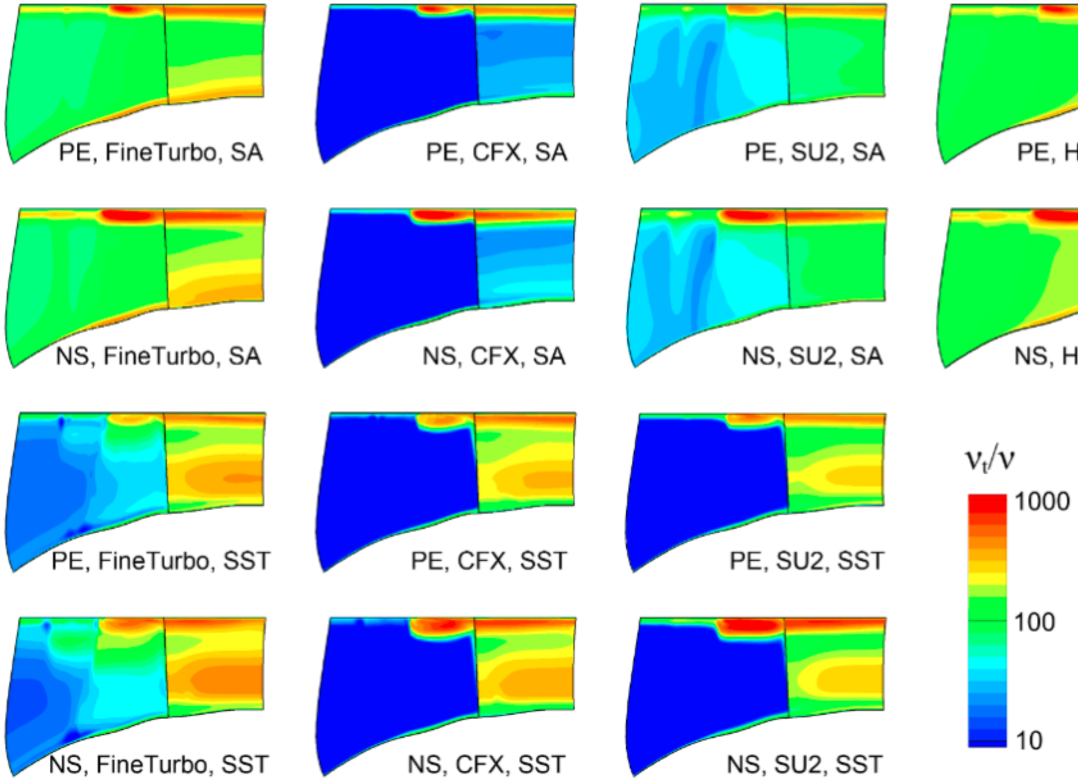


(a) PE condition, 100% design speed.





Verification: Periodic Surface Contours



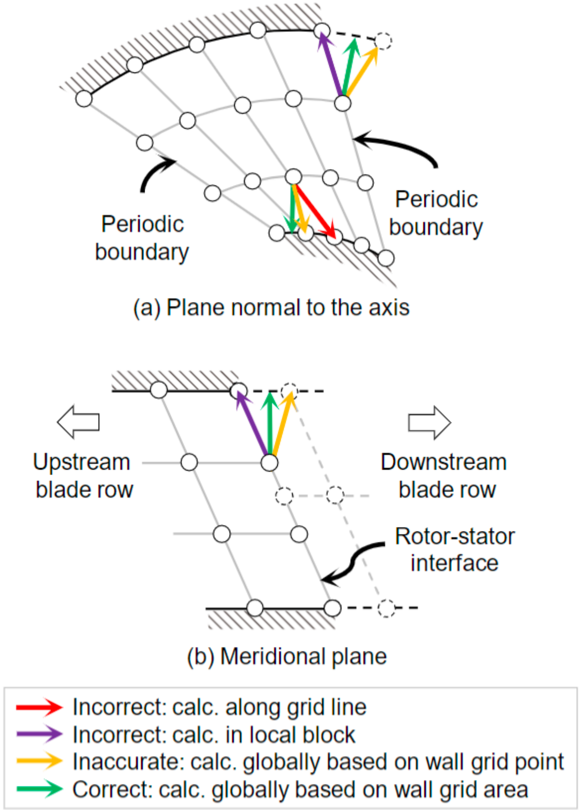
Verification: Investigation of Inconsistency

- Turbulence model inconsistency
  - Special flavor of a model is used (standard ver. recommended)
  - Reference frame: relative vs. absolute (recommended)
  - Wall distance calculation

- Rotor-stator interface model inconsistency
  - Slightly different treatment for non-reflection property, turbulence model quantity, numerical stability, grid type compatibility, etc.

- Wall function inconsistency
  - Blending functions, pressure gradient corrections, etc.

- Other factors
  - Inlet BC for turbulence models, iterative convergence, transition modeling, static aeroelastic deformation, etc.



Conclusions

Conclusions

Grid Convergence Study

- Rule of thumb: 1M / 3M grid points per blade passage for preliminary/detailed analysis of compressor
- Grid convergence achieved using one turbulence model can be applied to another

Validation (CFD vs. EXP)

- Overall uncertainty (w ≥ fine grid): Total pressure ratio: **±2.3%**; Isentropic efficiency: **±2.3%** (absolute) (these numbers were **±12%** and **±3%** in 1994 IGTI workshop)
- Key factors to improve accuracy: (1) Geometric error control: **stator hub cavity**; (2) turbulence model improvement (e.g., non-linear, RC correction, etc.)

Verification (CFD vs. CFD)

- Contemporary turbo solvers achieve qualitative but not quantitative consistency: relative difference ranging from [0.4%, **2.5%**] for SA model and [0.2%, **0.8%**] for SST model
- Key factors to improve consistency: (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**

Summary of Submissions

3rd GPPS Turbomachinery CFD Workshop (GPPS 2023)

Questions & Answers