Summary of Submissions

2nd GPPS Turbomachinery CFD Workshop (GPPS 2022)

Xiao He Imperial College London

GPPS

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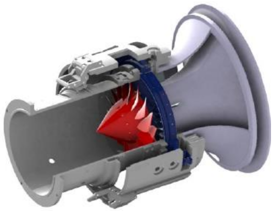
Design of the Workshop

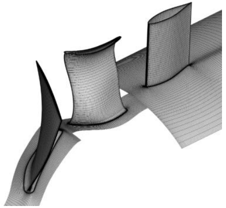
Timeline

Release of geometry and experimental data



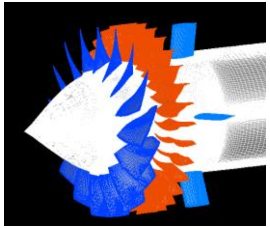
See also in 2021 release:
[1] Open_Stage_TUDa_Data_Info.pdf
[2] Open_Stage_TUDa_Geometry_Info.pdf

Release of official grids ver.1, boundary conditions and workshop submission guideline



See also in 2021 release:
[1] Open_Stage_TUDa_Grid_Info.pdf
[2] Open_Stage_TUDa_Submission_Guideline.pdf

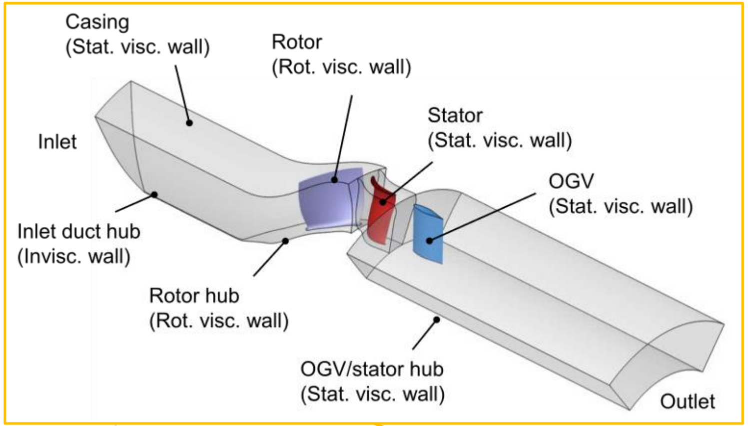
Release of official grids ver.2



See also in 2022 release:
[1] TUDa_mesh_information.pdf

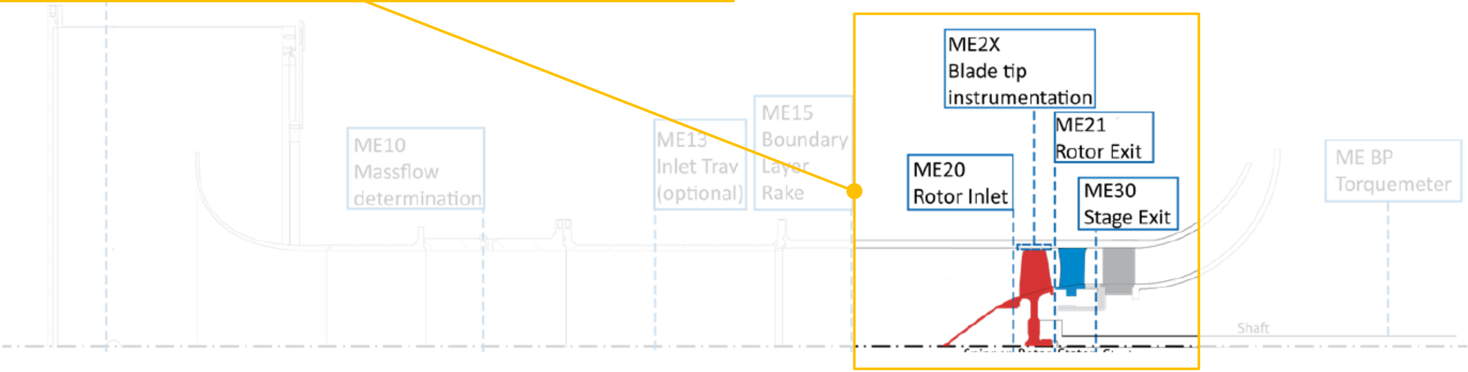
- 10/2020 – Release of geometry and experimental data
- 04/2021 – V&V paper submitted
- 06/2021 – Workshop proposal
- 07/2021 – Release of official grids ver.1, boundary conditions and workshop submission guideline
- 12/2021 – 1st Workshop
- 06/2022 – Repeat measurement
- 07/2022 – Release of official grids ver.2
- 09/2022 – 2nd Workshop

Flow Domain and Boundary Conditions



Major differences between CFD model and EXP

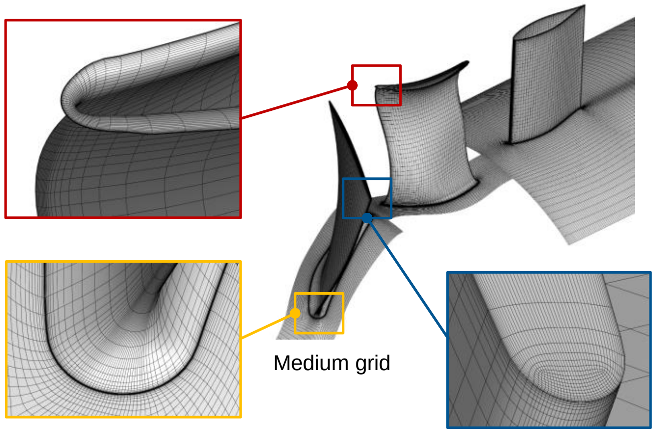
- The axial-to-radial duct is simplified as an axial duct.
- Changes of the inlet profile are not considered.
- Changes of blade tip gap size are not considered.

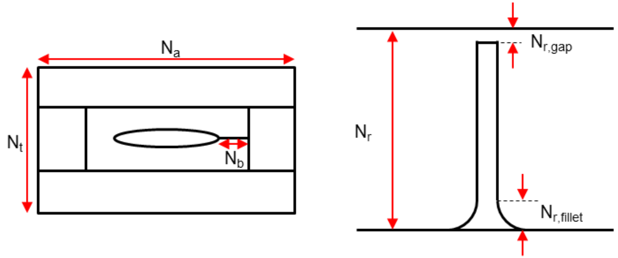


Official Grids Ver. 1 (1st Workshop)

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	-	-

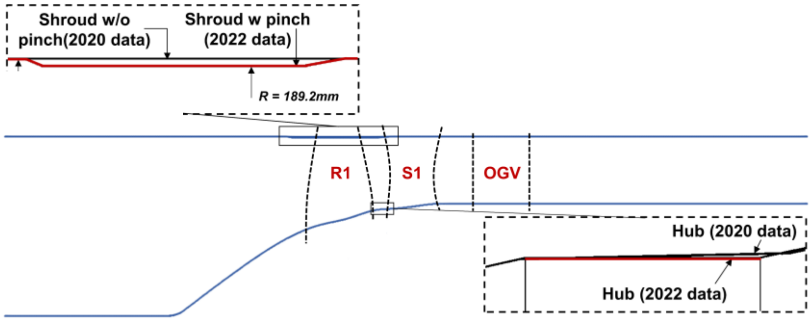
Official Grids Ver. 2 (2^{nd} Workshop)

Major updates on geometry

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

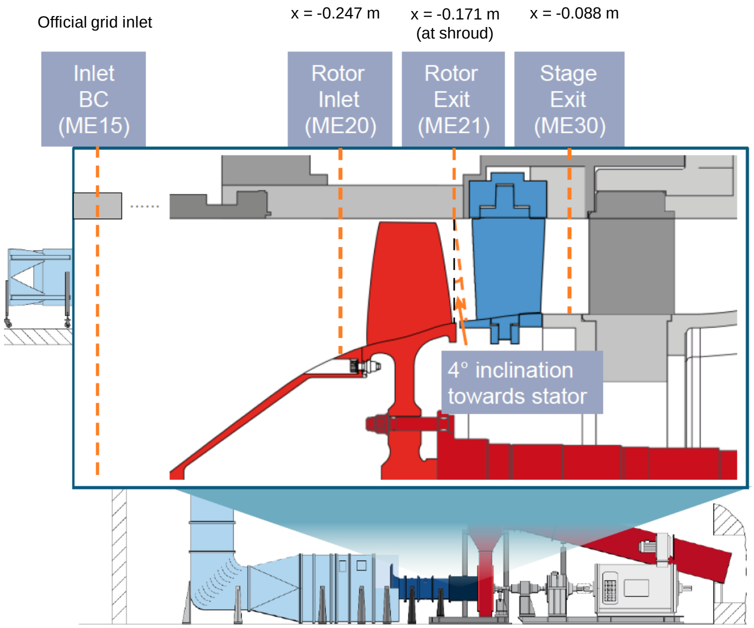
Major updates on grid quality

- 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

Flow Quantities of Interest

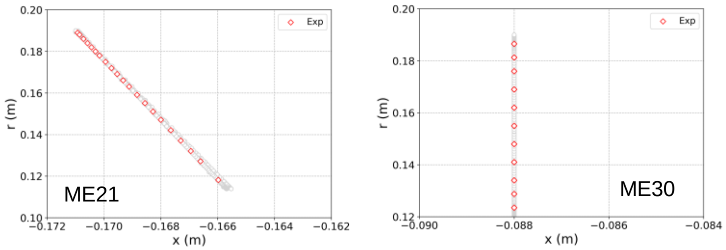


Collected data:

- **characteristics.csv**
  Corrected_speed(RPM), Corrected_mass_flow(kg/s), pt_AA_15(Pa), pt_MA_15(Pa), Tt_AA_15(K), Tt_MA_15(K), pt_AA_30(Pa), pt_MA_30(Pa), Tt_AA_30(K), Tt_MA_30(K), ptr_AA_15_30, Ttr_AA_15_30, Ttr_MA_15_30, Isentropic_Efficiency_15_30
- **profile_ME21.csv**
  Corrected_mass_flow(kg/s), r_21(m), x_21(m), Span, alpha(deg), gamma(deg), pt_AA_21(Pa), ptr_AA_15_21
- **profile_ME30.csv**
  Corrected_mass_flow(kg/s), r_30(m), x_30(m), Span, pt_AA_30(Pa), Tt_AA_30(K), ptr_AA_15_30, Ttr_AA_15_30

Quality control:

- Post-process check
- Location check



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CFD Setup Form

Collected CFD setup info:

- Grid details

  Number of grid nodes, y^+

- Flow solver numerical schemes

  Advection scheme, turbulence model, wall function, rotor-stator interface model

- Boundary conditions

  Inlet profile (mean flow quantities; turbulence model quantities), outlet boundary condition

- Convergence history

  Mass flow convergence at PE/NS conditions

1. Participant Information

First name:	[redacted]
Last name:	[redacted]
Organization:	[redacted]
Email:	[redacted]

2. Grid Information

If this submission used an official grid:

Grid name (e.g., medium, fine, etc.):	fine

If this submission used an in-house grid:

Average y^+ of the first layer grid:	
Number of grid points in the rotor domain:	
Number of grid points in the stator domain:	
Type of grid element: (e.g., hexahedron, tetrahedron, etc.)	

3. RANS Flow Solver Information

(1) General:

Solver name:	NUMECA FineTurbo
Major reference(s) (optional):	

(2) Advection Scheme:

Branch of scheme (e.g., JST, ROE, AUSM):	JST
If not listed above, please briefly describe the advection scheme and include a major reference to the scheme:	

(3) Turbulence Model:

Model name*:	SST
If not documented in NASA TMR, please briefly describe the turbulence model and include a major reference to it:	

*Please follow the naming convention of NASA TMR. Note that the turbulence model implemented in the solver may differ from the standard version of the model (e.g., SA vs. SA-noft2, SST vs. SST-2003, etc.)

(4) Viscous wall treatment:

Use of wall function (yes/no):	no
Use in-house grid with $y^+ > 10$ (yes/no):	no
If both yes, please briefly describe the wall function and include a major reference to it:	

(5) Rotor-stator interface model:

Type of model for mean flow quantities*: (e.g., frozen rotor, mixing plane, non-reflecting (Giles))	mixing plane
Type of model for turbulence quantities*: (e.g., frozen rotor, mixing plane)	mixing plane
If not listed above, please briefly describe the rotor-stator interface model and include a major reference to it:	

* Mean flow quantities are p, T, u_x, u_y, u_z, etc.; turbulence quantities are eddy viscosity, k, ω, etc.

(6) Other details (optional):

Fluid model (e.g., real gas, idea gas):	idea gas
Linear system solver (e.g., Jacobi, etc.):	Incomplete Lower Upper(ILU)
Have you verified your solver in NASA 2D flat plate against established RANS solvers? (yes/no)	no

4. Boundary conditions

(1) Inlet:

How were the mean flow quantities determined? (e.g., from InletBC.input file; uniform inlet at standard conditions)	from InletBC.input file
How was the turbulence quantity(s) determined? (e.g., values and units of inlet k and ω)	$k = 35\ m^2/s^2$ $\varepsilon = 2.0\times10^3\ m^2/s^2$

(2) Outlet (optional):

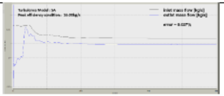
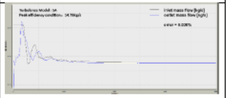
What type of boundary condition is used? (e.g., uniform backpressure, radial equilibrium backpressure, mass flow, Riemann, etc.)	radial equilibrium backpressure

(3) Periodic boundary (optional):

Have you checked the periodicity of mean flow quantities? (yes/no)	yes
Have you checked the periodicity of turbulence quantities? (yes/no)	yes

5. Convergence History

A figure of mass flow rate (rotor inlet, rotor exit/stator inlet, and stator exit) versus iteration

Peak efficiency condition (16.00 ± 0.10 kg/s)	Near stall condition (14.78 ± 0.10 kg/s)
	

Submission Statistics of Workshops

Submission Statistics of Workshops

60 characteristic curves submitted by 14 authors from 11 institutes

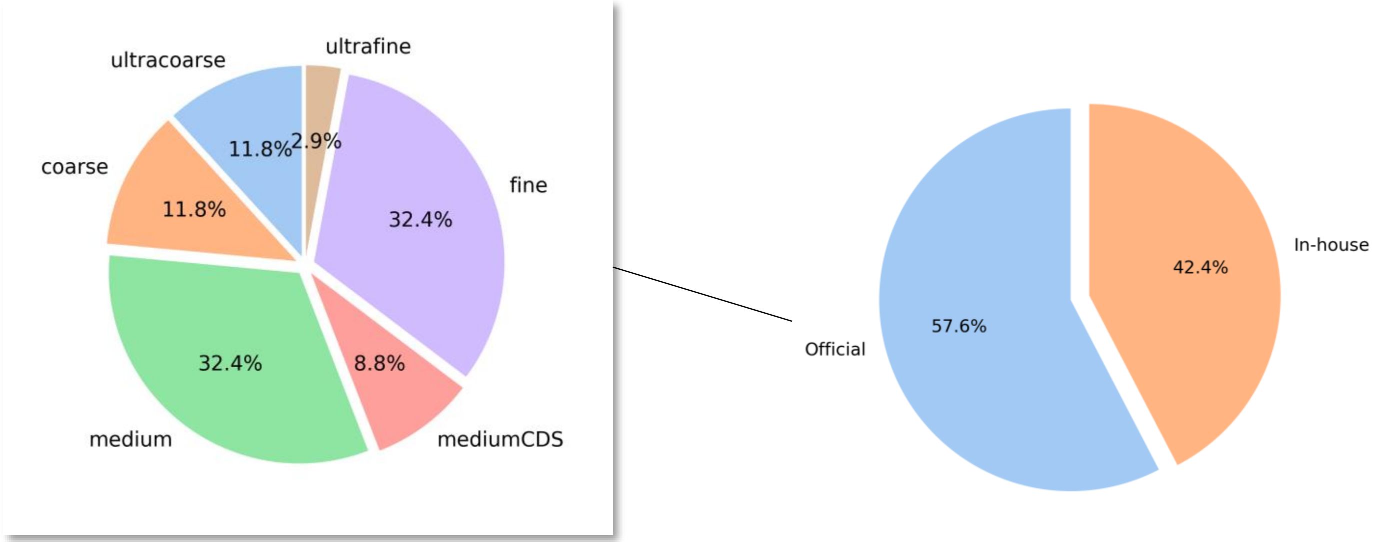
- 54 curves at 100% speed, 6 curves at 65% speed
- 5 universities, 5 companies and 1 research institute

12 CFD solvers

- 5 commercial solvers: Ansys CFX, Ansys Fluent, Fine/Turbo, Leo, Turbostream
- 1 open-source solver: SU2
- 6 in-house solvers: ASPAC, HADES, HGAE, MAP, TurboXD, UPACS

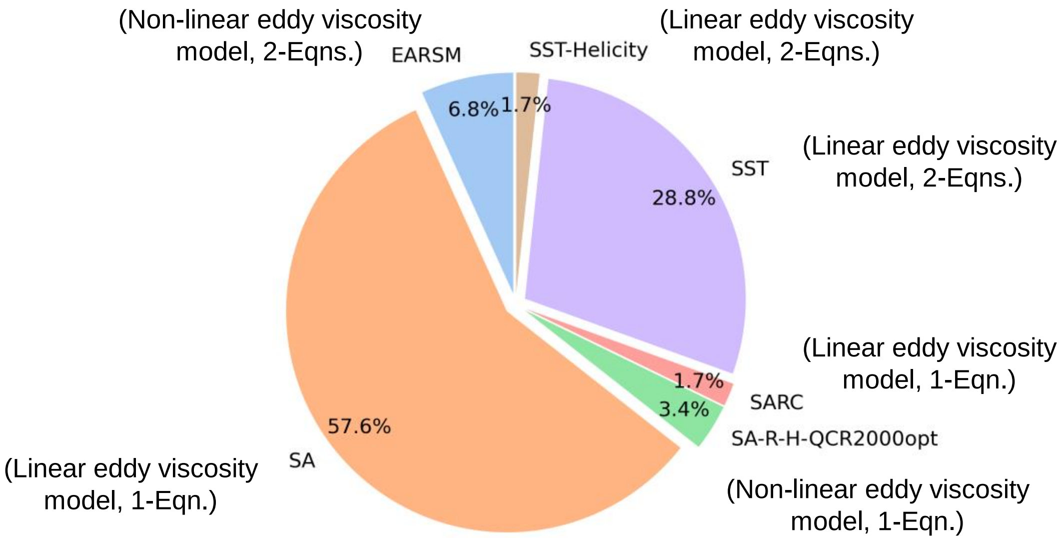
Submission Statistics of Workshops

Grid usage: 58% using official grids, 42% using in-house grids.



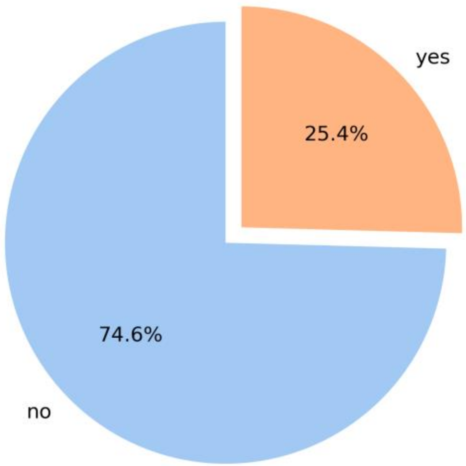
Submission Statistics of Workshops

Turbulence model: SA and SST are most popular



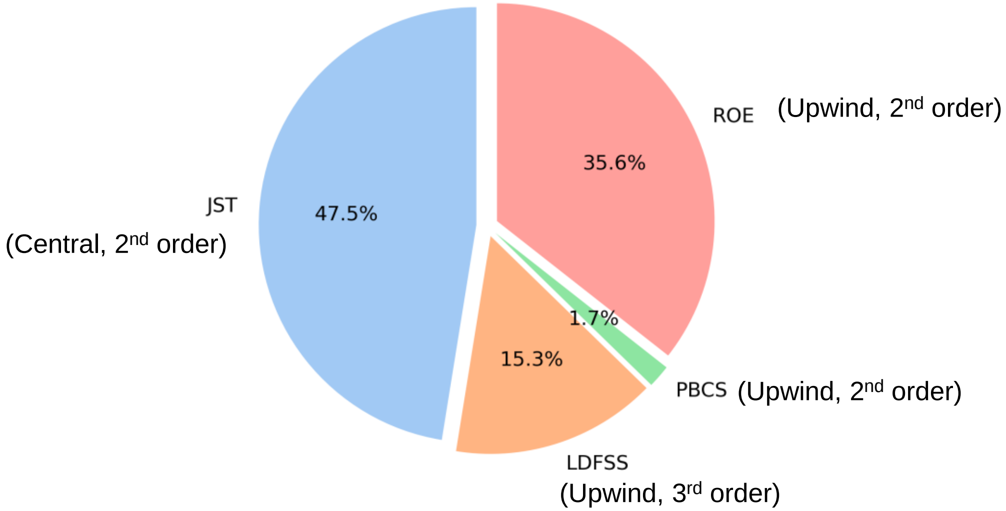
Submission Statistics of Workshops

Wall functions: 25% uses wall function and 75% does not



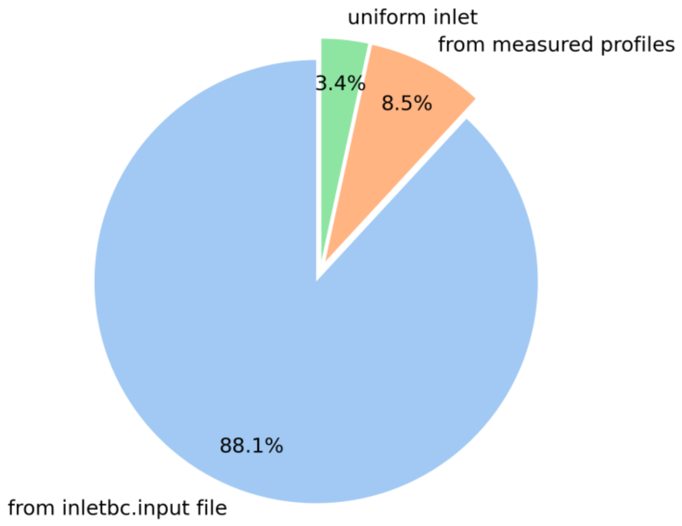
Submission Statistics of Workshops

Advection scheme: All submission are ≥ 2nd order accurate in space



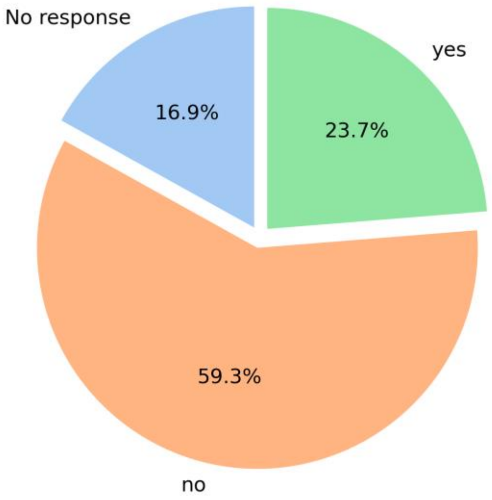
Submission Statistics of Workshops

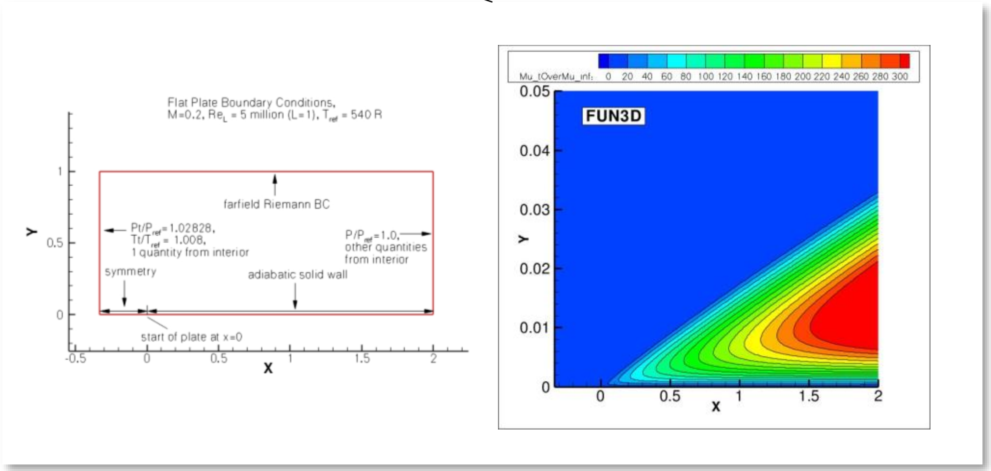
Inlet boundary conditions: most submissions used official .bc file



Submission Statistics of Workshops

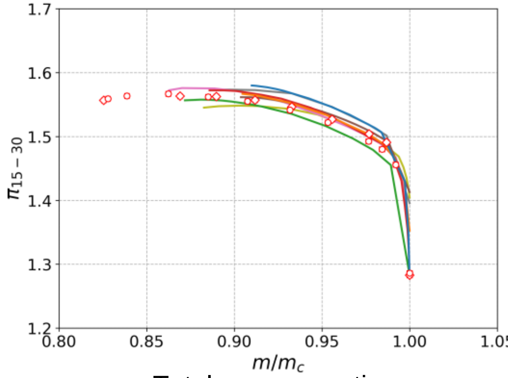
Have you verified your solver in NASA 2D flat plate against established RANS solvers? (yes/no)



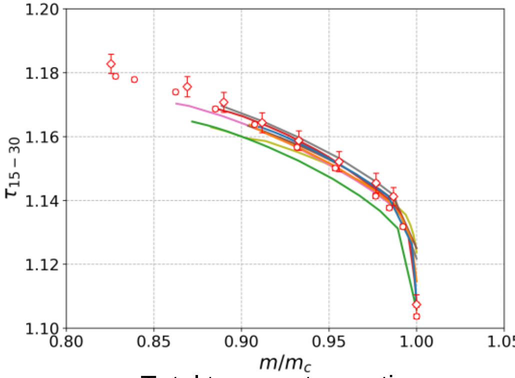


GPPS 2021 Geometry Verification: CFD versus CFD

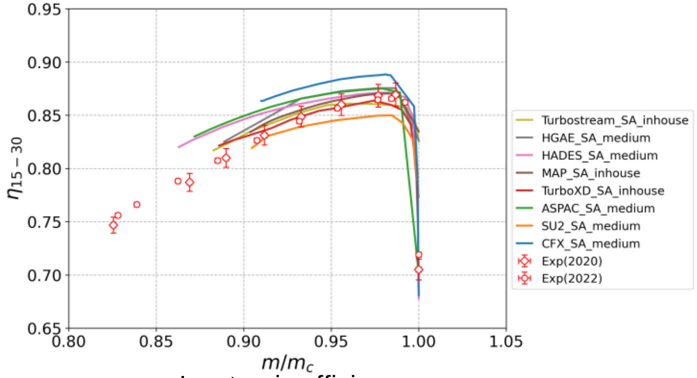
SA Model Verification: Performance Characteristics



Total pressure ratio



Total temperature ratio



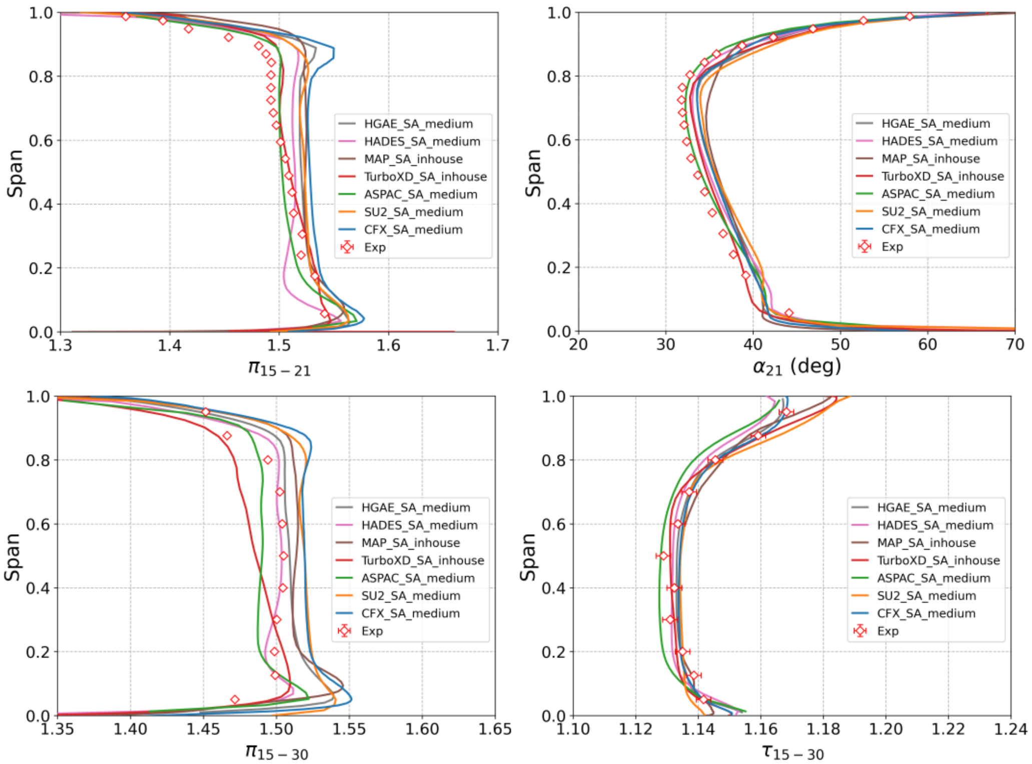
Isentropic efficiency

Design speed characteristics

SA Model Verification: Peak Efficiency Profiles

Rotor exit (ME21)

Stage exit (ME30)

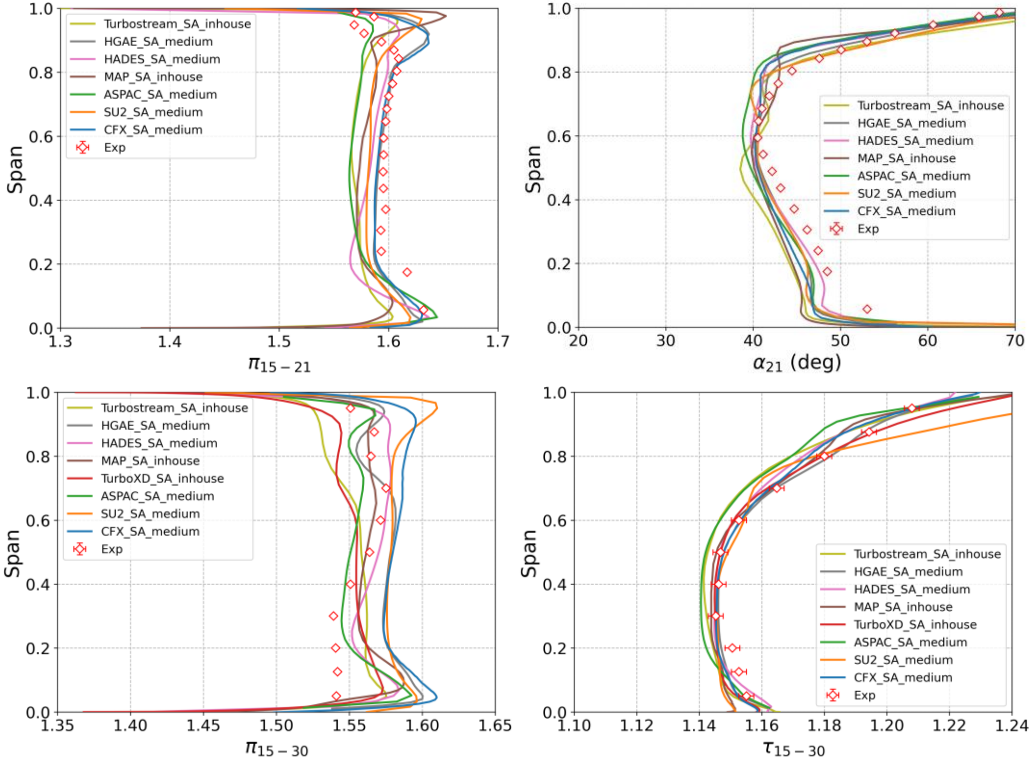


Design speed, near stall (m=16.00±0.10kg/s)

SA Model Verification: Near Stall Profiles

Rotor exit (ME21)

Stage exit (ME30)



Design speed, near stall (m=14.78±0.20kg/s)

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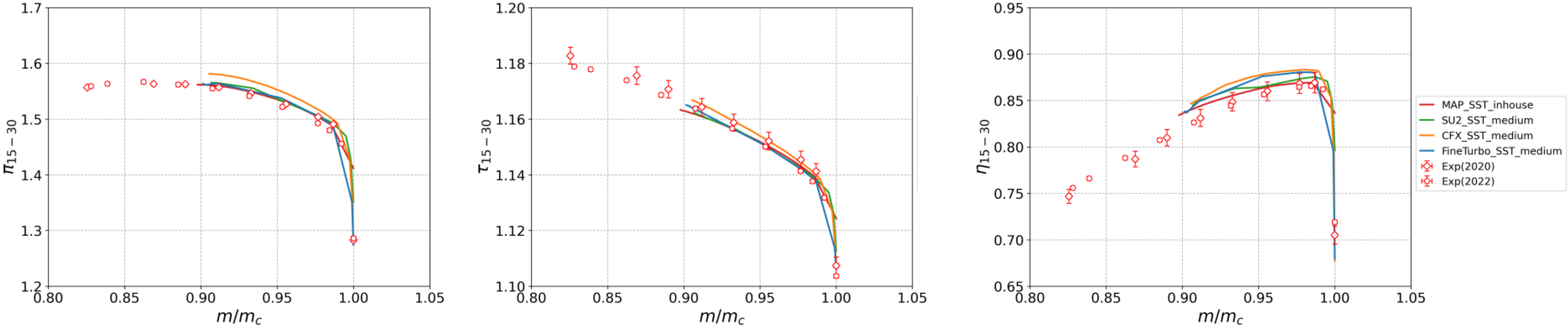
SA Model Verification: Summary

- No results are overlapping with each other (i.e., **verification goal not achieved**)
- **Diverse SA model versions** were implemented from further communications

Solver	Ansys CFX	ASPAC	Fine/Turbo	HADES	HGAE	MAP	SU2	Turbostream	TurboXD
SA flavor	SA-noft2	SA	SA-fv3-noft2	SA-noft2	SA	SA-noft2-RC van Direst Strain rate	SA-noft2-R in rotor SA-noft2 in stator	SA	SA
Reference frame	Absolute	Absolute	Relative	Relative	Relative	Absolute	Absolute	Absolute	Absolute

- Effect of **wall function, R-S interface, SA inlet b.c. and SA advection term** needs to be investigated

SST Model Verification: Performance Characteristics



Design speed characteristics

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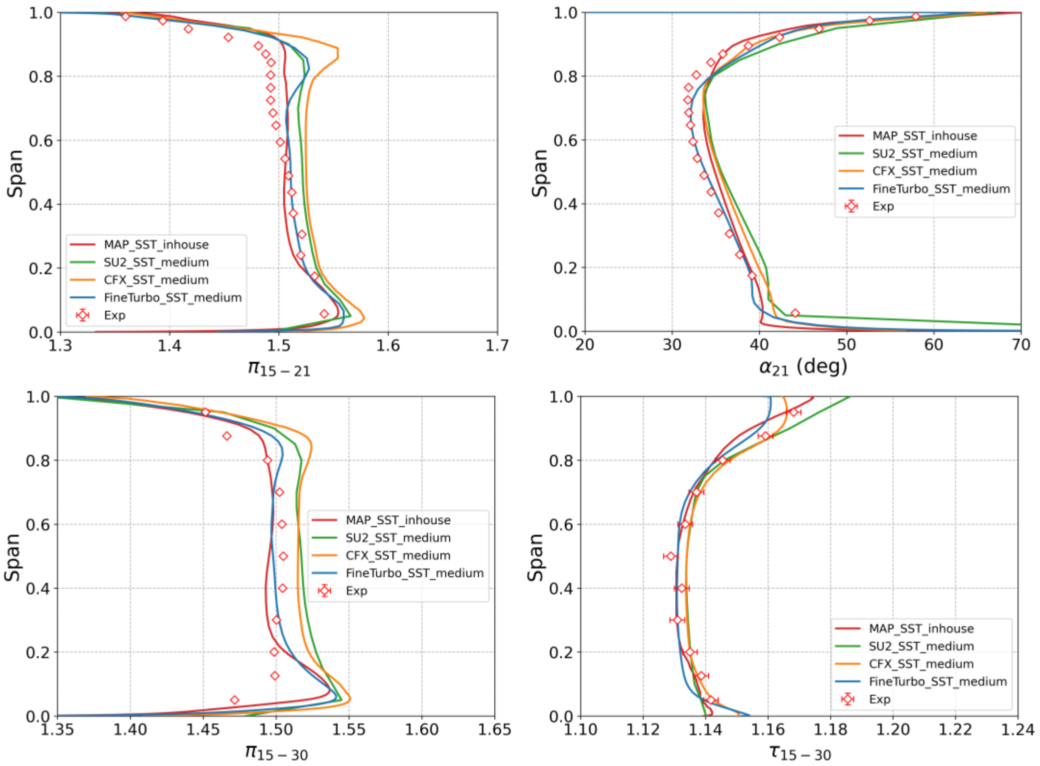
SST Model Verification: Peak Efficiency Profiles

Rotor exit (ME21)

Stage exit (ME30)

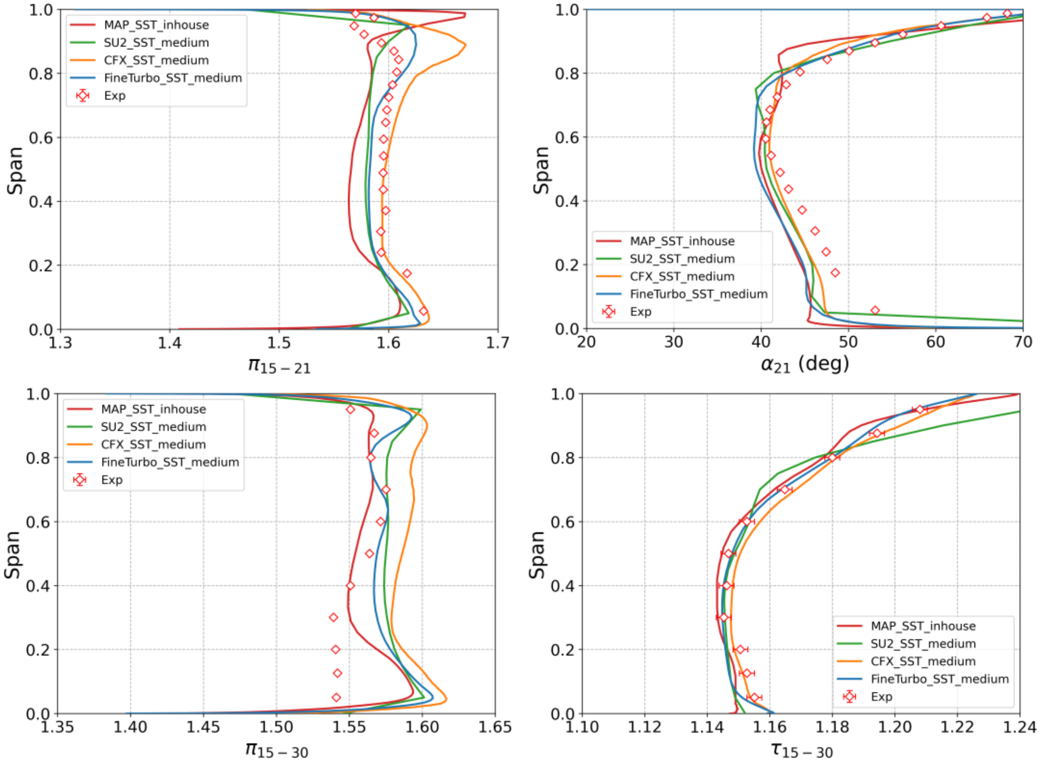


Design speed, peak efficiency (m=16.00±0.10kg/s)

SST Model Verification: Near Stall Profiles

Rotor exit (ME21)

Stage exit (ME30)



Design speed, near stall (m=14.78±0.20kg/s)

SST Model Verification: Summary

- Results match with each other (better than SA), but still not perfect
- **Less diverse SST model versions** were implemented from further communications

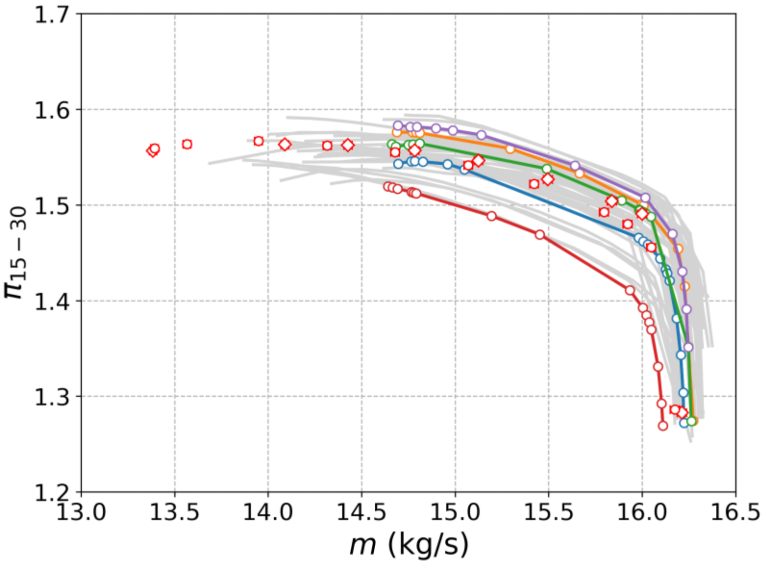
Solver	Ansys CFX	Fine/Turbo	MAP	SU2
SST flavor	SST-2003	SST	SST-2003-RC	SST
Reference frame	Absolute	Relative	Absolute	Absolute

- Effect of **wall function, R-S interface, SST inlet b.c. and SST advection term** needs to be investigated

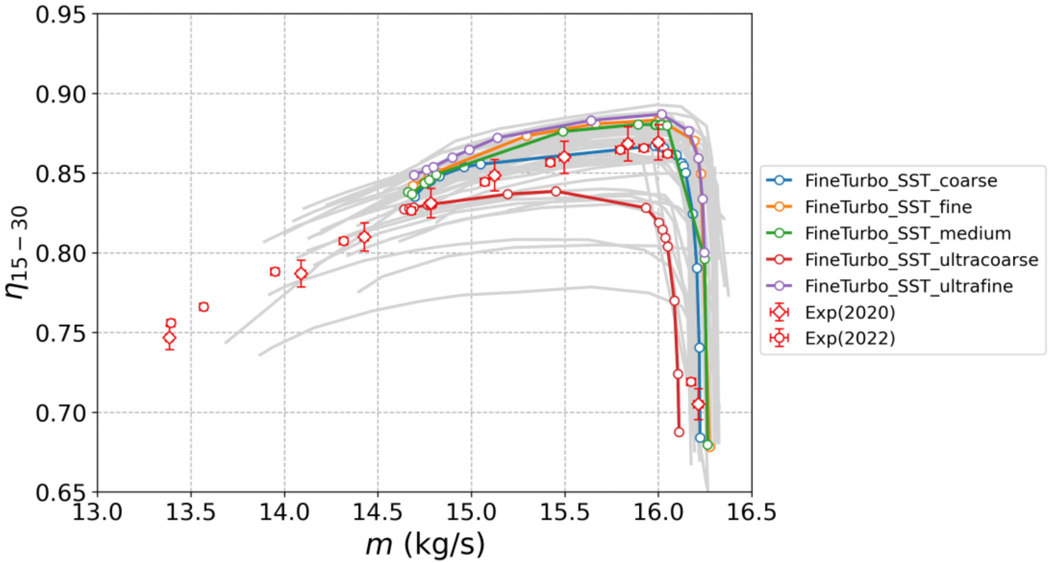
GPPS 2021 Geometry
Validation: Experiment versus CFD

Validation: Grid Independence

- Convergence on performance MAP



Total pressure ratio



Isentropic efficiency

Design speed

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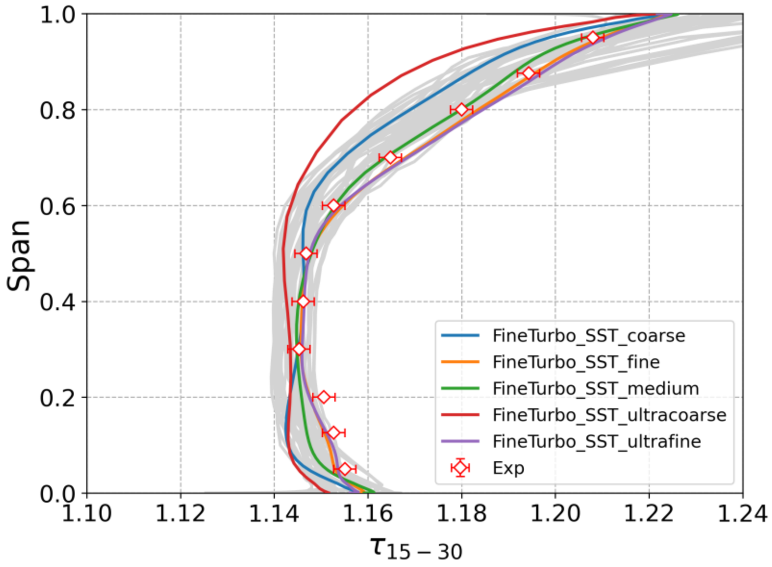
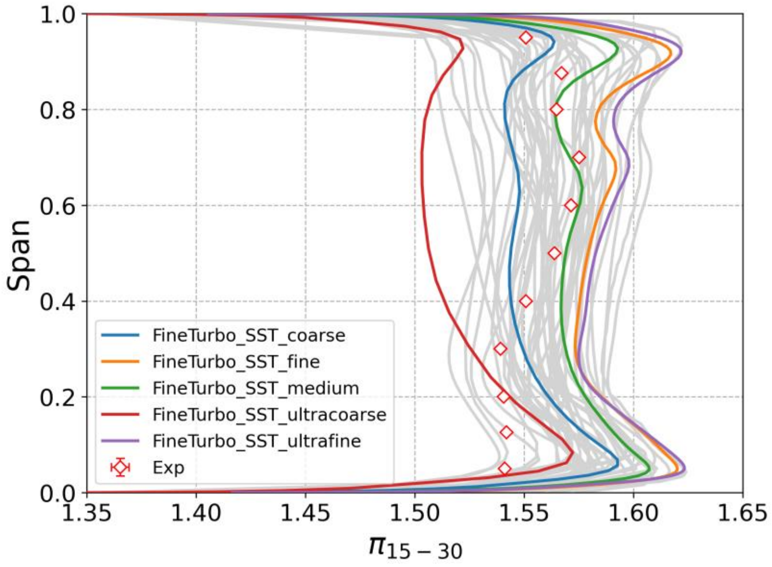
Validation: Grid Independence

- Convergence on stage exit (ME30) spanwise profiles



Total temperature ratio



Total pressure ratio

Design speed, near stall (m=14.78±0.10kg/s)

Validation: Grid Independence

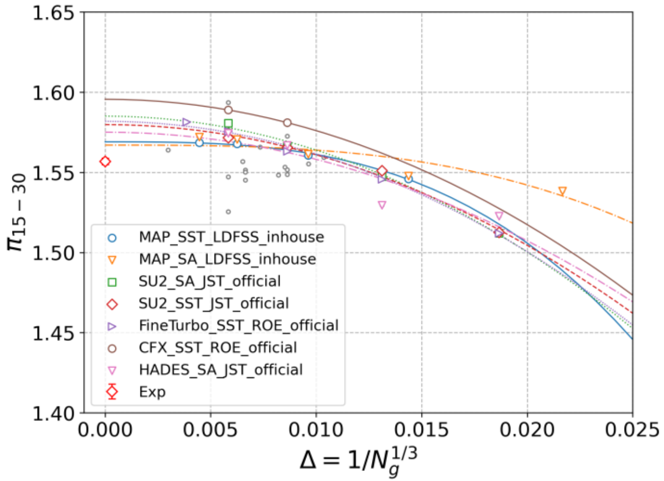
- Estimate discretization error [1]

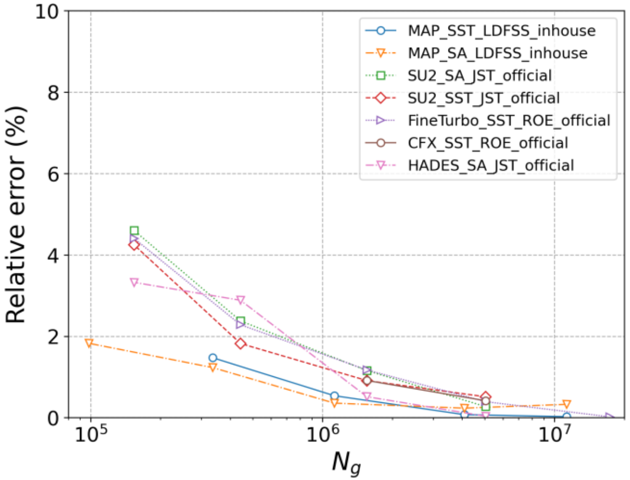
$$q = \underline{k\Delta^n} + q_{ideal} \qquad \varepsilon_q = \left(\frac{q}{q_{ideal}} - 1\right) \times 100\%$$

discretization error

q	flow quantity of interest
q_{ideal}	ideal flow quantity of interest free of discretization error
Δ	grid spacing
n	order of spatial accuracy of advection scheme

- Design speed, near stall (m=14.78±0.10kg/s)

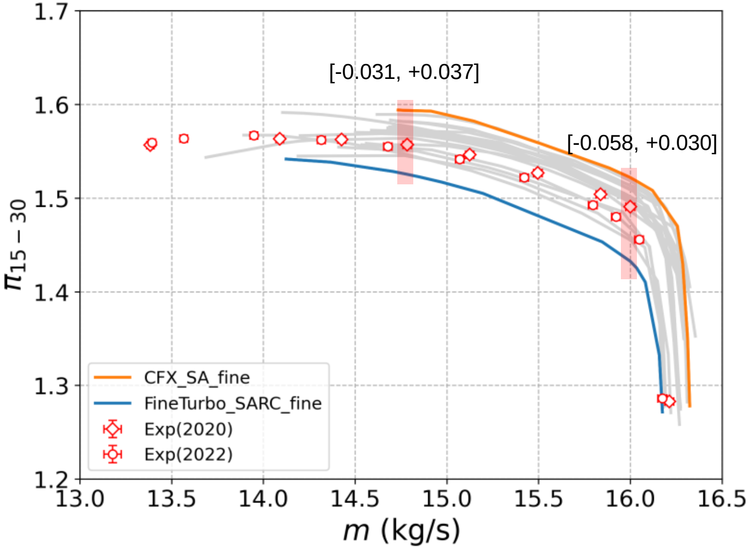




[1] Roache, P. J., 1998.Verification and Validation in Computational Science and Engineering. Hermosa Albuquerque, NM.

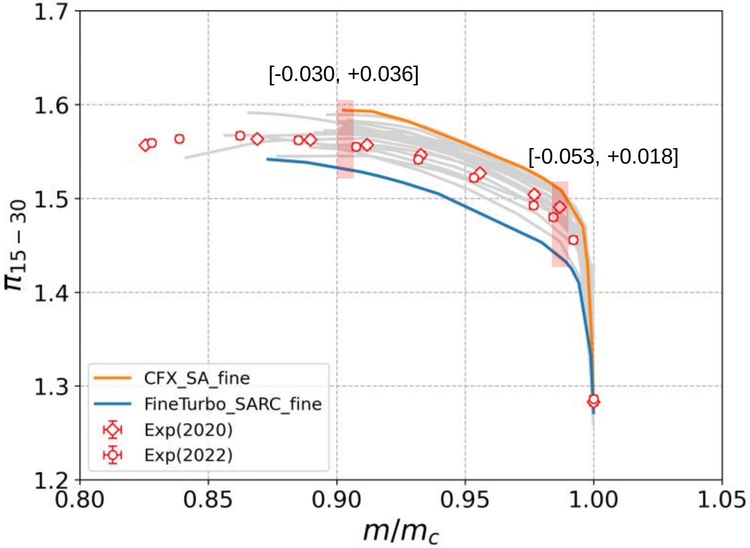
Validation: Total Pressure Ratio Characteristics

Exclude coarse grid ($N_g \geq 3M$)



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

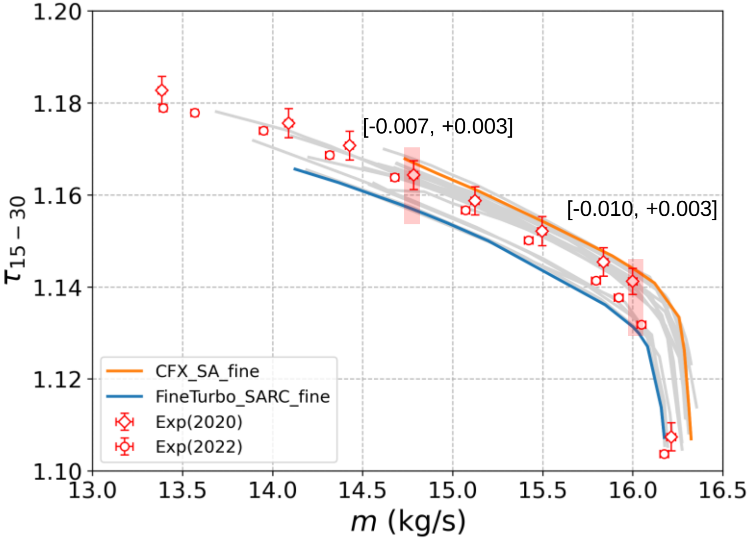
Normalize mass flow



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

Validation: Total Temperature Ratio Characteristics

Exclude coarse grid ($N_g \geq 3M$)



- Discretization
- Uncertainty in inlet BC
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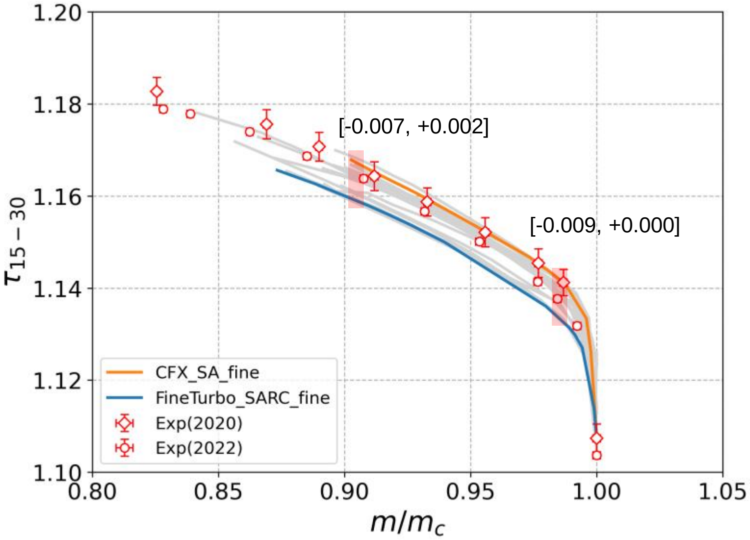
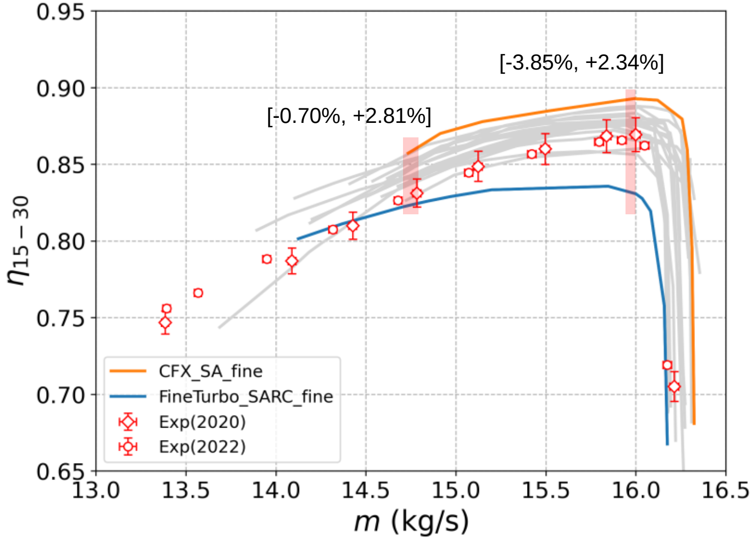
Normalize mass flow



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

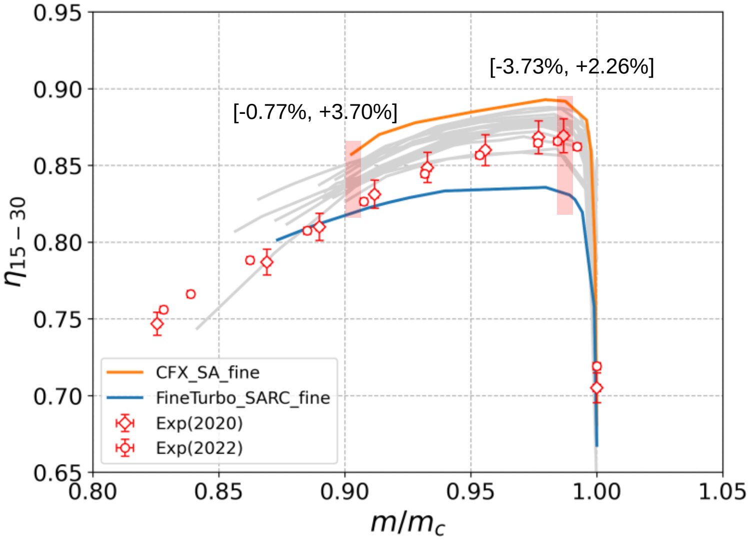
Validation: Isentropic Efficiency Characteristics

Exclude coarse grid ($N_g \geq 3M$)



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

Normalize mass flow

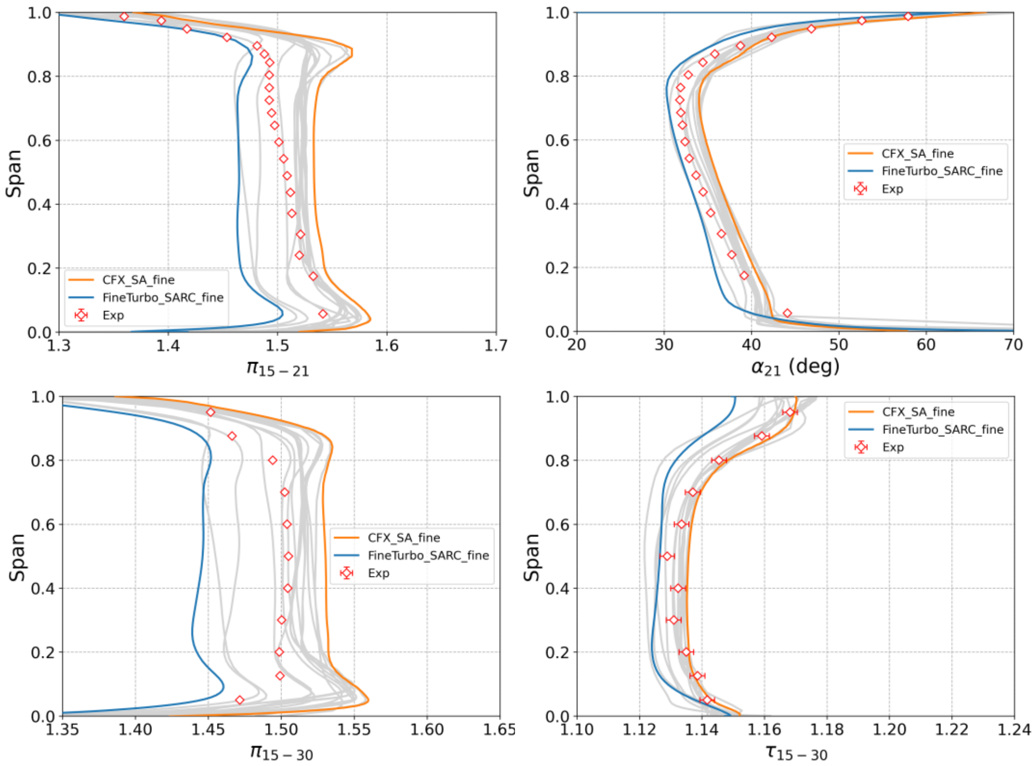


- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

Validation: Peak Efficiency Profiles

Rotor exit (ME21)

Stage exit (ME30)



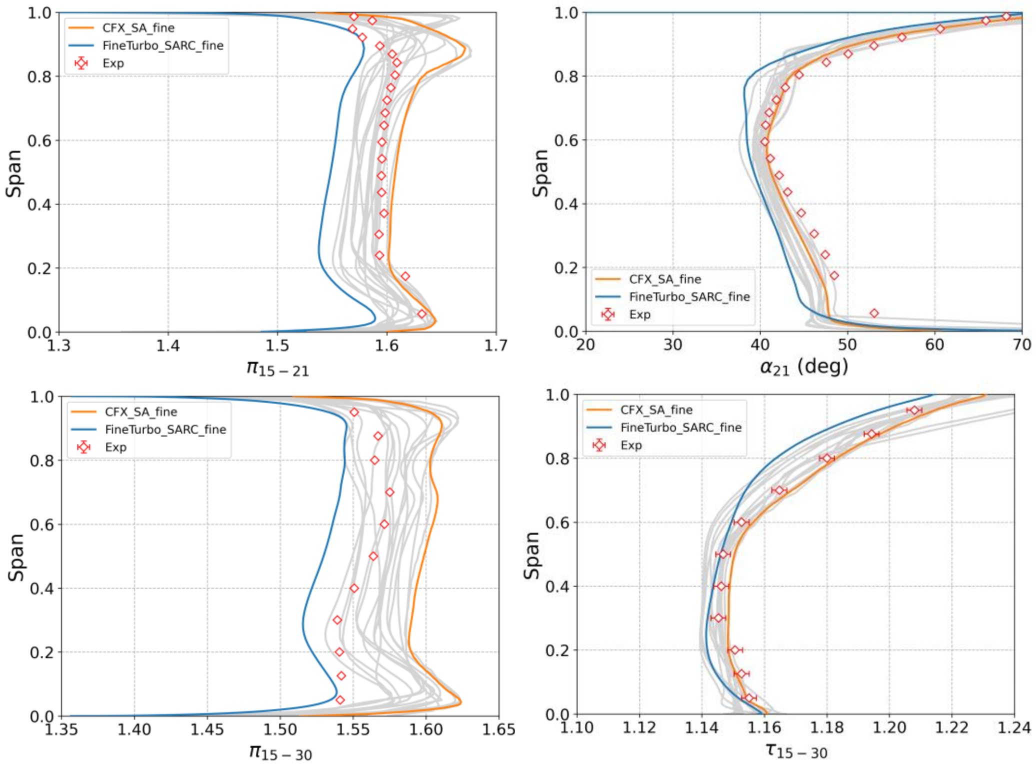
Design speed, peak efficiency (m=16.00±0.10kg/s)

GPPS TECHNISCHE UNIVERSITÄT DARMSTADT Imperial College London

Validation: Near Stall Profiles

Rotor exit (ME21)

Stage exit (ME30)



Design speed, near stall (m=14.78±0.20kg/s)

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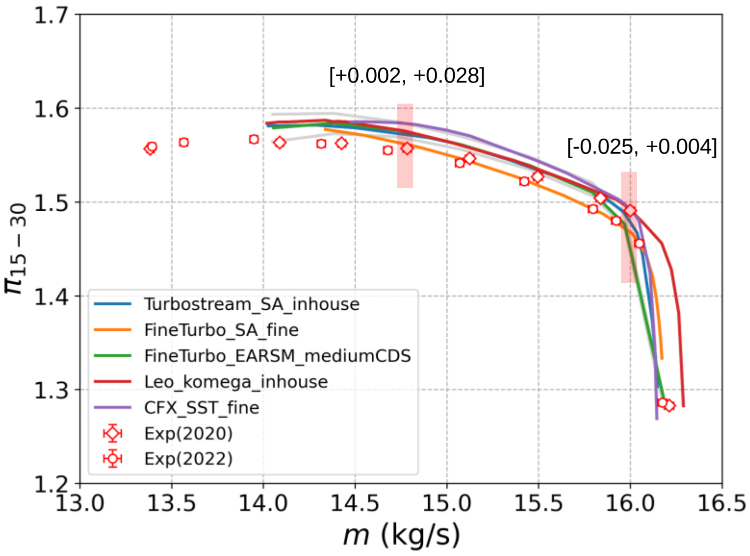
Imperial College London

GPPS 2022 Geometry
Validation: Experiment versus CFD

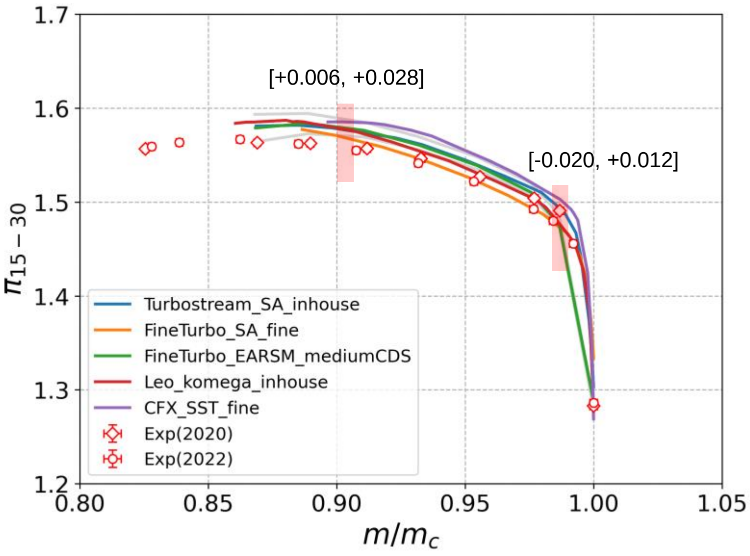
Validation: Total Pressure Ratio Characteristics

Exclude coarse grid ($N_g \geq 3M$)



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

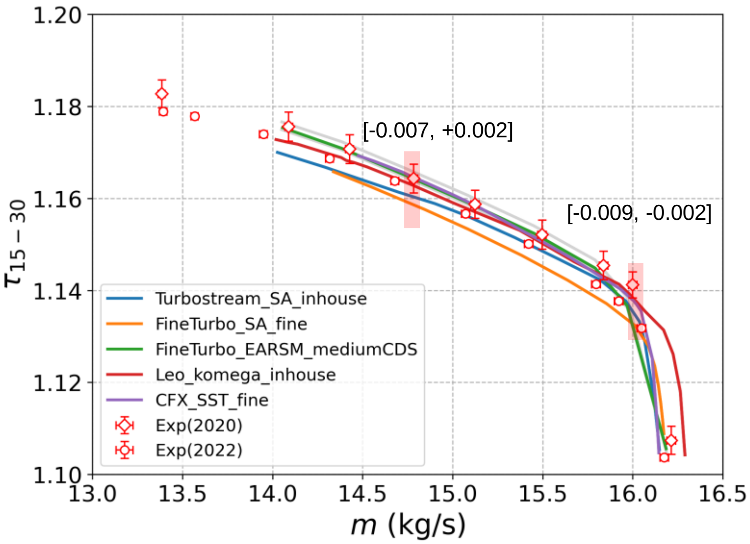
Normalize mass flow



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

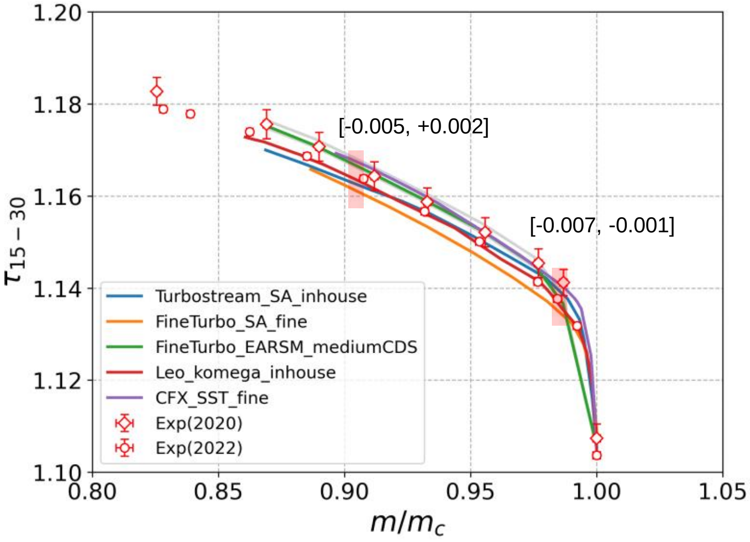
Validation: Total Temperature Ratio Characteristics

Exclude coarse grid (N_g≥3M)



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

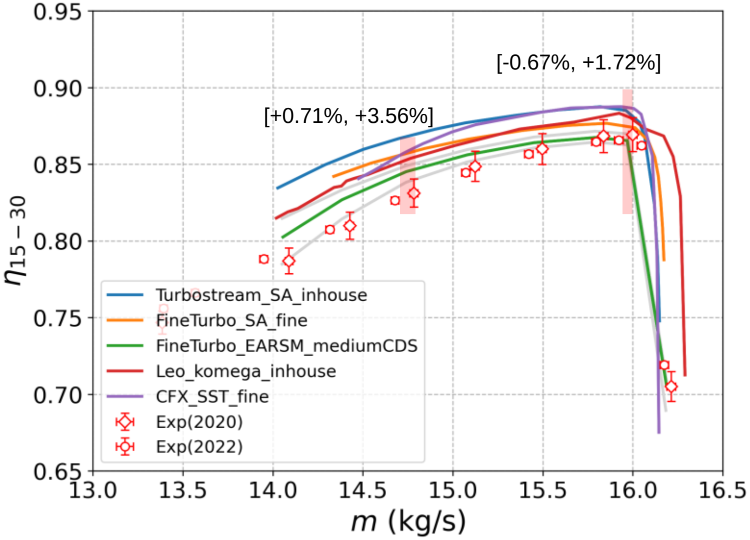
Normalize mass flow



- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

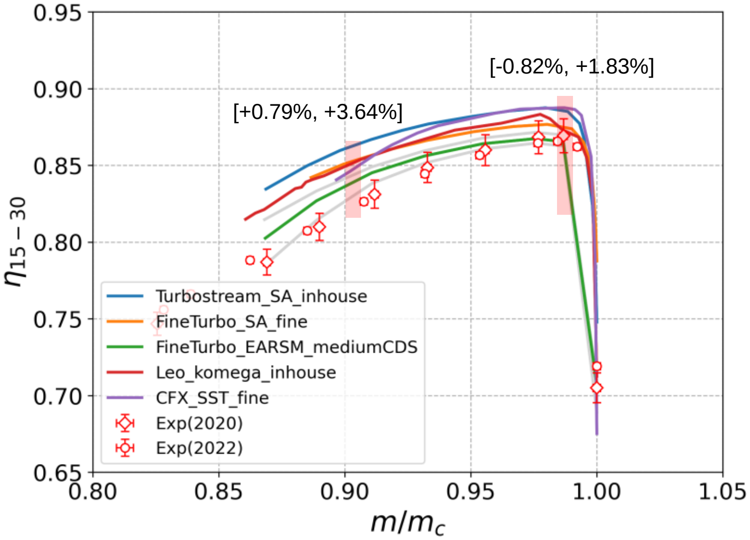
Validation: Isentropic Efficiency Characteristics

Exclude coarse grid (N_g≥3M)



- ~~Discretization~~
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

Normalize mass flow

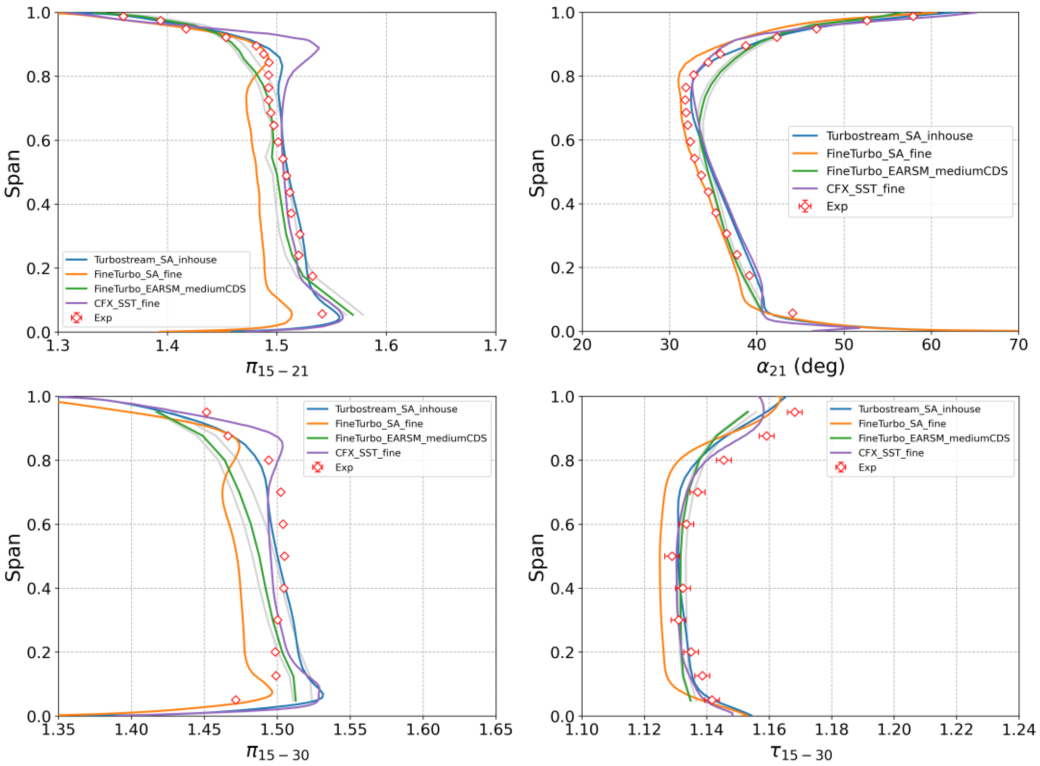


- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

Validation: Peak Efficiency Profiles

Rotor exit (ME21)

Stage exit (ME30)



Design speed, peak efficiency (m=16.00±0.10kg/s)

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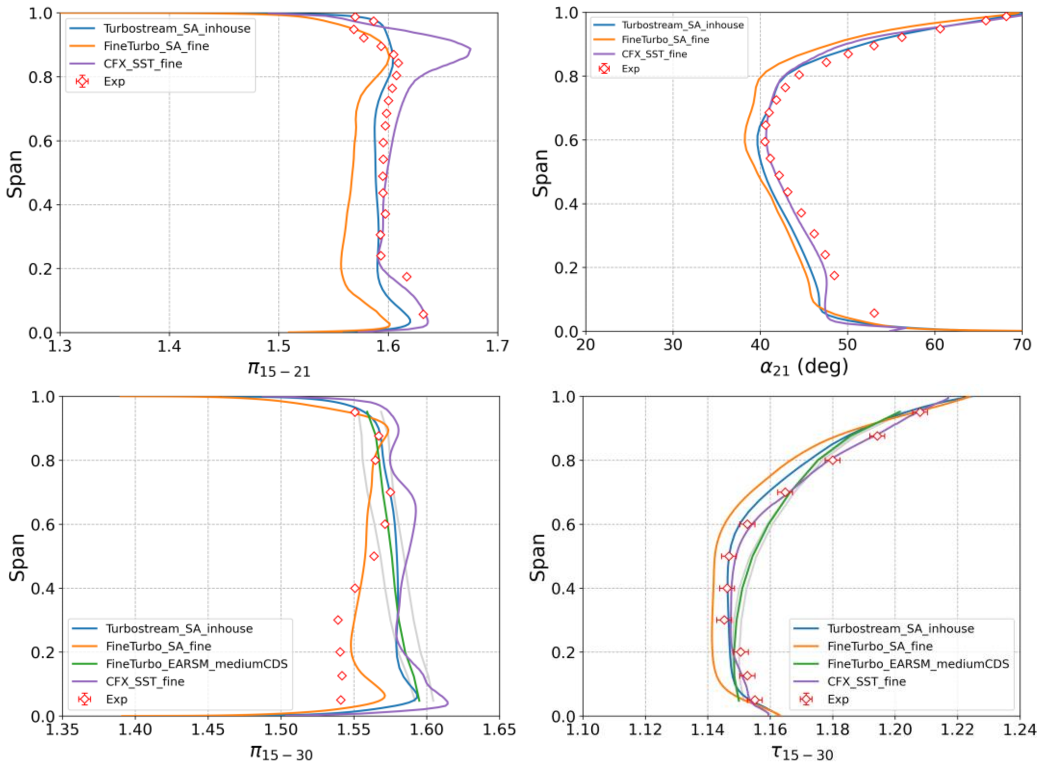
Validation: Near Stall Profiles

Rotor exit (ME21)

Stage exit (ME30)



Design speed, near stall (m=14.78±0.20kg/s)

Conclusions and Future Works

Conclusions

Verification (CFD vs. CFD)

- SA model(s) in different solvers yield evidently different results
- SST model(s) in different solvers yield results similar to each other, but still not perfectly matched
- Further V&V workshops on low TRL cases needed

Validation (CFD vs. EXP)

- Overall uncertainty (different users and solvers, same inlet b.c., and refined grids)

  Total pressure ratio: **±2.4%**; Total temperature ratio: **±0.4%**; Isentropic efficiency: **±3.0%** (absolute)

- Major differences between CFD and EXP

  Stator exit: **near-hub TPR overshoot** (unknown geometric error?)

- Most influential factors: grid density and turbulence model

  Mind the “engineered” grid independence results: are the **grids refined uniformly**?

  “Best-practice” turbulence model: SA = SST in this case

Future Works (Open Discussion)

Further workshop events

- Simpler cases, e.g., rotor-only (exclude R-S interface effect); channel flow (debug periodic BC); etc.
- More complex cases: will CFD and EXP obtain the same performance “delta” before/after flow control?

Documentation and investigation of rotor-stator interface models

- An online Wiki page for version control? An expert review paper?
- Which mean flow/turbulence quantities should be passed through? How to average?

Turbulence modelling for turbomachinery

- Beyond Galilean invariance: consistent turbulence modelling in rotating and stationary frame

Develop a common open-source RANS solver with basic turbomachinery capabilities

……

Summary of Submissions

2nd GPPS Turbomachinery CFD Workshop (GPPS 2022)

Questions & Answers