Summary of Submissions

1st GPPS Turbomachinery CFD Workshop (GPPS 2021)

Xiao He Imperial College London

Motivation (Untold)

“CFD is a reliable workhorse for turbomachinery” … but is that so?

How did you predict the performance map so well? Any special sauces?

You may try solver A with model B and option C turned on…

Solver D with model E and a coarse mesh will also work…

I have mixed up all the CFD settings but still a bit short on the pressure ratio…

Oh, you may try this tip gap size and that map data.

These data are from private emails of the authors though…

Reasons of Inconsistency

CFD side:

- Commercial solvers: intellectual property
- Version control of models
  (turbulence models; R-S interfaces; wall functions, etc.)
- Potential bugs in the solver
  (lack of data for validation and verification)
- Difference in user inputs
  (preferred mesh, models, etc.)

Exp side:

- Limit of Exp technique in the 90s
- Version control of data
- Limit availability of data in public

Solution: Open-Source

SU2 code

HiFiLES High-Order CFD Simulation

OpenFOAM

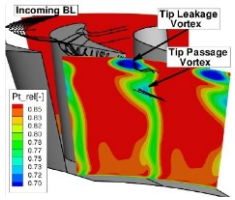
CFL3D Version 6

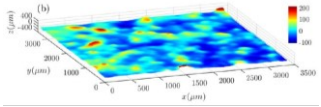
PyFR

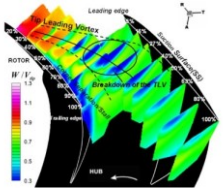
NEKTAR++ SPECTRAL/HP ELEMENT FRAMEWORK

code_saturne

CFD solvers

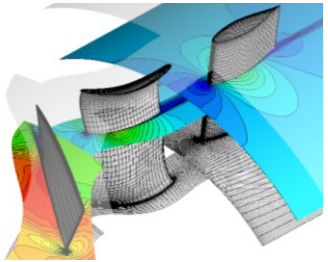






Common research models

GPPS 1st Turbomachinery CFD Workshop



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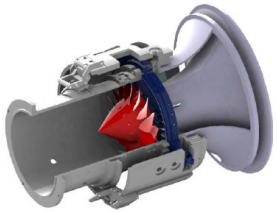
Validation & verification campaign

Scope of GPPS CFD workshop series

Design of the Workshop

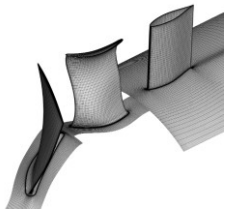
Timeline

Release of geometry and experimental data



See also:
[1] Open_Stage_TUDa_Data_Info.pdf
[2] Open_Stage_TUDa_Geometry_Info.pdf

Release of official grids, boundary conditions and workshop submission guideline



See also:
[1] Open_Stage_TUDa_Grid_Info.pdf
[2] Open_Stage_TUDa_Submission_Guideline.pdf

10/2020 — 04/2021: V&V paper submitted

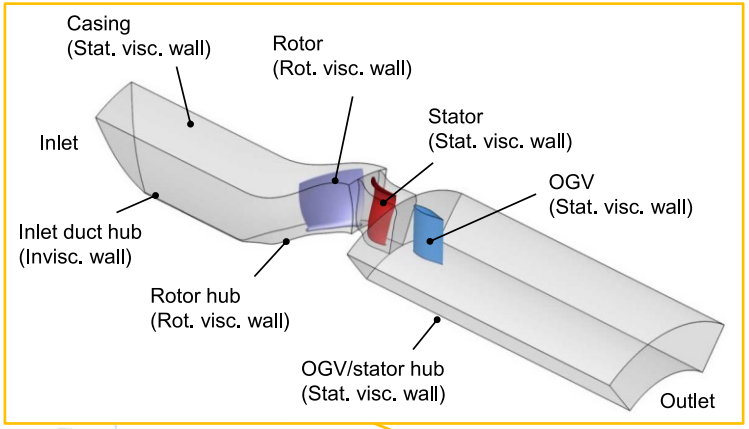
06/2021: Workshop proposal

07/2021 — 11/2021: Submission deadline

12/2021: Workshop day

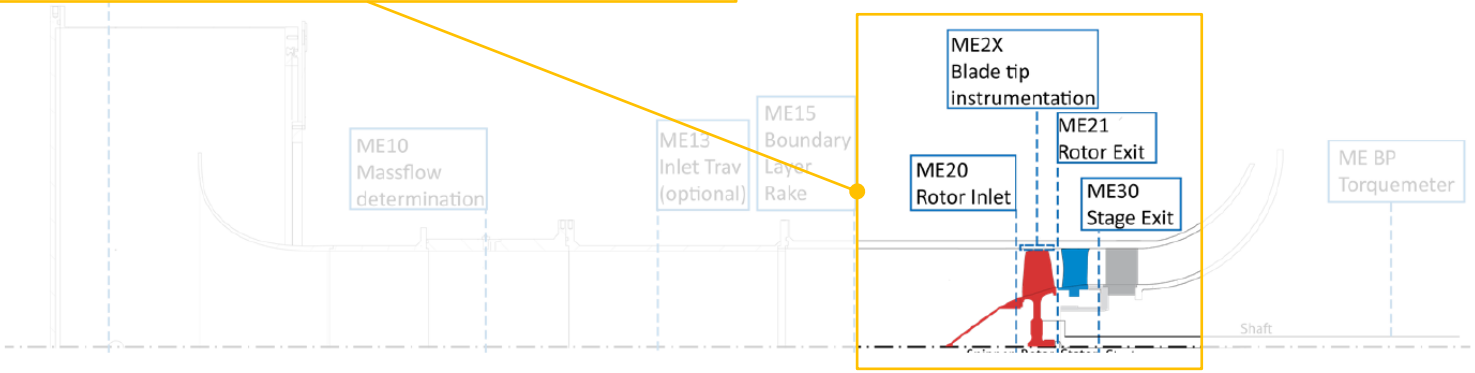
06/2022: All data become public domain

Flow Domain and Boundary Conditions



Major differences between CFD model and EXP

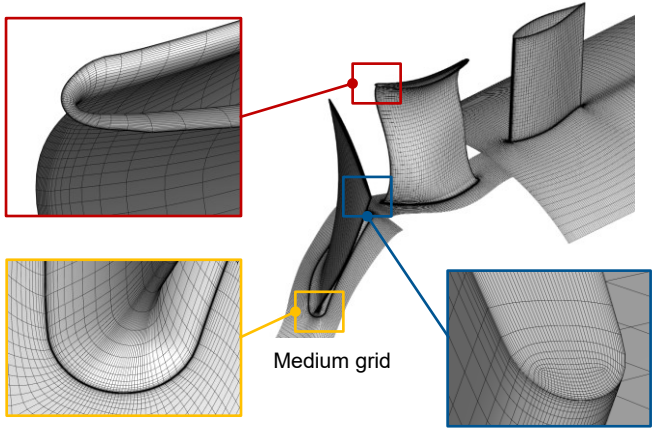
- The axial-to-radial duct is simplified as an axial duct.
- The stator hub cavity flow is not considered.
- Changes of the inlet profile are not considered.
- Changes of blade tip gap size are not considered.

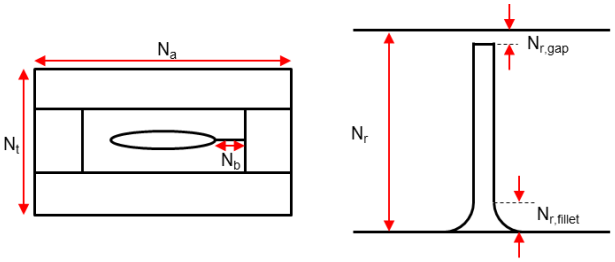


Official Grids

Major features of official grids

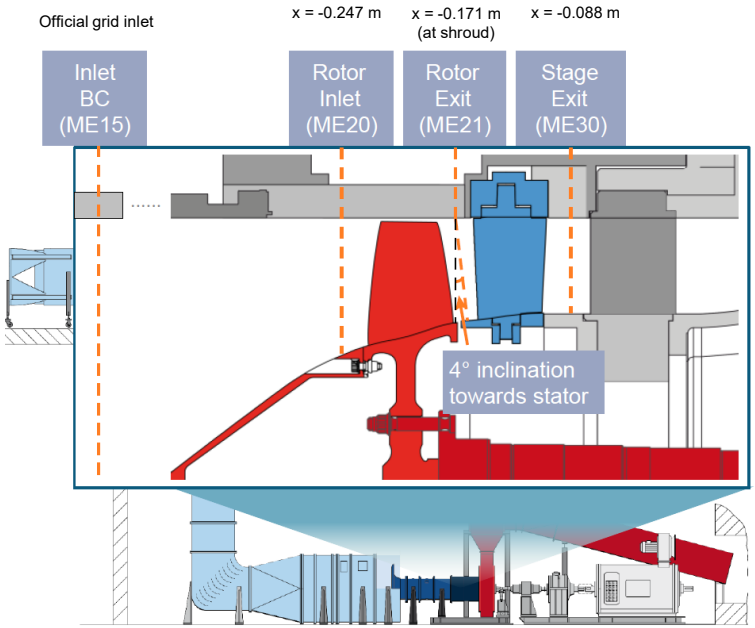
- All grid cells are hexahedron.
- Five sets of grids (uniformly refined) in structured/unstructured .cgns format and .trb format.
- Boundary layers are refined with an average $y^+<3$
- Tip gap and fillets are considered.





	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	-	-

Flow Quantities of Interest

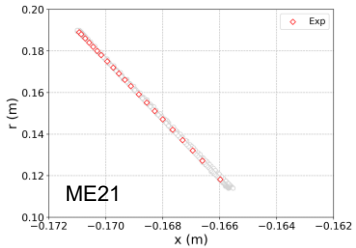


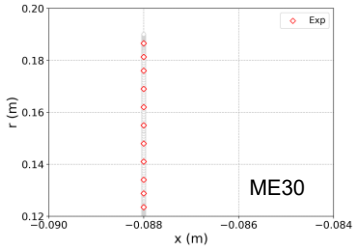
Collected data:

- 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





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:	
Last name:	
Organization:	
Email:	

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)	$k = 35\ m^2/s^2$ $\epsilon = 2.0 \times 10^3\ m^2/s^2$

(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

Submission Statistics

47 characteristic curves submitted by 9 authors from 6 institutes

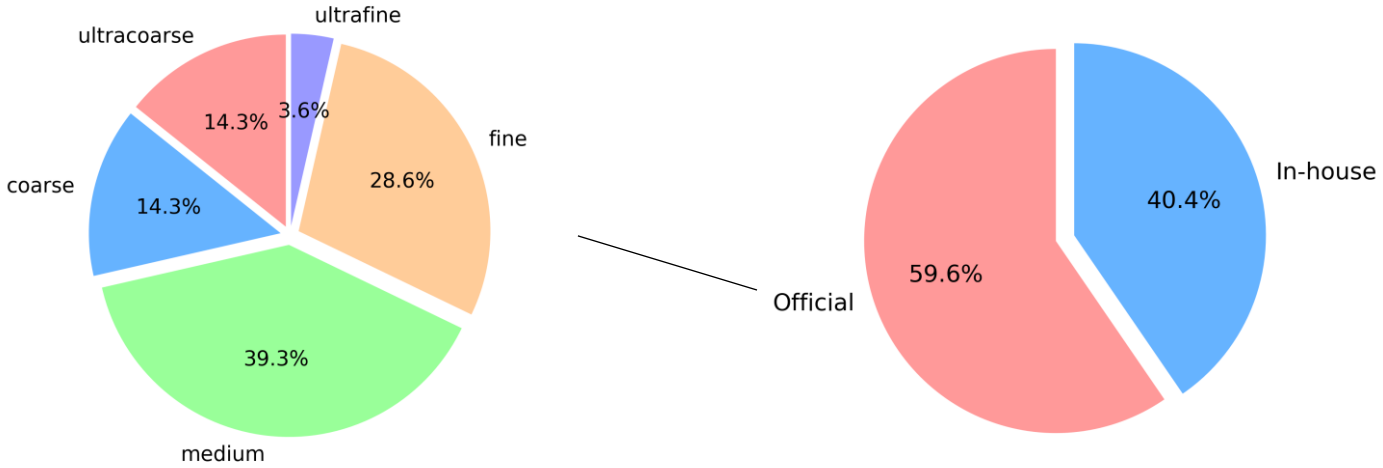
- 41 curves at 100% speed, 6 curves at 65% speed
- 5 universities and 1 research institute

9 CFD solvers

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

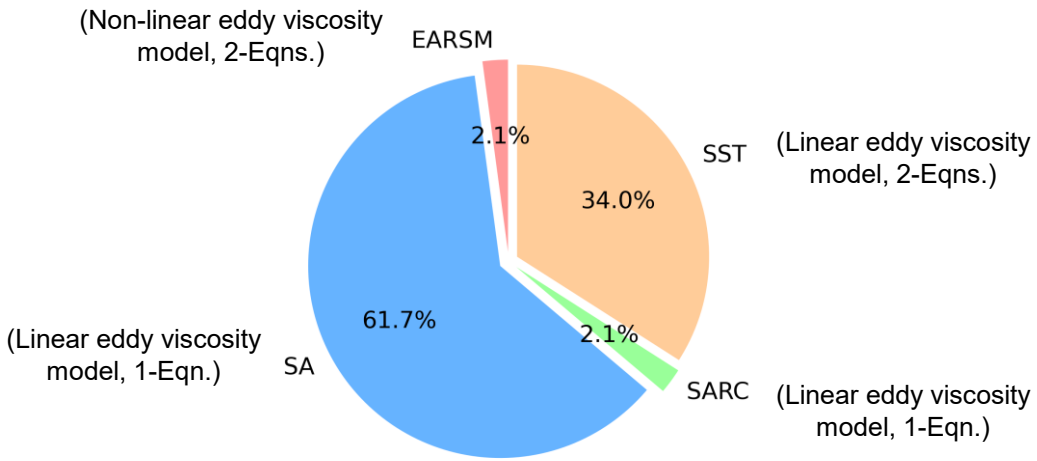
Submission Statistics

Grid usage: 60% using official grids, 40% using in-house grids.



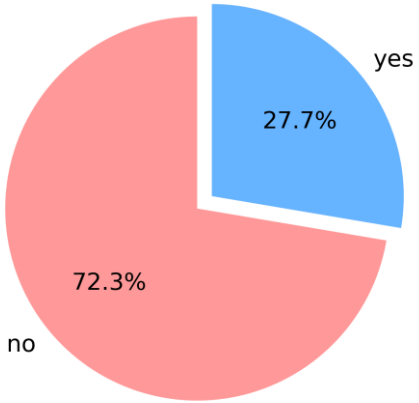
Submission Statistics

Turbulence model: SA and SST are most popular



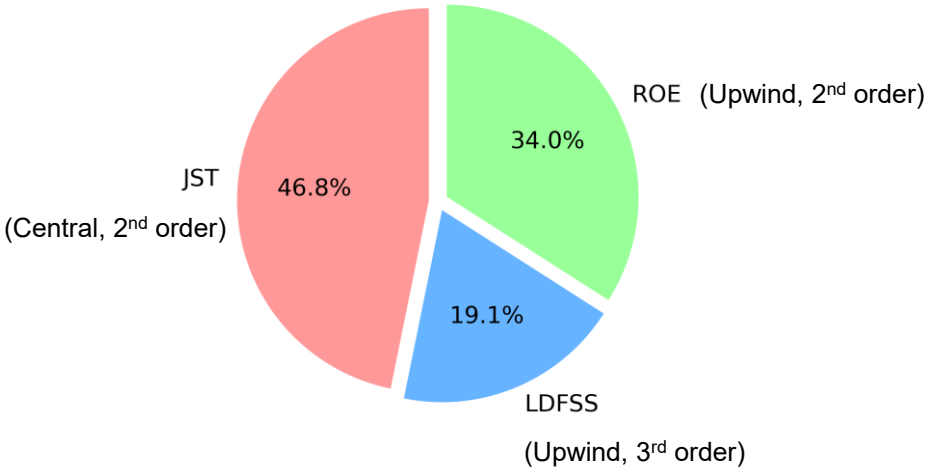
Submission Statistics

Wall functions: 30% uses wall function and 70% does not



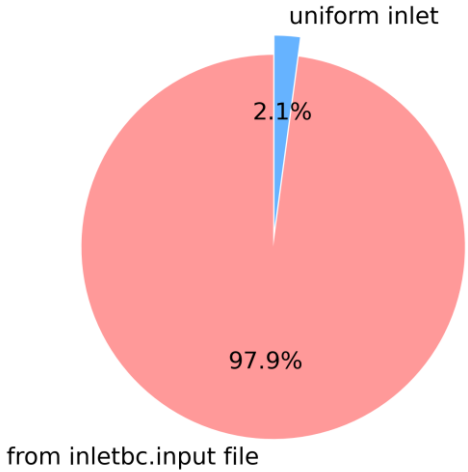
Submission Statistics

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



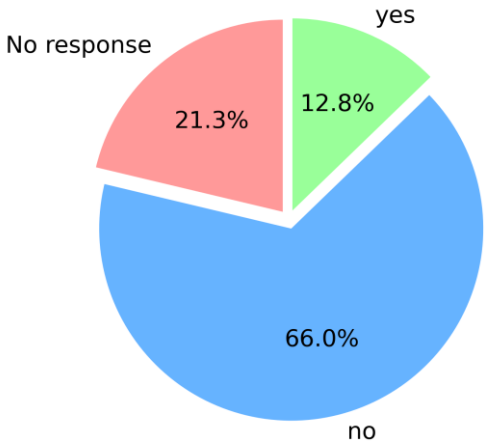
Submission Statistics

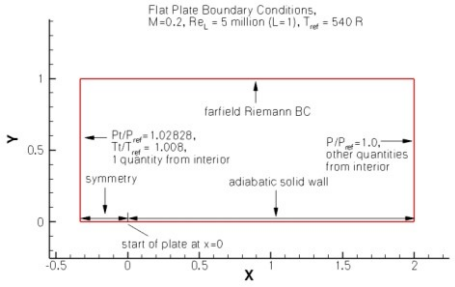
Inlet boundary conditions: most submissions used official .bc file for mean flow quantities

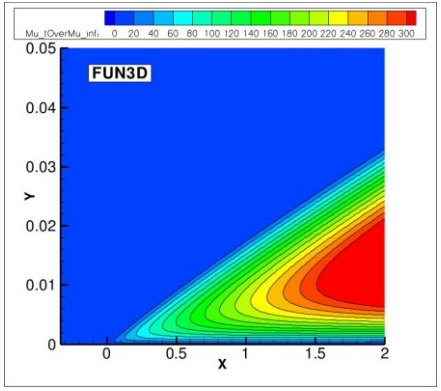


Submission Statistics

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







Validation: Experiment versus CFD

Grid Independence

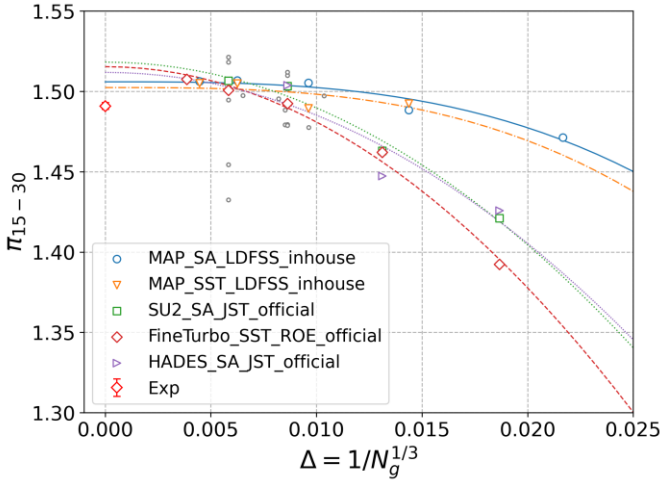
- Estimate discretization error

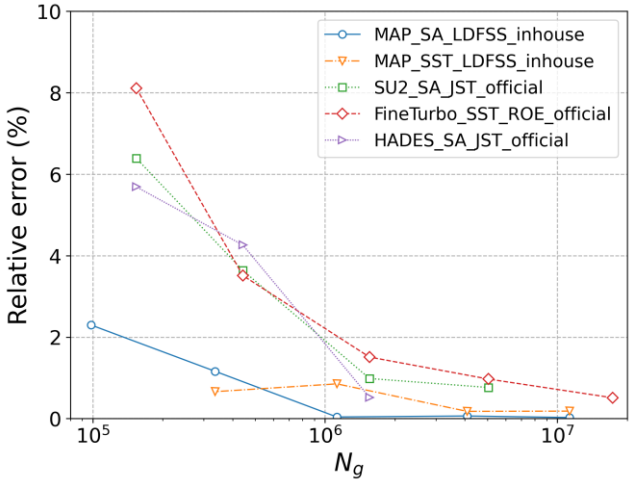
$$q = k\Delta^n + q_{ideal} \qquad \varepsilon_q = \left(\frac{q}{q_{ideal}} - 1\right) \times 100\%$$

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, peak efficiency (m=16.00±0.10kg/s)





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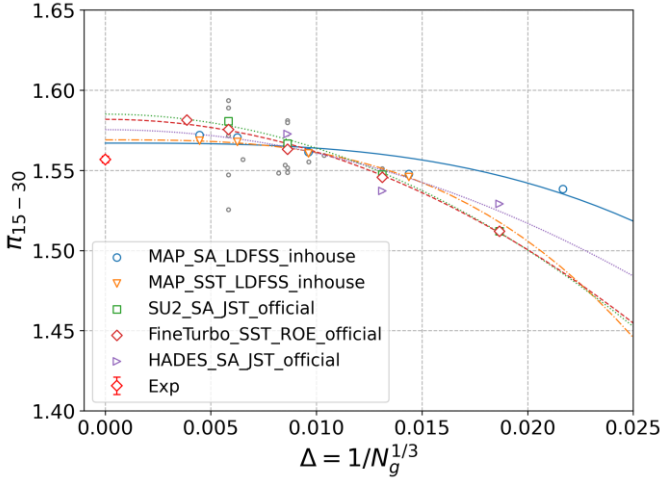
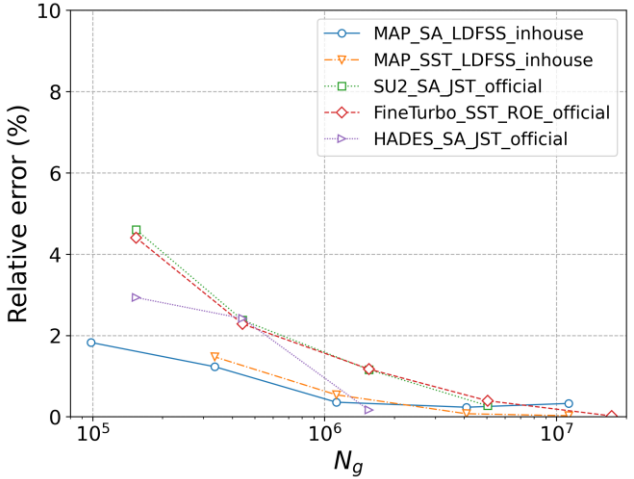
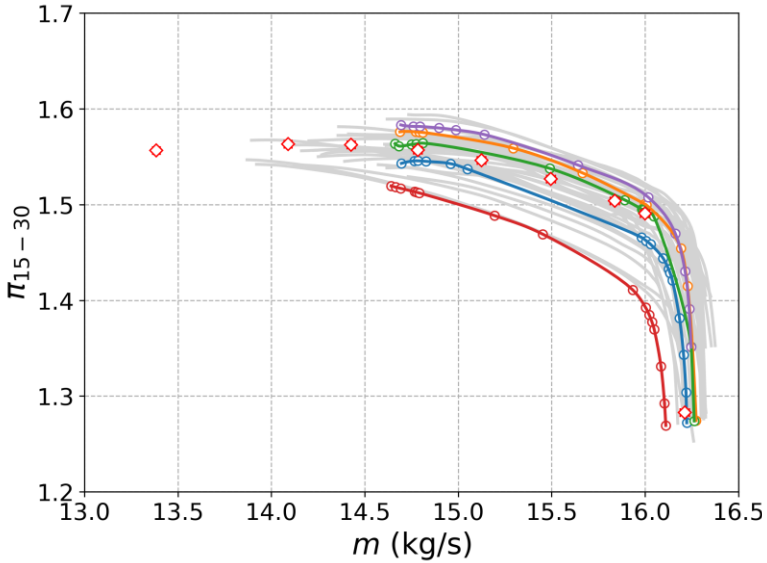
- Design speed, near stall (m=14.78±0.10kg/s)



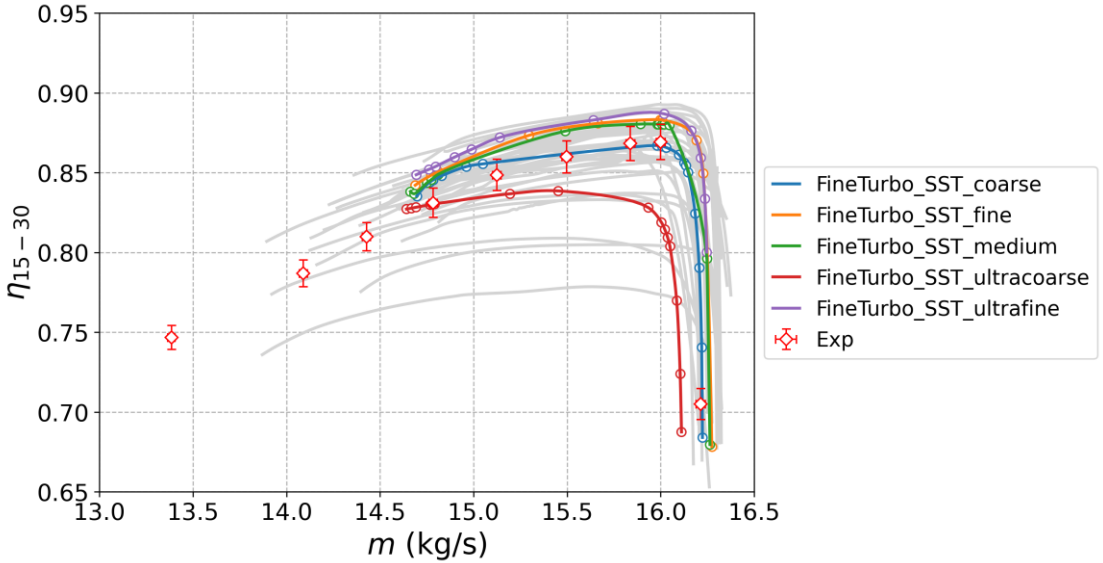


Grid Independence

- Convergence on performance MAP



Total pressure ratio

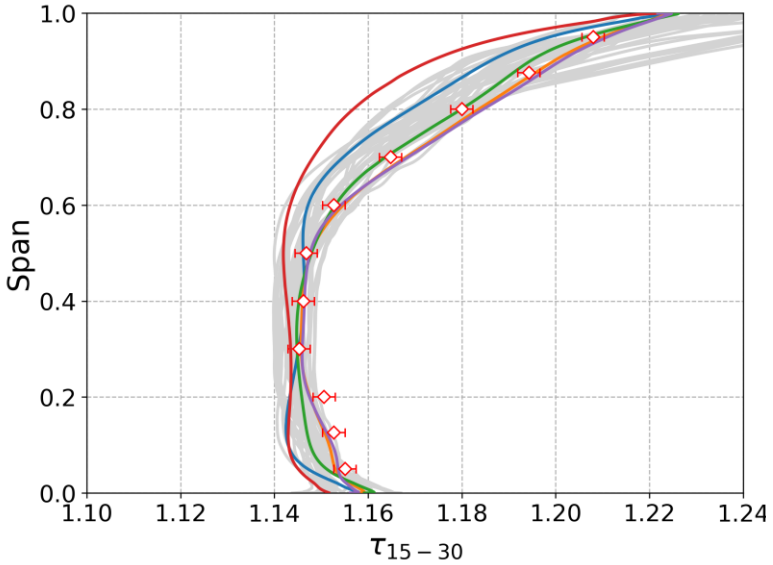


Isentropic efficiency

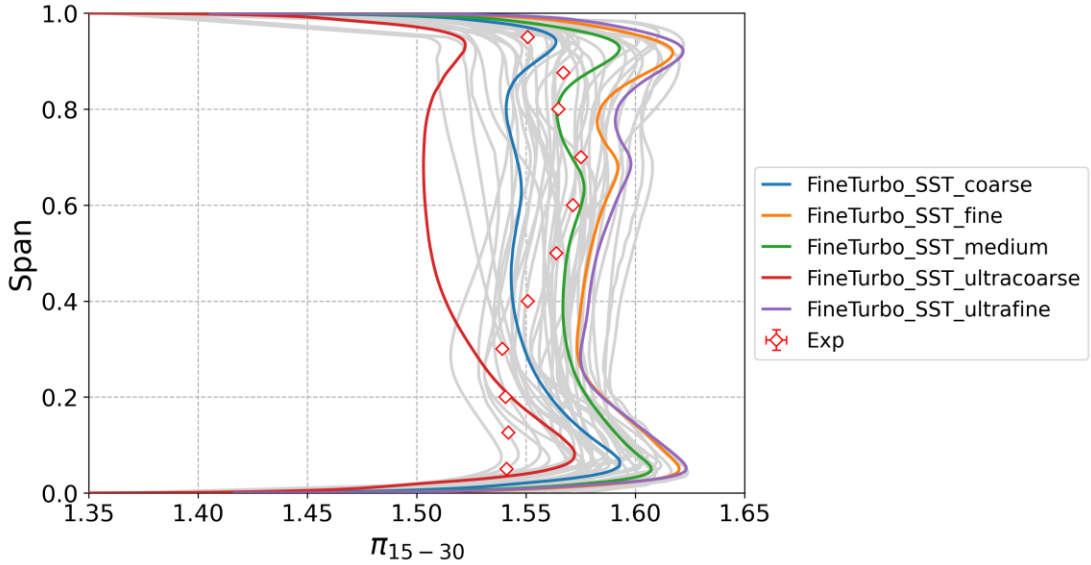
Design speed

Grid Independence

- Convergence on stage exit (ME30) spanwise profiles



Total temperature ratio

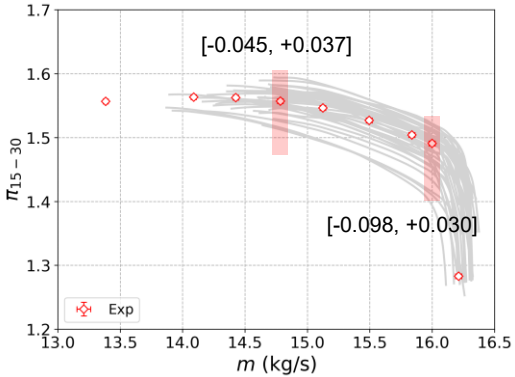


Total pressure ratio

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

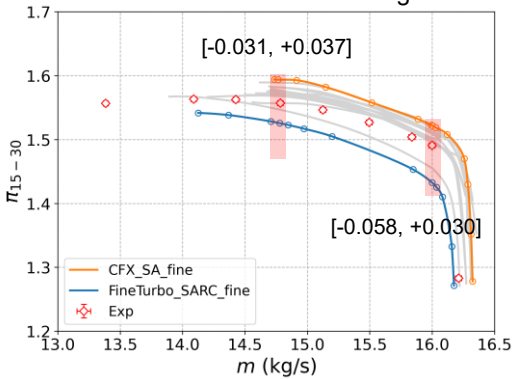
Total Pressure Ratio Characteristics

All data



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

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



Design speed

- ~~Discretization~~
- Uncertainty in inlet BC
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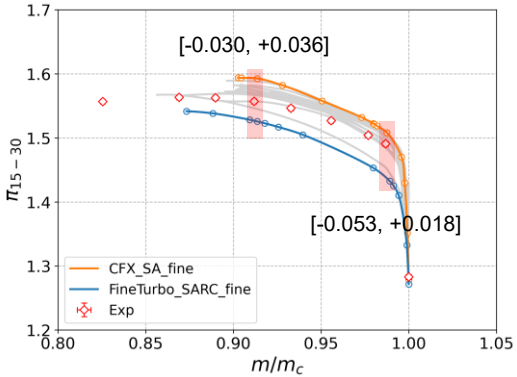
- Other geometric uncertainties

Normalize mass flow



- ~~Discretization~~
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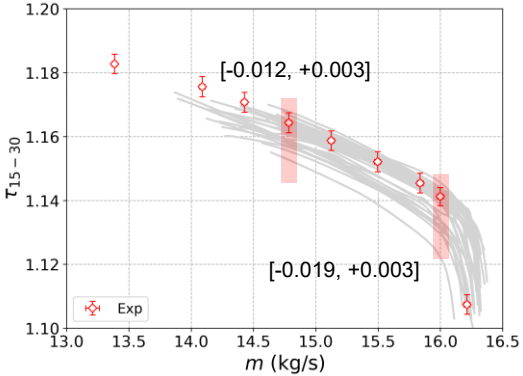
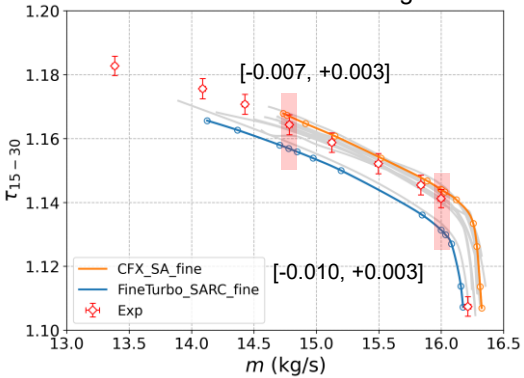
Total Temperature Ratio Characteristics

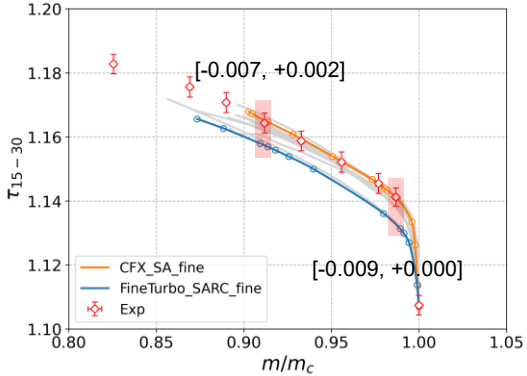
All data



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



Normalize mass flow



Design speed

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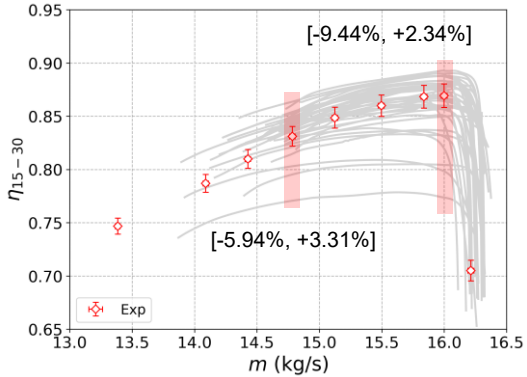
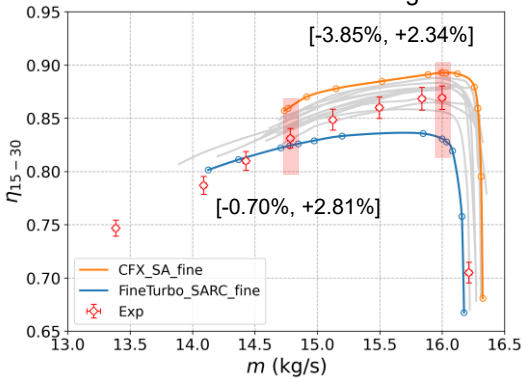
- Other geometric uncertainties

Isentropic Efficiency Characteristics

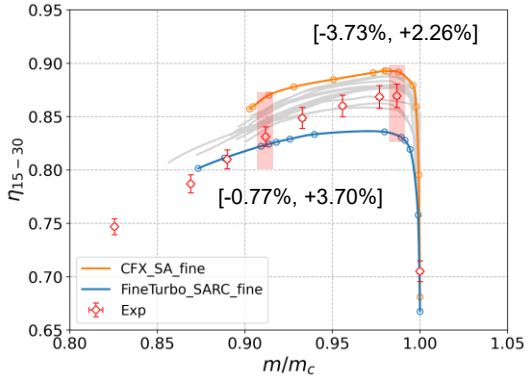
All data



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



Normalize mass flow



Design speed

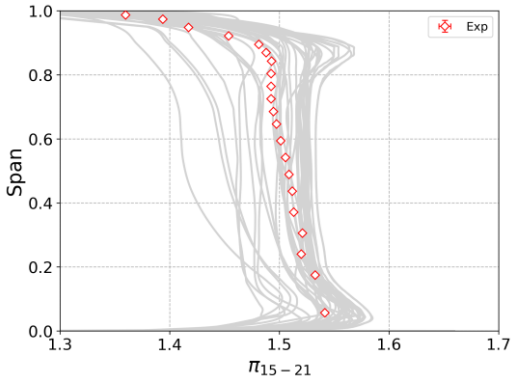
- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

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

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

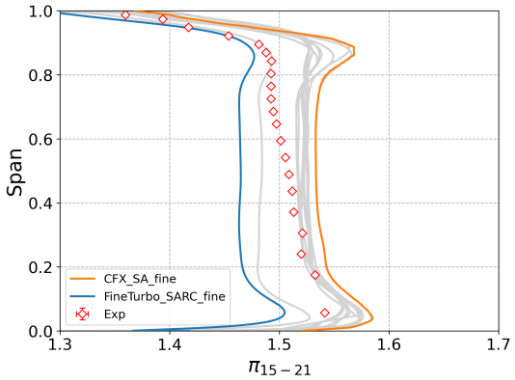
Rotor Exit (ME21) Total Pressure Ratio Profile

All data (m=16.00±0.10kg/s)



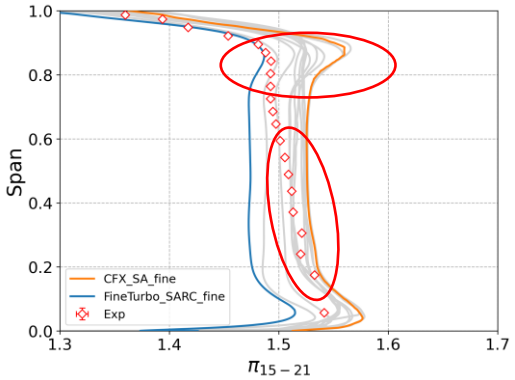
- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

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

Correct to m/m_c=0.9868

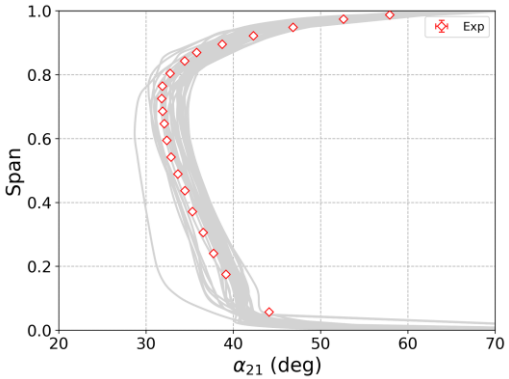


- ~~Discretization~~
- ~~Uncertainty in inlet BC~~
- ~~Uncertainty in throat area~~
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

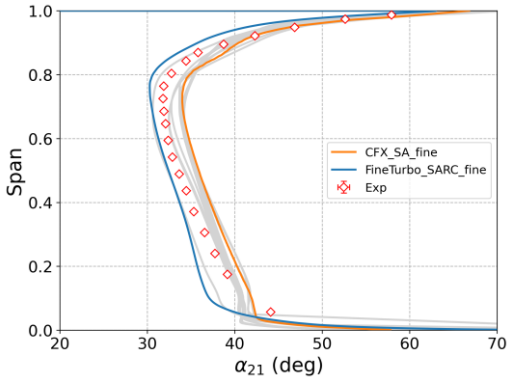
Design speed, peak efficiency

Rotor Exit (ME21) Absolute Flow Angle Profile

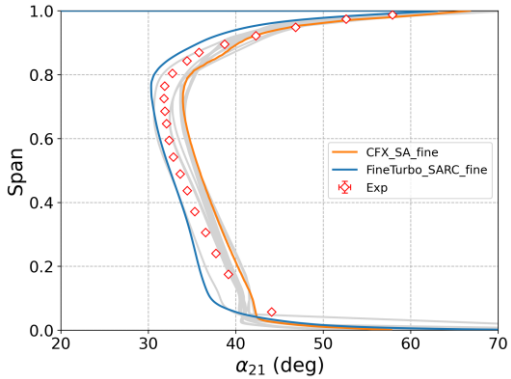
All data (m=16.00±0.10kg/s)



Exclude coarse grid (N_g≥3M)



Correct to m/m_c=0.9868



Design speed, peak efficiency

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

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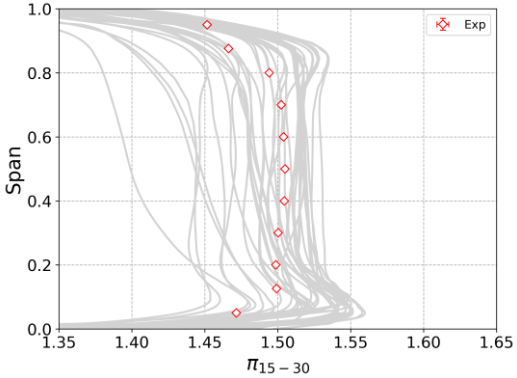
- Periodic and R-S BC
- Other geometric uncertainties

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

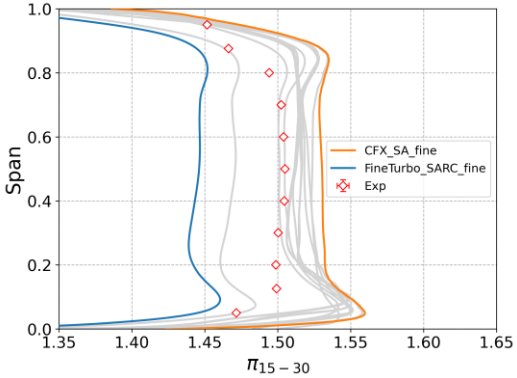
Stator Exit (ME30) Total Pressure Ratio Profile

All data (m=16.00±0.10kg/s)



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

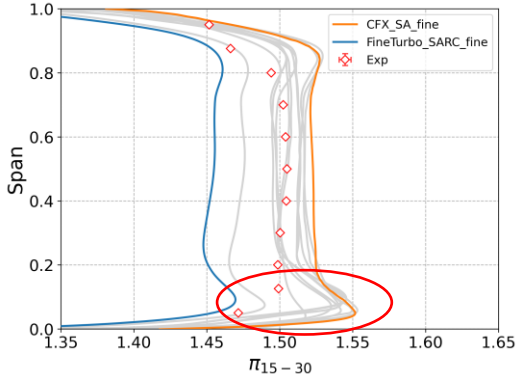
Exclude coarse grid (N_g≥3M)



Design speed, peak efficiency

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

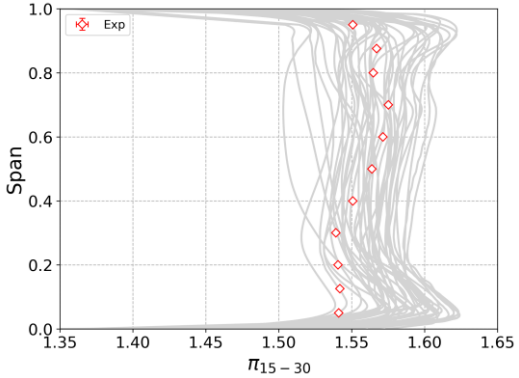
Correct to m/m_c=0.9868



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

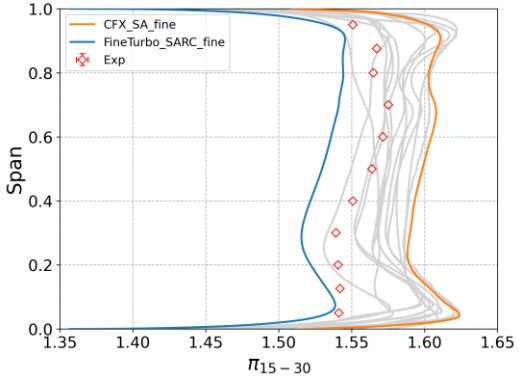
Stator Exit (ME30) Total Pressure Ratio Profile

All data (m=14.78±0.10kg/s)



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

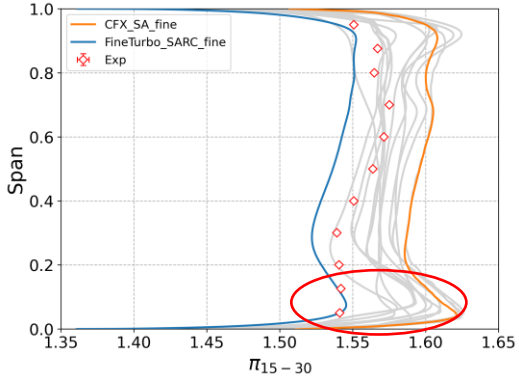
Exclude coarse grid (N_g≥3M)



Design speed, near stall

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

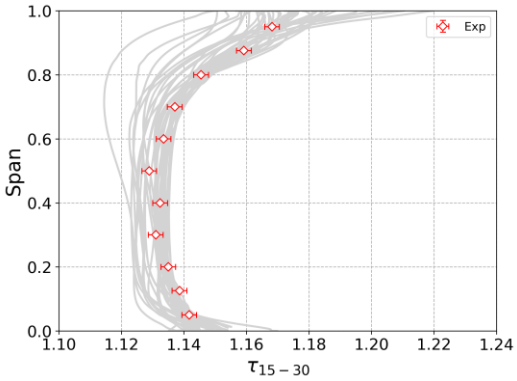
Correct to m/m_c=0.9116



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

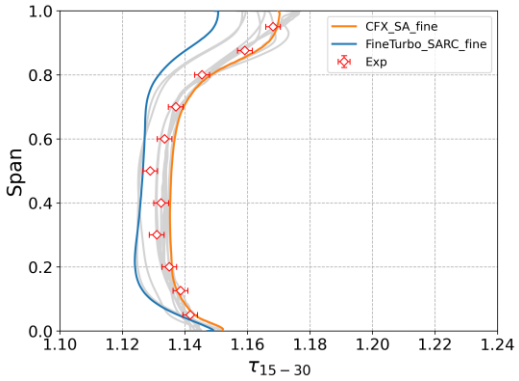
Stator Exit (ME30) Total Temperature Ratio Profile

All data (m=16.00±0.10kg/s)



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

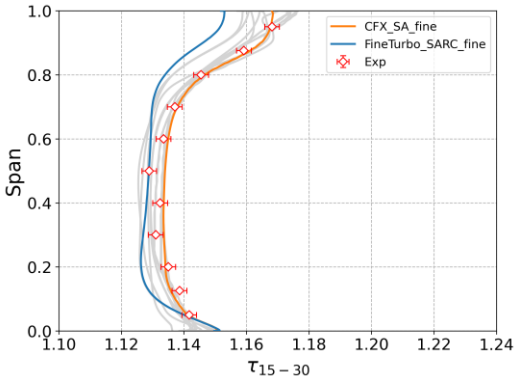
Exclude coarse grid (N_g≥3M)



Design speed, peak efficiency

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

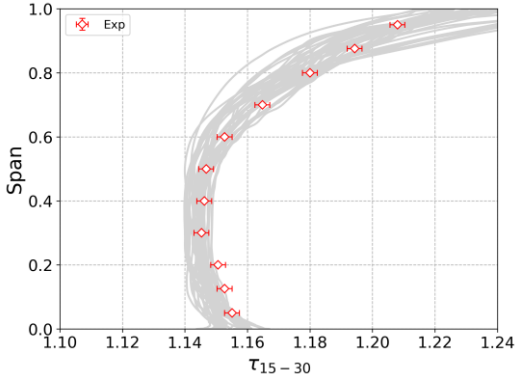
Correct to m/m_c=0.9868



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

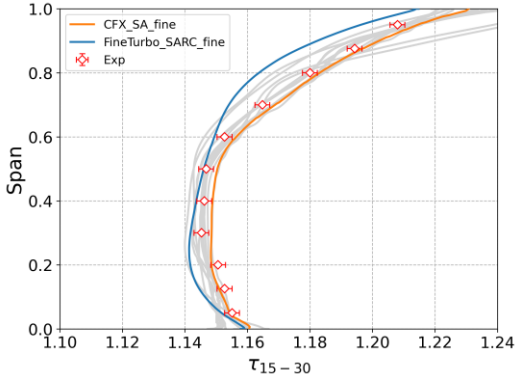
Stator Exit (ME30) Total Temperature Ratio Profile

All data (m=14.78±0.10kg/s)



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

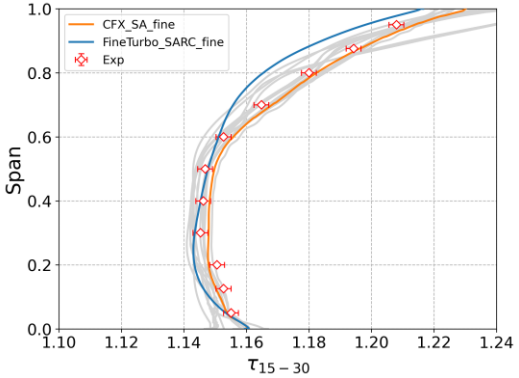
Exclude coarse grid (N_g≥3M)



Design speed, near stall

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

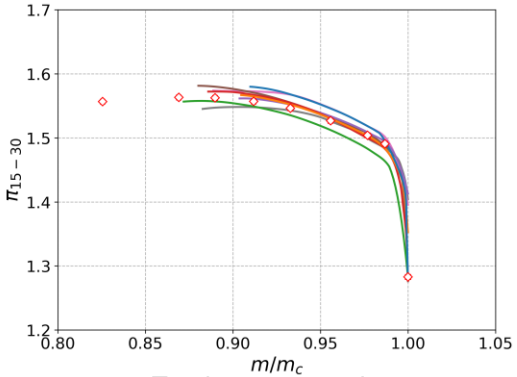
Correct to m/m_c=0.9116



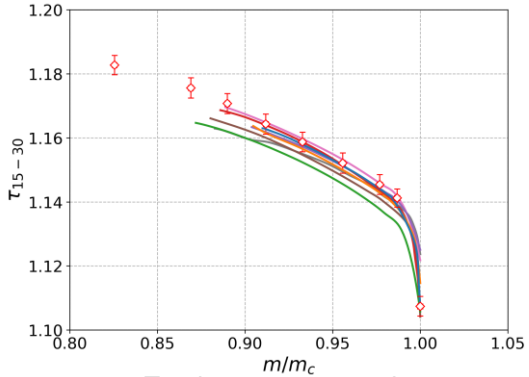
- Discretization
- Uncertainty in inlet BC
- Uncertainty in throat area
- Turbulence model
- Periodic and R-S BC
- Other geometric uncertainties

Verification: CFD versus CFD

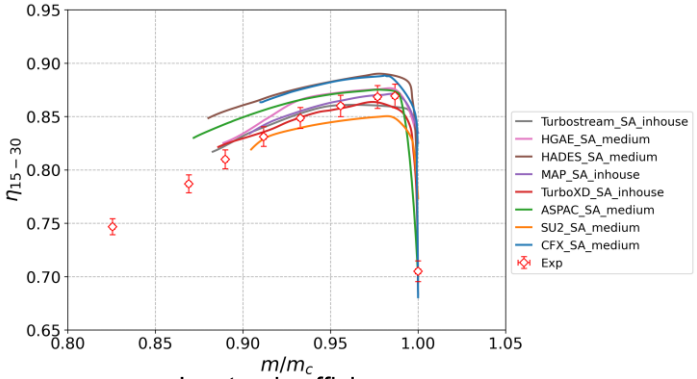
SA Model Verification: Performance Characteristics



Total pressure ratio



Total temperature ratio



Isentropic efficiency

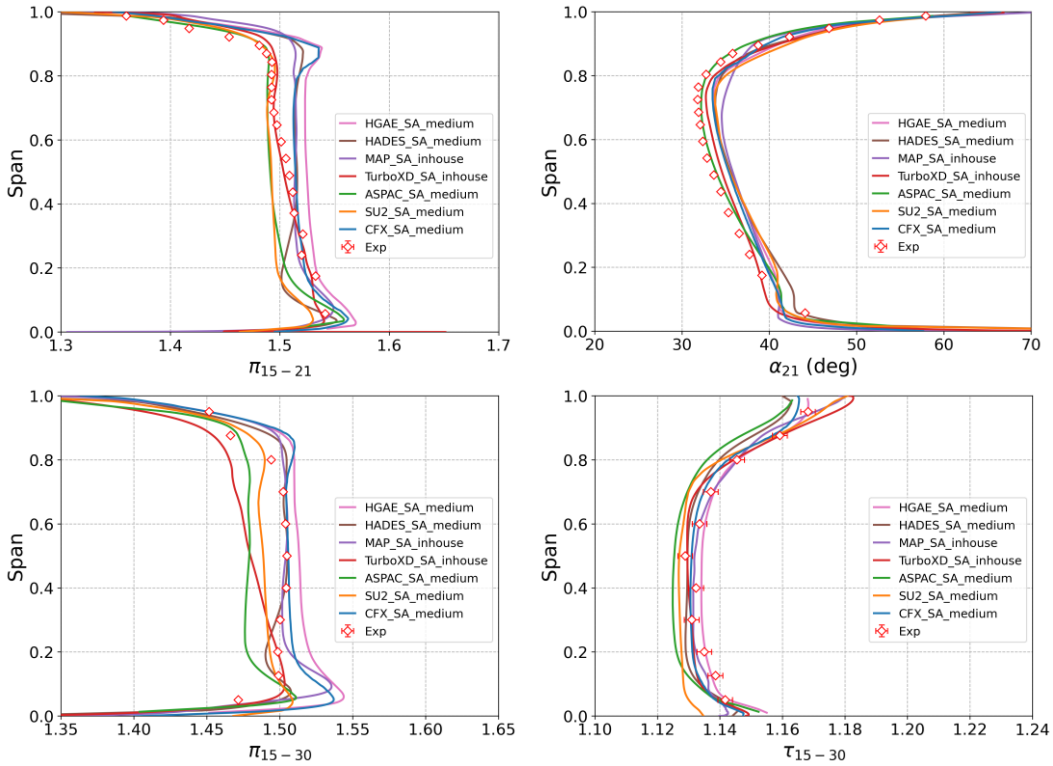
Design speed

- No results are overlapping with each other (i.e., **verification goal not achieved**)
- Further communications on the implemented **SA model version** need to be made
- Further **V&V on low TRL cases** need to be made in future workshops (hopefully off-line)
- Effect of **wall function, SA inlet b.c. and SA advection term** needs to be investigated

SA Model Verification: Peak Efficiency Profiles

Rotor exit (ME21)

Stage exit (ME30)

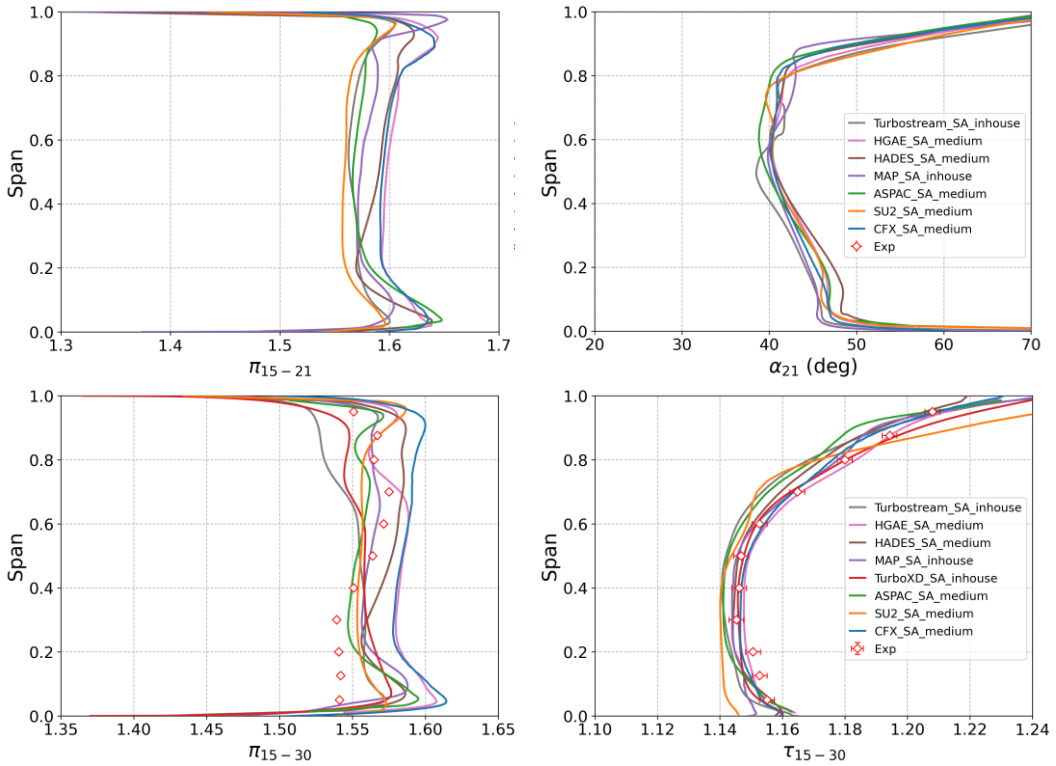


* All data corrected to m/m_c=0.9868

SA Model Verification: Near Stall Profiles

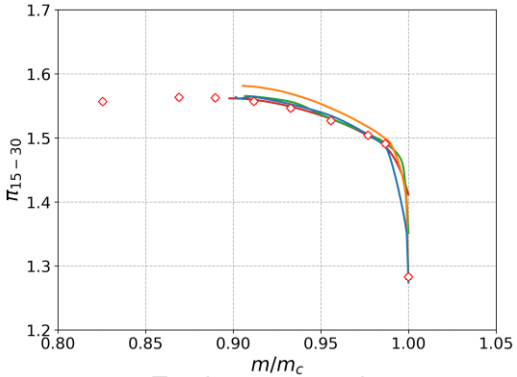
Rotor exit (ME21)

Stage exit (ME30)

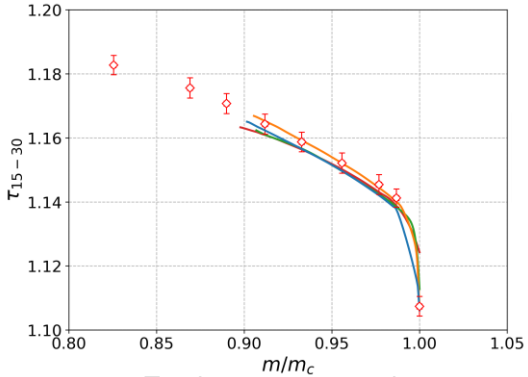


* All data corrected to m/m_c=0.9116

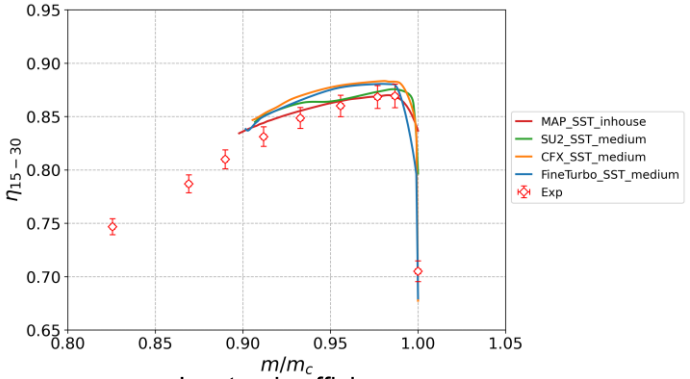
SST Model Verification: Performance Characteristics



Total pressure ratio



Total temperature ratio



Isentropic efficiency

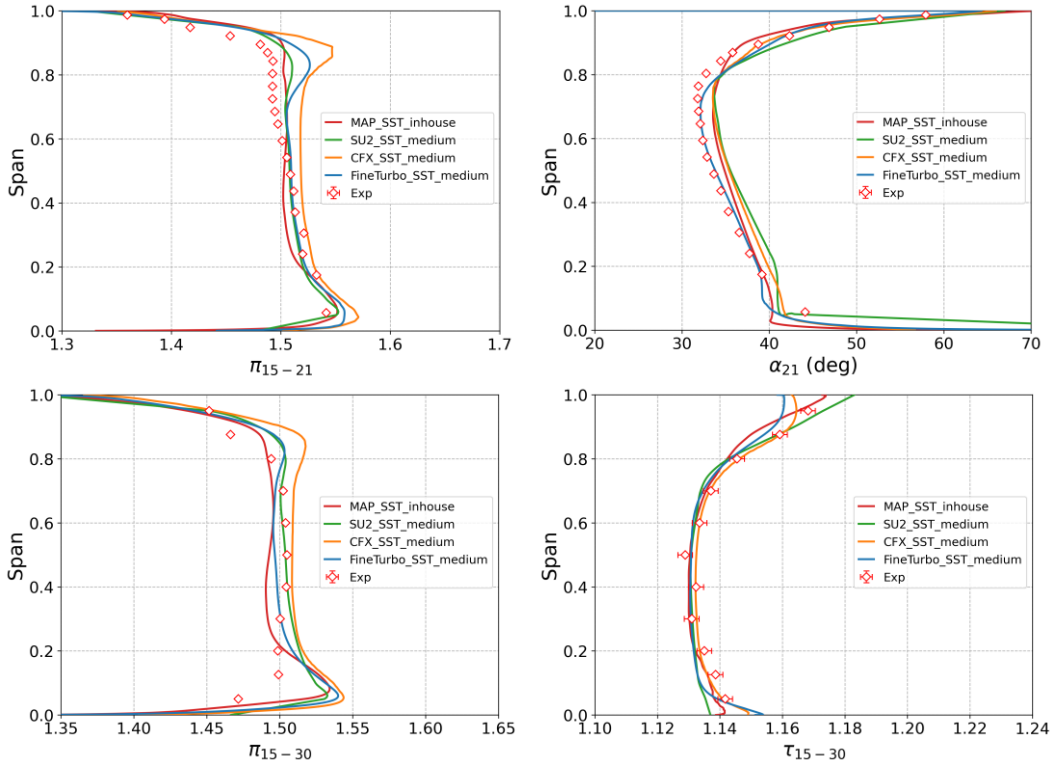
Design speed

- Results match with each other (better than SA), but still not perfect
- Further communications on the implemented **SST model version** need to be made
- Further **V&V on low TRL cases** need to be made in future workshops (hopefully off-line)
- Effect of **wall function, SST inlet b.c. and SST advection term** needs to be investigated

SST Model Verification: Peak Efficiency Profiles

Rotor exit (ME21)

Stage exit (ME30)

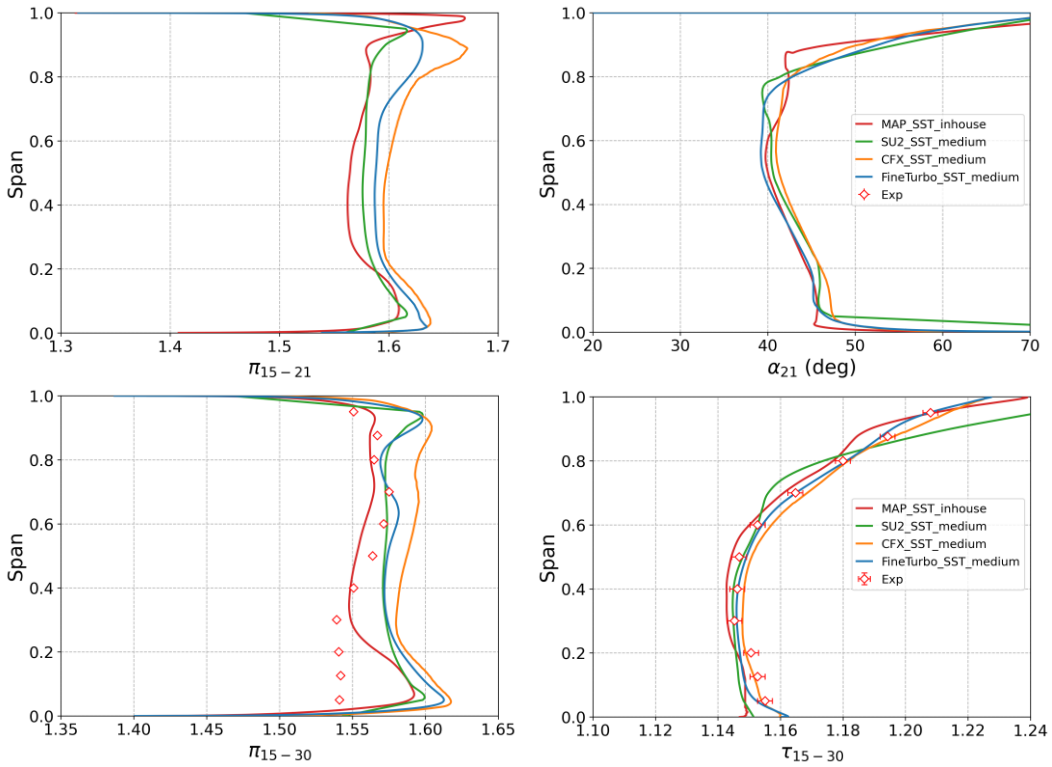


* All data corrected to m/m_c=0.9868

SST Model Verification: Near Stall Profiles

Rotor exit (ME21)

Stage exit (ME30)



* All data corrected to m/m_c=0.9116

Conclusions

Conclusions

Validation (CFD vs. EXP)

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

  Total pressure ratio: **±2.5%**; Total temperature ratio: **±0.4%**; Isentropic efficiency: **±2.6%** (absolute)

- Major differences between CFD and EXP

  Rotor exit: **near-tip TPR overshoot** (rotor tip geometrical uncertainty?); radial TPR gradient missed

  Stator exit: **near-hub TPR overshoot** (stator hub cavity?)

- Most influential factors: grid density and turbulence model

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

  “Best-practice” turbulence model: how universal would that be? case-by-case? (more cases needed) solver-by-solver? (verification is essential)

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**

Summary of Submissions

1st GPPS Turbomachinery CFD Workshop (GPPS 2021)

Questions & Answers

TECHNISCHE
UNIVERSITÄT
DARMSTADT

Imperial College
London