中国航空发动机研究院
AERO ENGINE ACADEMY OF CHINA

Steady RANS Simulation of the TUDa-GLR-Openstage Using ANSYS Fluent 19.2

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Outline

CFD Setup

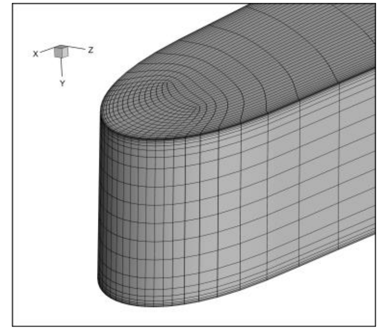
CFD Solver: ANSYS Fluent 19.2

- Developed by ANSYS Inc.
- Pressure-based & Density-based solver
- Unstructured Grid
- Edge-based dual-control volume method
- Scheme adopted: Pressure-based pressure-velocity coupling scheme (default discretization scheme of all transport equations: 2nd-order upwind), ILU
- Ideal Gas model
- Turbulence model: SST-2003、SST-2003-Helicity
- Operating condition: N100

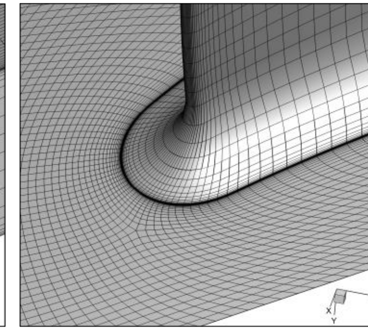
CFD Setup

Grid Generation

- Geometry: released by 1st V&V workshop in 2021
- NUMECA Autogrid^{V8} & Pointwise v18.1
- Average y^+ of first cell layer: <2, no wall function
- Grid density: between "medium" and "fine" versions of the official grid released



Rotor tip gap mesh



Rotor hub fillet mesh

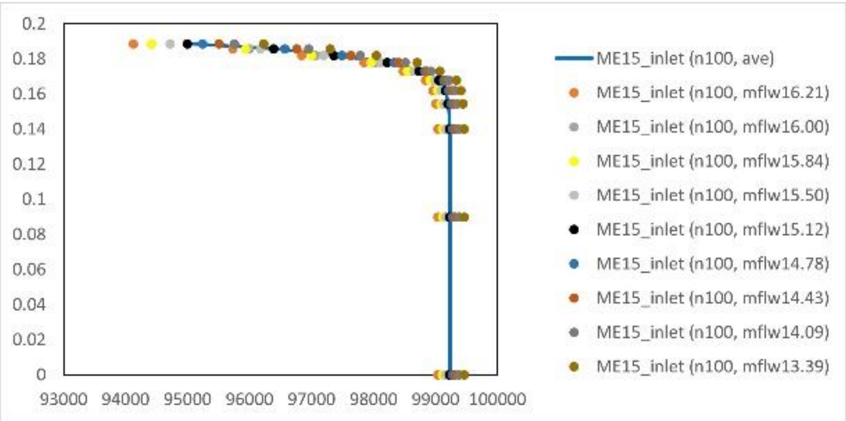
Row	Dimension	No.	Row	Dimension	No.	Row	Dimension	No.	Rows	Overall No.
rotor	Radial (including tip gap)	93	stator	Radial	93	OGV	Radial	77	R1+S1 +OGV	3.11 million
	Radial (tip gap)	21		Radial (tip fillet)	17		Radial (tip fillet)	17		
	Radial (hub fillet)	17		Radial (hub fillet)	17		Radial (hub fillet)	17		
	Pitchwise (per passage)	65		Pitchwise (per passage)	73		Pitchwise (per passage)	81		
	Streamwise (within blade passage)	129		Streamwise (within blade passage)	113		Streamwise (within blade passage)	85		
	Blade boundary layer (within skin O block)	21		Blade boundary layer (within skin O block)	21		Blade boundary layer (within skin O block)	17		
	Pitchwise (Tip-clearance O block)	17								
	Total cell count	1.56 million		Total cell count	0.96 million		Total cell count	0.59 million		

CFD Setup

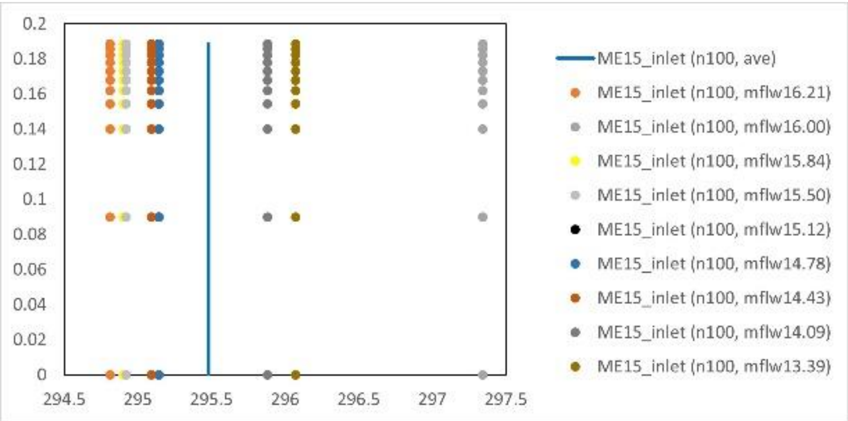
Boundary Conditions

Inlet Mean-flow conditions

- From data package “TUDa-GLR_Open_Stage_N100_Rad” and “N65_Rad” at ME15
- Ensemble average of experimental Pt&Tt profiles over 9 operating conditions
- Axial flow direction



Pt average (ME15), N100



Tt average (ME15), N100

Inlet turbulence conditions

- From “inlet_BC.input”: Tu 4%, Turb Length Scale: 0.09mm

Rotation Speed: Ensemble average over 9 operating conditions, 20298 rpm

Outlet conditions: Radial equilibrium backpressure

CFD Setup

Turbulence model

- Menter's SST-2003 model (SST-2003)
- SST-2003 with velocity helicity correction (SST-2003-Helicity)
  - Helicity model (Liu et al.[1-2]):

$$\widetilde{P_{kh}}=\nu_t(c_{h1}h^{c_{h2}})\Omega^2$$

$$h=\left|\frac{\vec{v}\cdot\vec{\omega}}{|\vec{v}||\vec{\omega}|+0.00001}\right| \qquad c_{h1}=0.71 \qquad c_{h2}=0.6$$

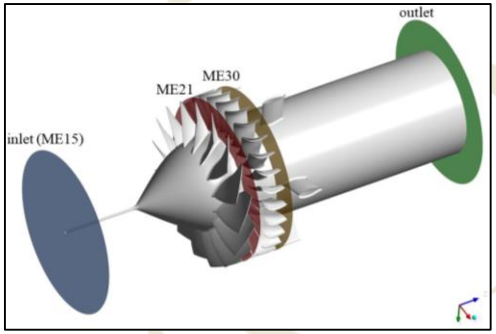
  - SST-2003-Helicity:

$$\frac{\partial k}{\partial t}+\frac{\partial\left(u_j k\right)}{\partial x_j}=\tau_{ij}\frac{\partial u_i}{\partial x_j}+\widetilde{P_{kh}}-\beta^* k\omega+\frac{\partial}{\partial x_j}\left[\left(\nu+\sigma_k\nu_t\right)\frac{\partial k}{\partial x_j}\right]$$

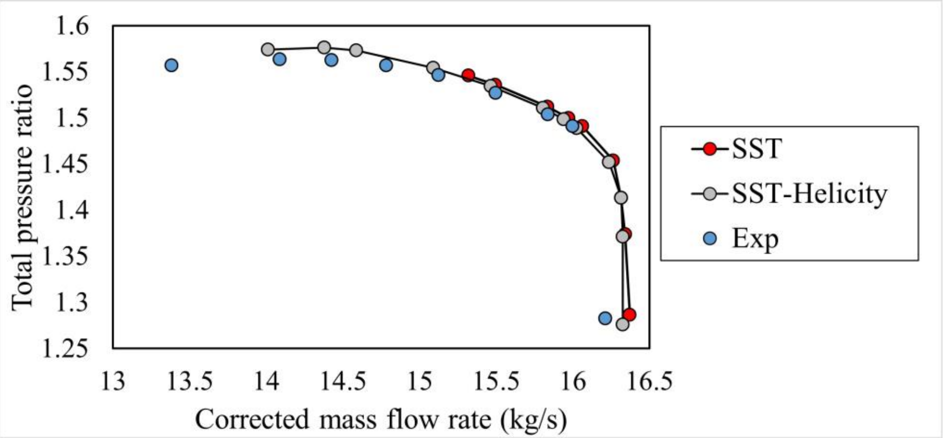
$$\frac{\partial \omega}{\partial t}+\frac{\partial\left(u_j \omega\right)}{\partial x_j}=\frac{\gamma}{\nu_t}\widetilde{P_k}+\frac{\gamma}{\nu_t}\widetilde{P_{kh}}-\beta\omega^2+\frac{\partial}{\partial x_j}\left[\left(\nu+\sigma_\omega\nu_t\right)\frac{\partial \omega}{\partial x_j}\right]+2\left(1-F_1\right)\frac{\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}$$

- Helicity model implemented via UDF
  - Not Galilian invariant
  - For rotating zones: $\vec{v}$、 $\vec{\omega}$ becomes relative ones

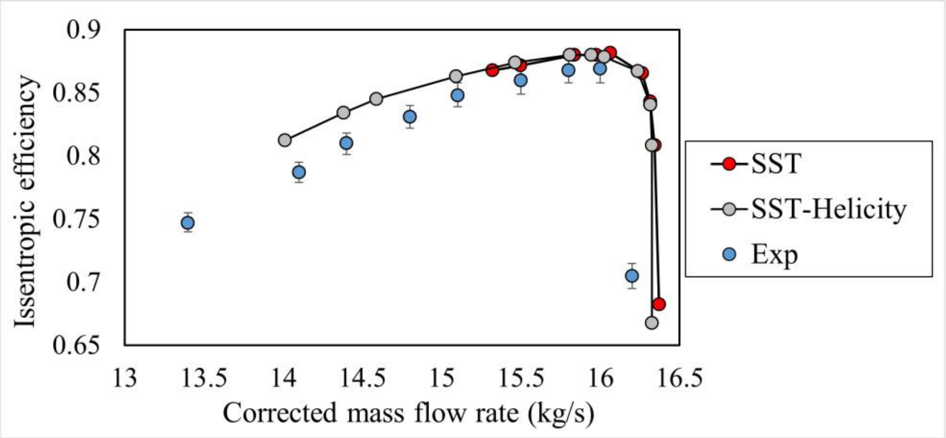
Multi-reference Frame



Overall Performance



Total pressure ratio (N100)



Isentropic Efficiency (N100)

Table 1. Aerodynamic parameters prediction results (PE condition)

Measured/Calculated	Total pressure ratio	Relative error of total pressure ratio (%)	Isentropic efficiency (%)	Isentropic efficiency error (%)
Exp	1.491	—	86.92%	—
SST	1.491	0.0%	88.17%	+1.25%
SST-Helicity	1.489	-0.134%	88.00%	+1.08%

Table 2. Aerodynamic parameters prediction results (NS condition)

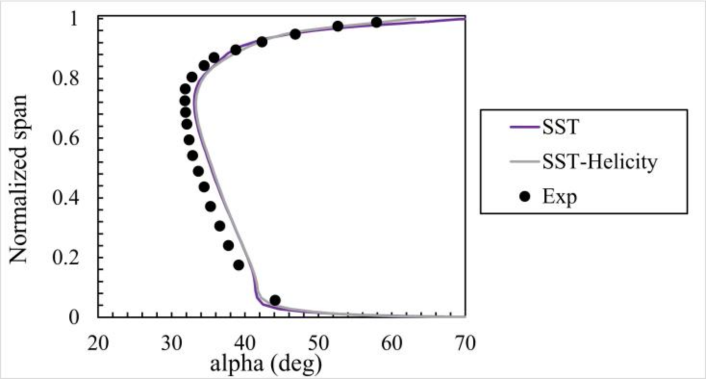
Measured/Calculated	Mass flow rate (kg/s)	Mass flow rate error (kg/s)	Stall margin* (%)	Stall margin error (%)
Exp	13.375	—	24.81%	—
SST	15.319	+1.934kg/s	8.71%	-16.1%
SST-Helicity	14.011	+0.626kg/s	20.9%	-3.91%

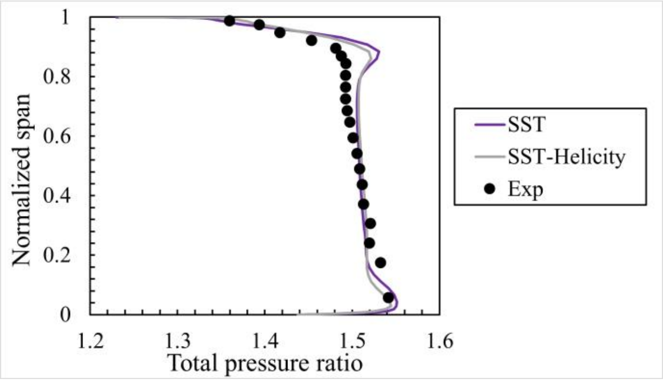
*Stall margin: $(P_{t,NS}\times m_{corr,PE}/(P_{t,PE}\times m_{corr,NS})\text{-}1.0)\times100\%$

- PE condition: SST & SST-Helicity high accuracy
- NS condition: achieved by increment of backpressure by 0.2KPa, stall margin (SST-Helicity) more than double

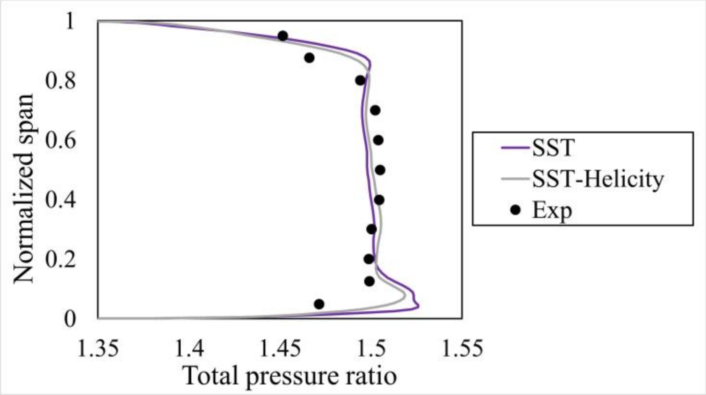
Aerodynamic Parameter Distributions

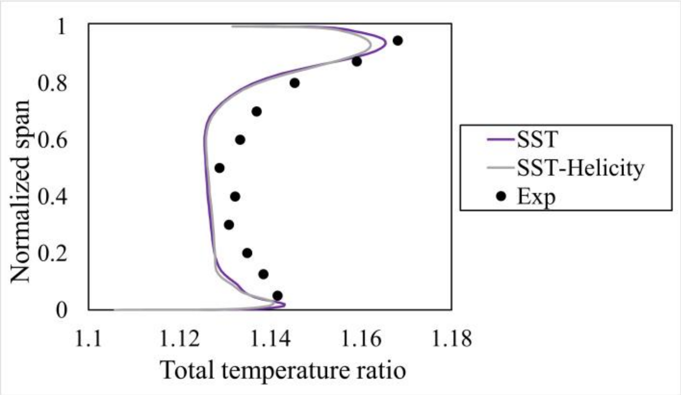
ME21 (PE)





ME30 (PE)





Rotor exit:

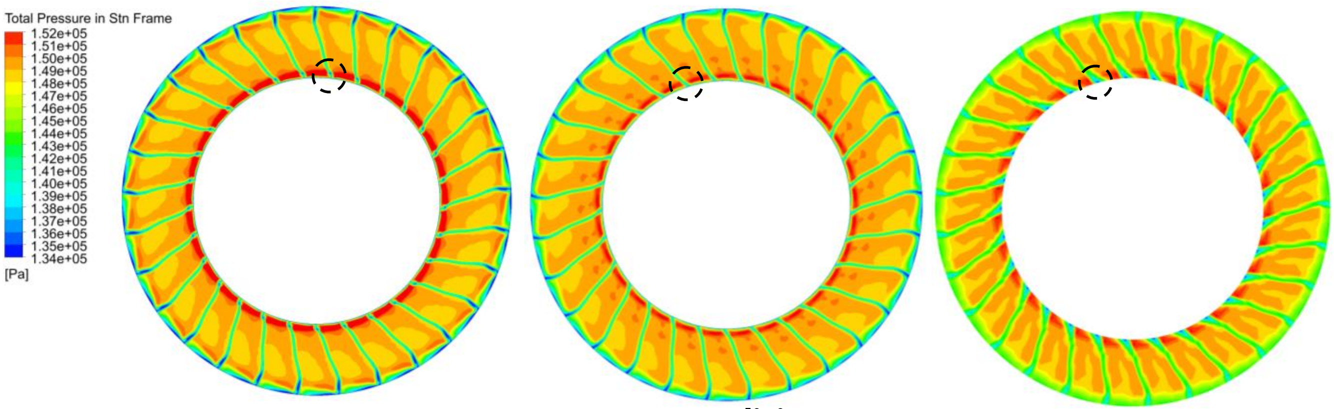
- Pt prediction deviation over upper span (60% span up) for both SST & SST-Helicity
- Absolute yaw angle overpredicted over most of span: “thinner” blade surface boundary layer predicted?

Stator exit:

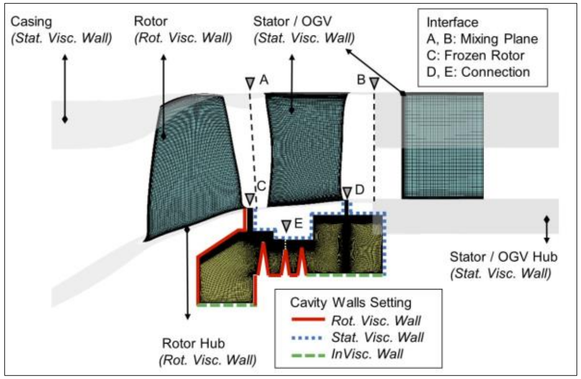
- Reasonable Pt & Smaller Tt predicted: lower loss, corresponding to “thinner” boundary layer
- Pt overpredicted near hub: neglection of stator hub leakage flow

Aerodynamic Parameter Distributions

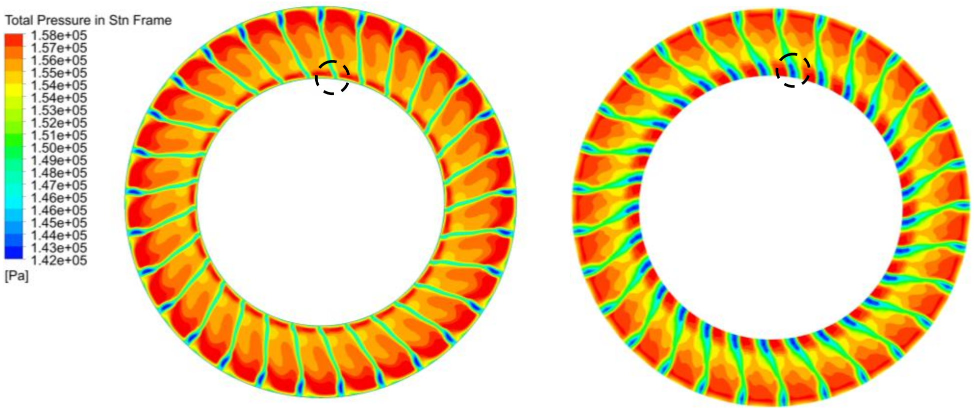
ME30 (PE)



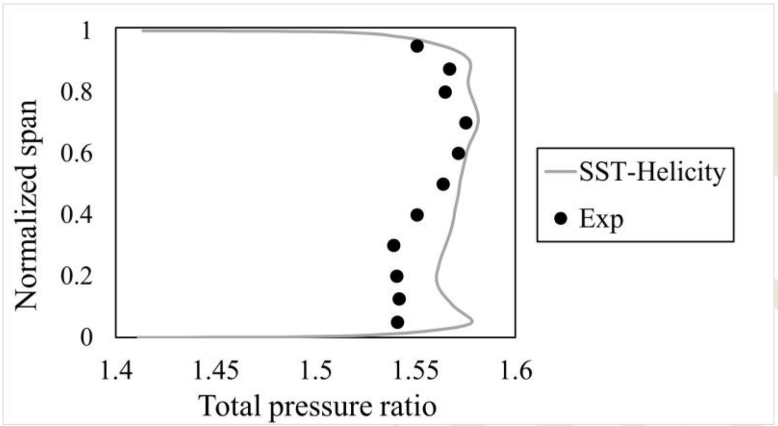
SST **SST-Helicity** **Exp**



ME30 (NS)



SST-Helicity **Exp**

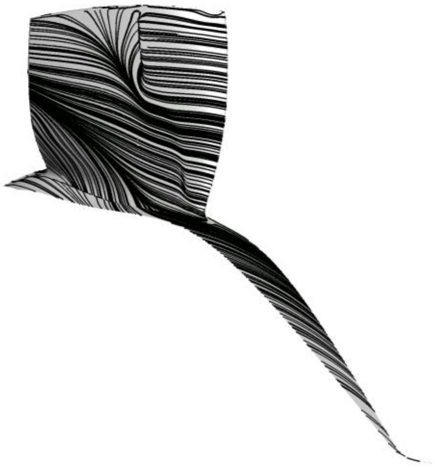


- PE: hub Pt deviation due to neglection of stator hub leakage effect (no hub cavity)
- NS: pre-mature stall for SST (>14.784kg/s), stator hub leakage effect much more significant

Flow Field Visualization (15.49kg/s)

- Rotor (surface limiting streamline)

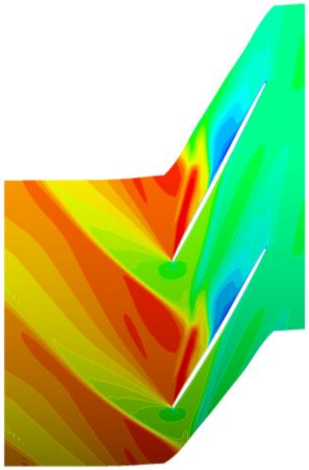
SST



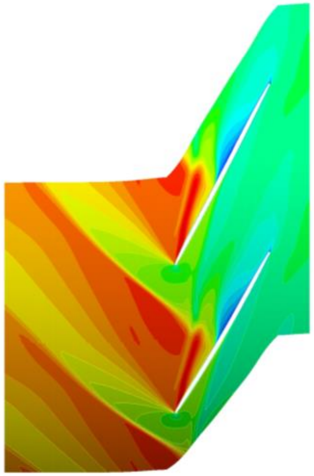
SST-Helicity

- Rotor (99% span)

SST



SST-Helicity



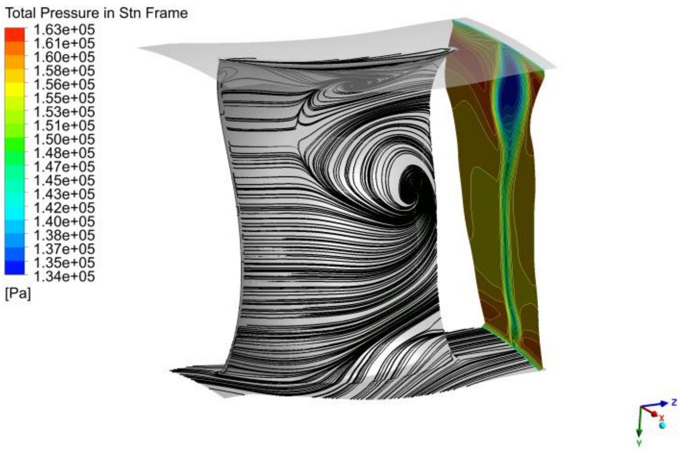
SST-Helicity

- smaller shock-induced separation bubble
- smaller corner separation

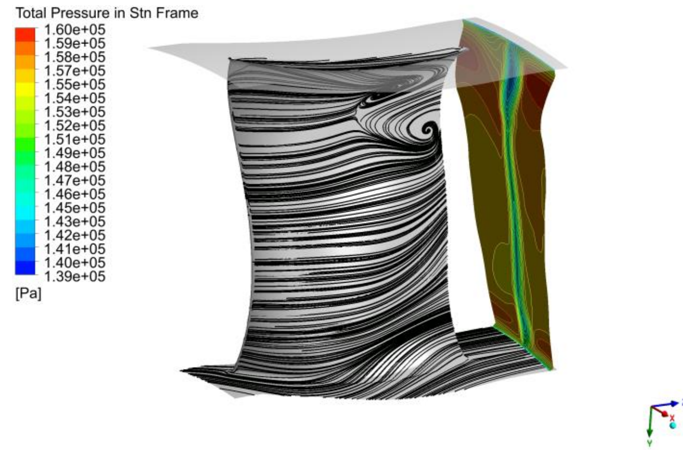
Flow Field Visualization (15.49kg/s)

- Stator (surface limiting streamline)

SST

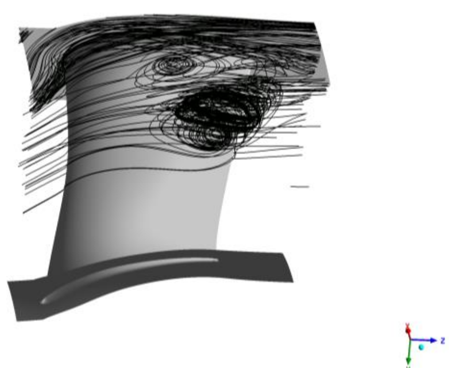


SST-Helicity

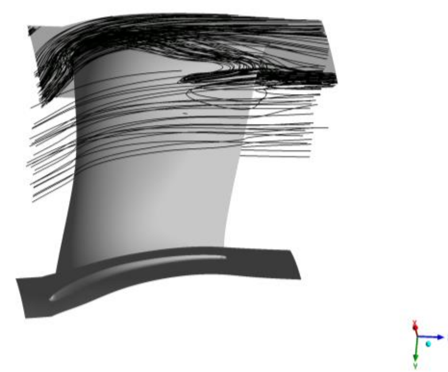


- Stator (particle traces)

SST



SST-Helicity



SST-Helicity

- smaller blockage due to casing corner separation region
- reduction of blockage in both rotor & stator contributes to increased stall operating range

References

1. Liu Y, Lu L, Fang L, Gao F. Modification of Spalart-Allmaras model with consideration of turbulence energy backscatter using velocity helicity. *Phys lett, A* 2011;375(24):2377-2381.
2. Liu Y, Tang Y, Scillitoe AD, Tucker PG. Modification of shear stress transport turbulence model using helicity for predicting corner separation flow in a linear compressor cascade. *J Turbomach* 2020;142(2): 021004.

Thank you for your attention！