Disk Cavity Analysis Tool Validation

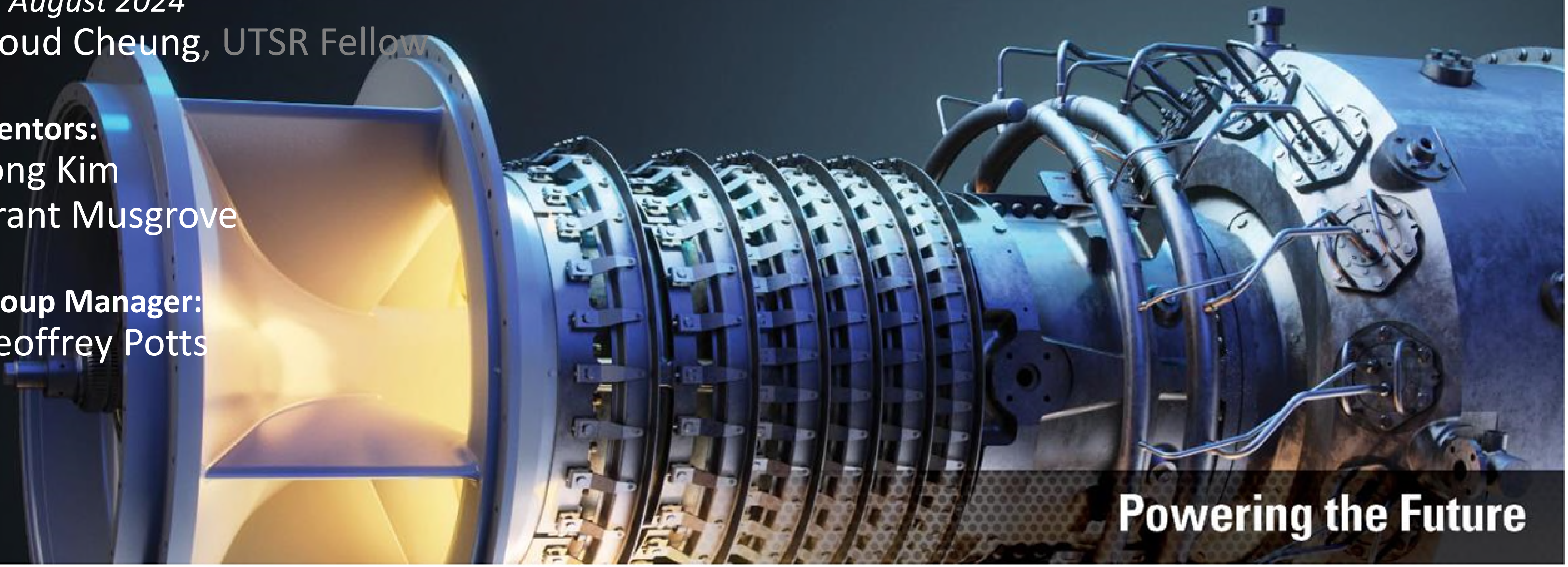
Summer 2024 Internship

06 August 2024

Cloud Cheung, UTSR Fellow

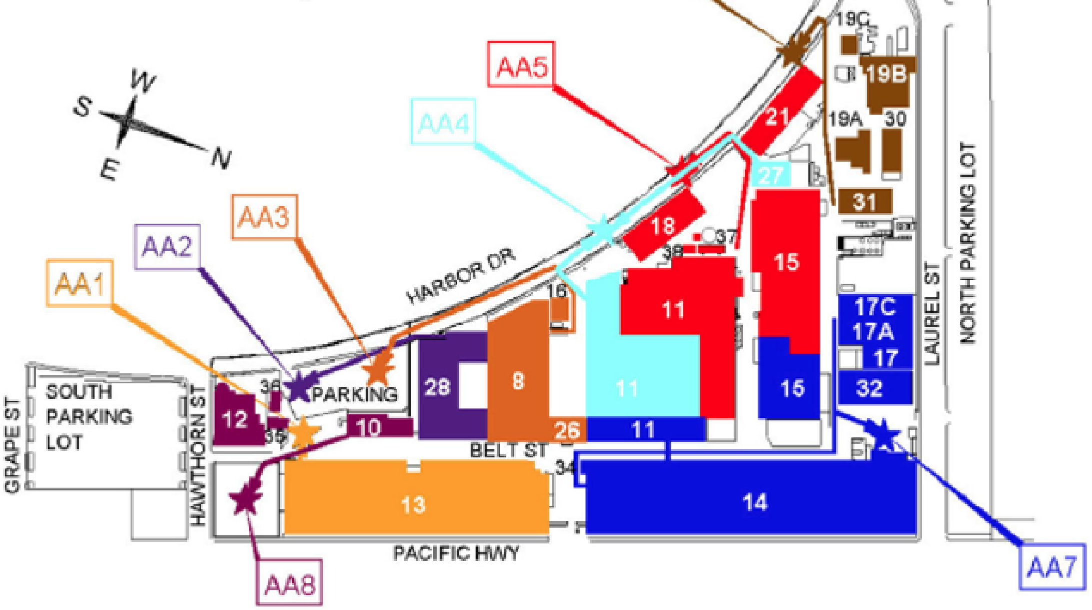
Mentors:
Yong Kim
Grant Musgrove

Group Manager:
Geoffrey Potts



Solar Turbines
A Caterpillar Company

Harbor Drive Evacuation Map



If access to assigned assembly area is unsafe, use closest alternate area.

EMERGENCY NUMBER

HD 619-544-5555

KM 858-694-6500

FIRE EXTINGUISHER

AED

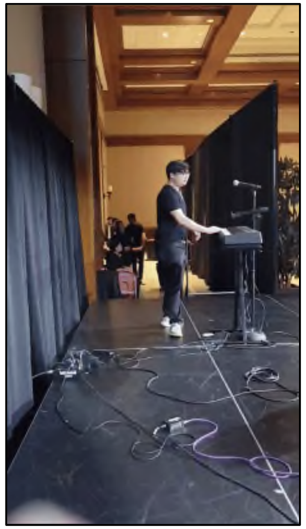
AGENDA

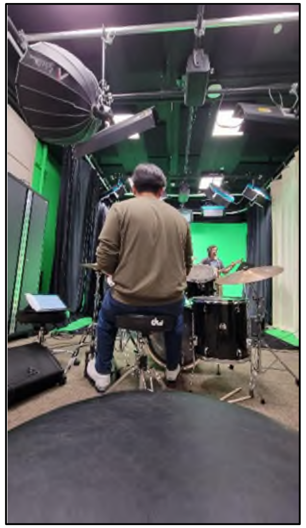
1. About me & Background
2. Projects
   - ASU Rig DCAT Modeling in Finesse (FNS)
   - CFD Analysis
3. Takeaways
4. Solar Summer
5. Acknowledgements

About Me

- Cloud Cheung (張榮峻)
- MSAE at San Diego State University
  - Expected Graduation: May 2026
  - B.S. Aerospace Engineering, SDSU
    - Minor in Mathematics

Tau Beta Pi — The Engineering Honor Society | MESA Math · Engineering · Science Achievement | asian pacific student alliance SDSU APSA EST 1972



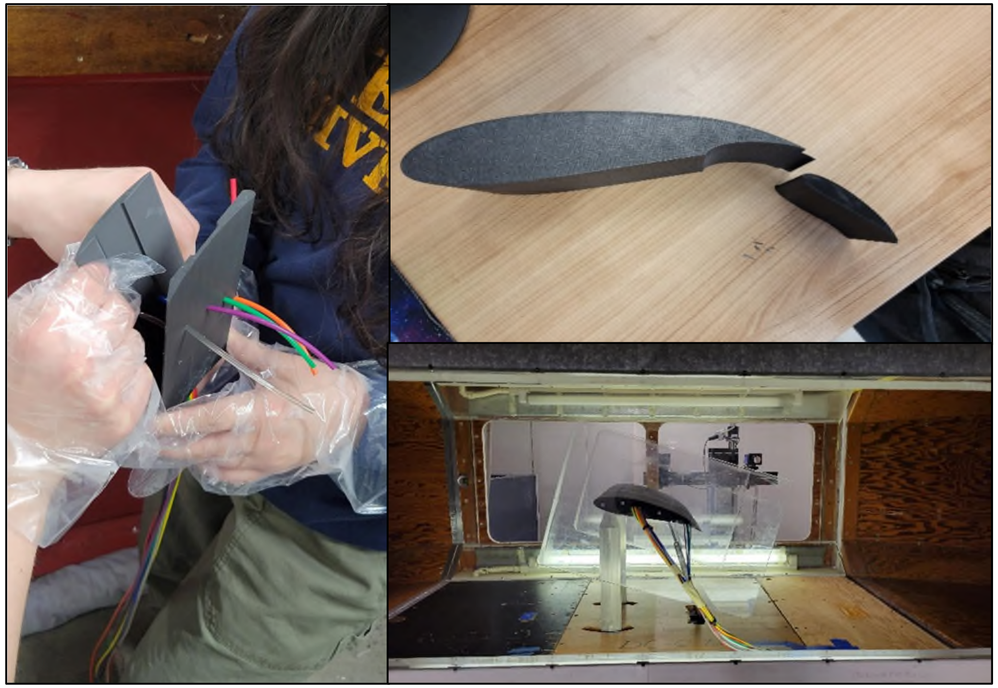


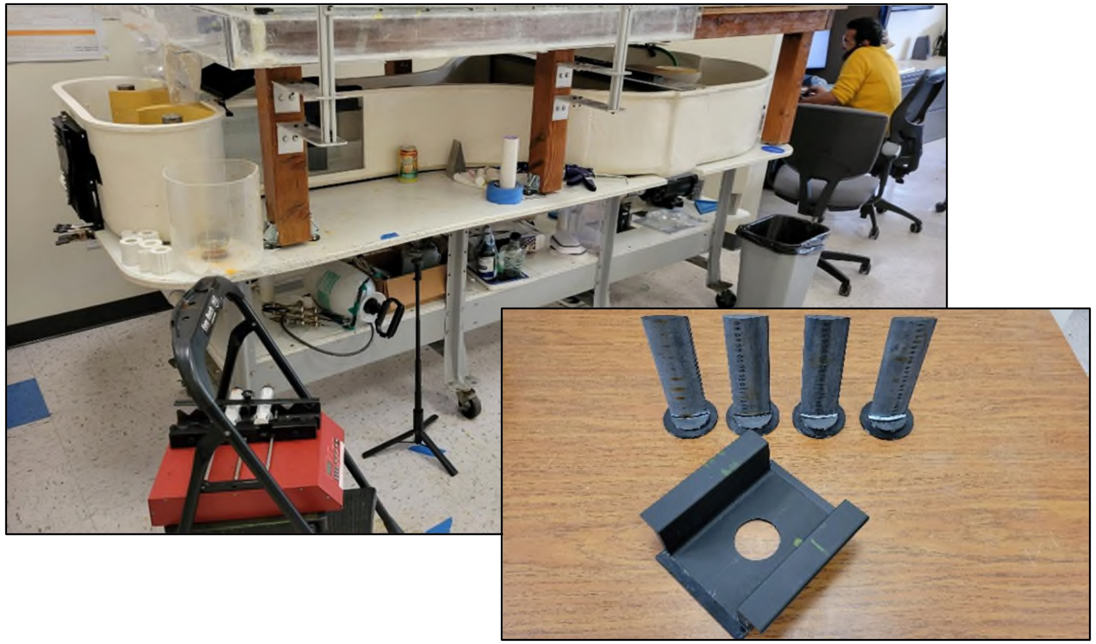
Hobbies:
- Cooking
- Rock climbing
- Drumming
- Video games
- Foodie

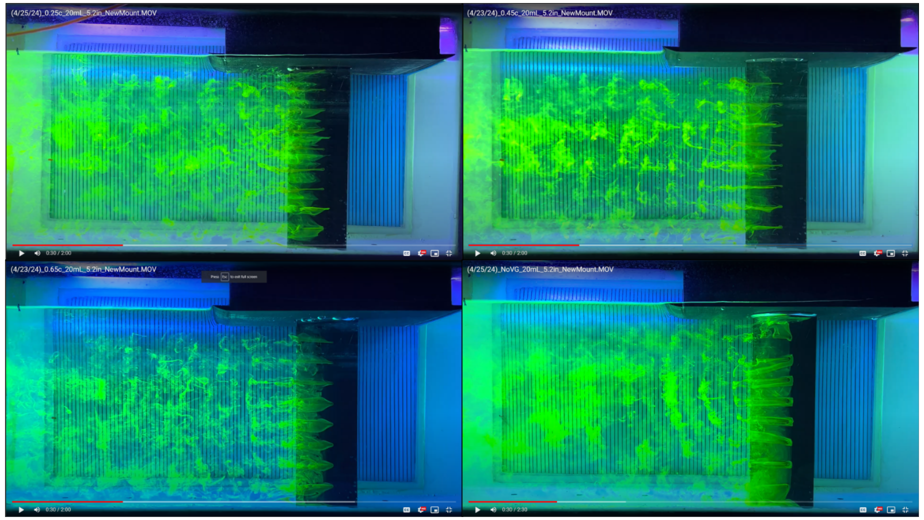
About Me

Projects:

- Compressor Blade Flow Control
  - Water tunnel visualization with fluorescent dye
  - Experimental PZT diaphragm testing
- Other Projects
  - Fowler flap optimization for take off and landing
  - High-lift devices for close-air support aircraft design







AGENDA

1. About me & Background
2. Projects
   - ASU Rig DCAT Modeling in Finesse (FNS)
   - CFD Analysis
3. Takeaways
4. Solar Summer
5. Acknowledgements

AGENDA

1. About me & Background
2. Projects
   - ASU Rig DCAT Modeling in Finesse (FNS)
     - Literature survey
     - Assemble the model in FNS
     - Preswirler adjustments
     - Solving for mass flow and Convergence
     - Comparison to CFD and revisit model
     - Update FNS model and compare against CFD and Data
3. Takeaways
4. Solar Summer
5. Acknowledgements

Titan 250 Stage 1 Rotor Disk Cavity

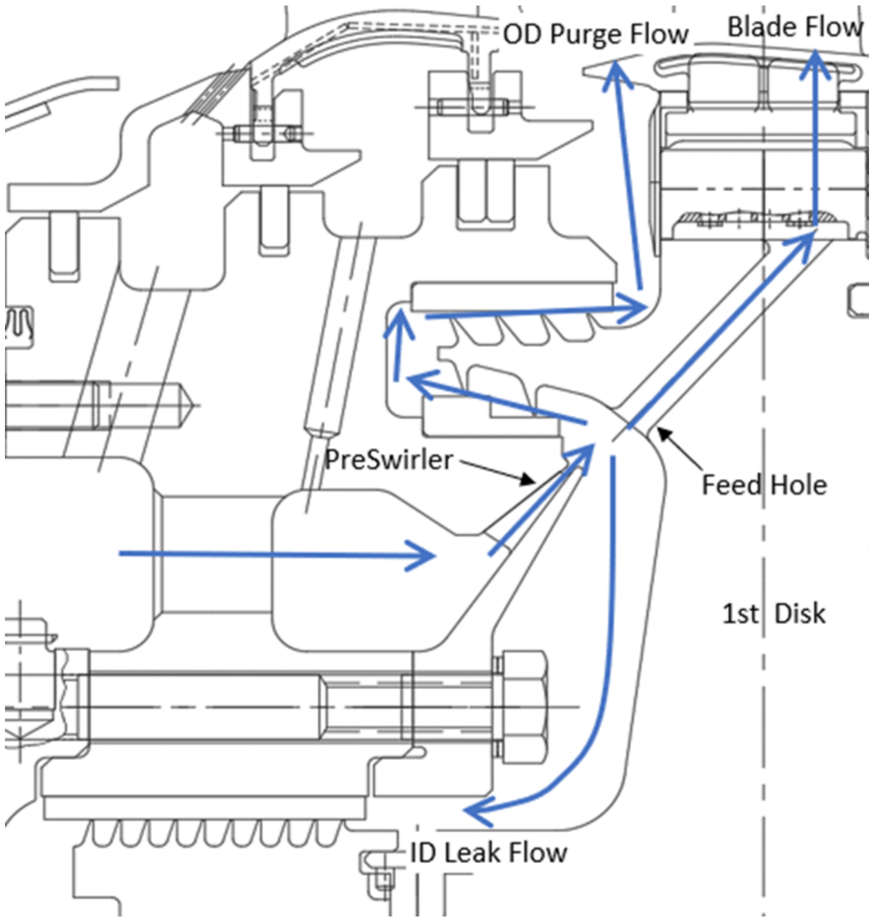
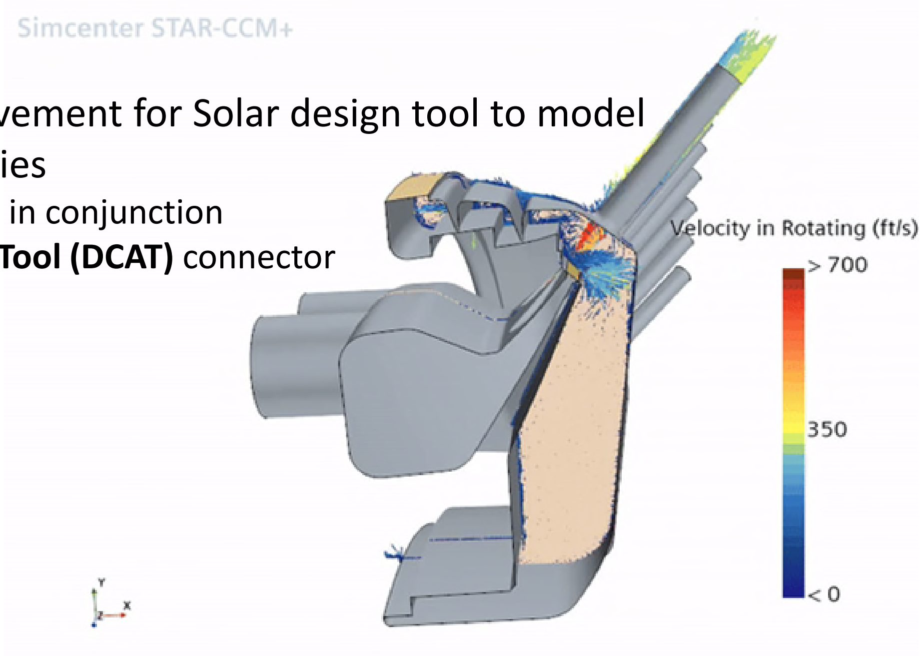
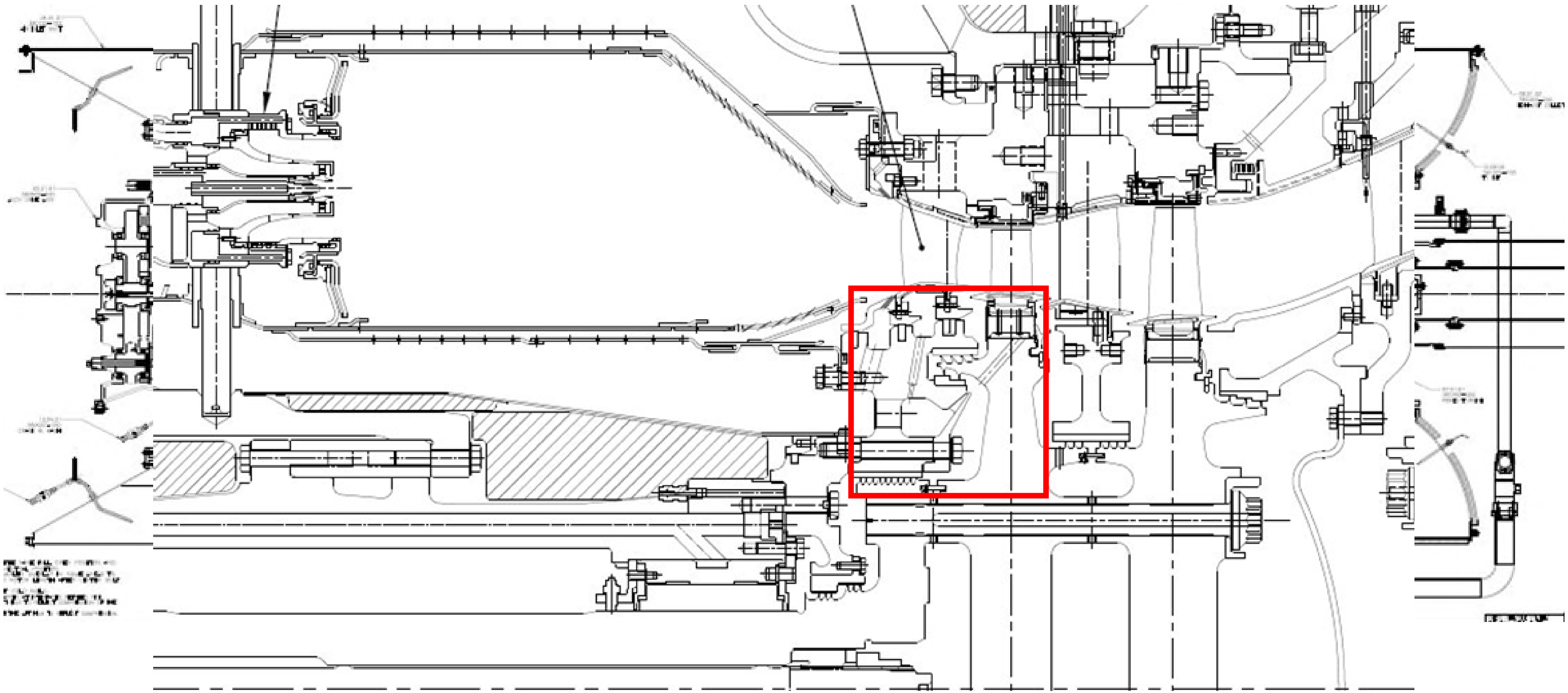


Fig. 1 The Titan 250 Stage 1 Rotor Disk Cavity with arrows indicating the direction of cooling flow.

<u>Primary problem: rotating cavity flow</u>

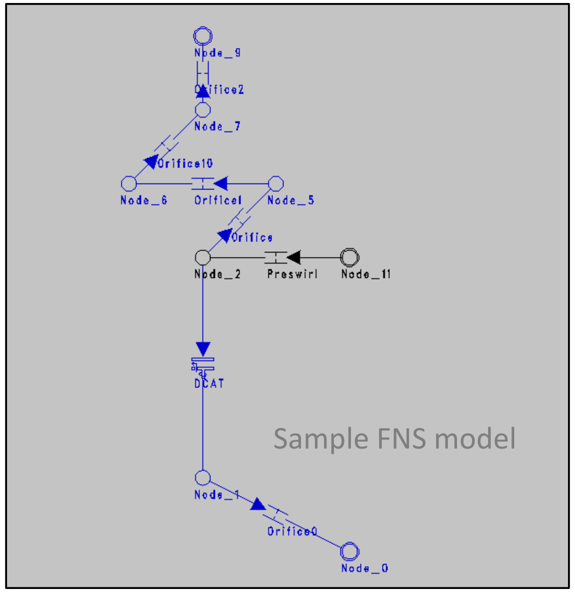
- Secondary flow system is designed to feed cooled components such as stage 1 blades and purge turbines disk cavities
- Preswirler accelerates the cooling flow to disk surface speed with the benefit of lowered blade cooling inlet temperature
  - **Radial in-flow** is created to route cooling air to other secondary flow systems in this engine
- Currently there is room for improvement for Solar design tool to model radial in-flow within rotating cavities
  - In this case we are using Finesse in conjunction with the **Disk Cavity Analysis Tool (DCAT)** connector

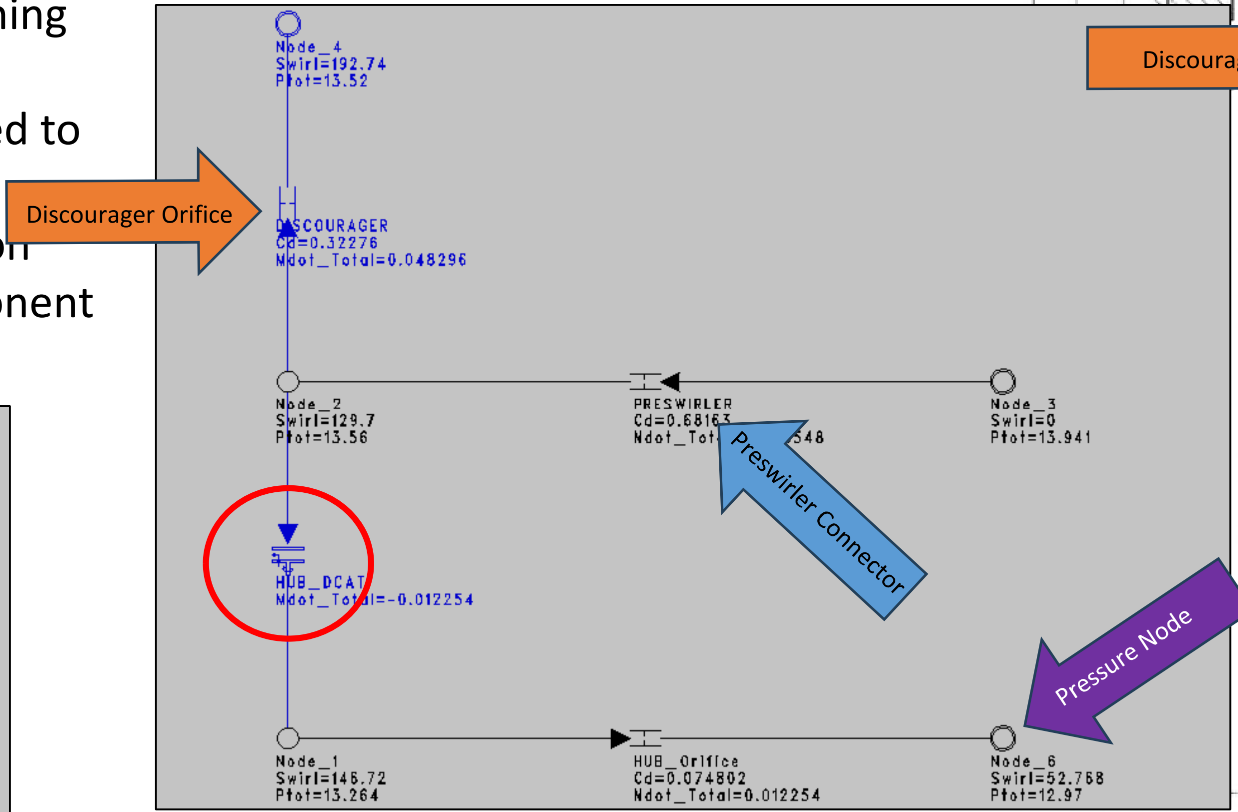


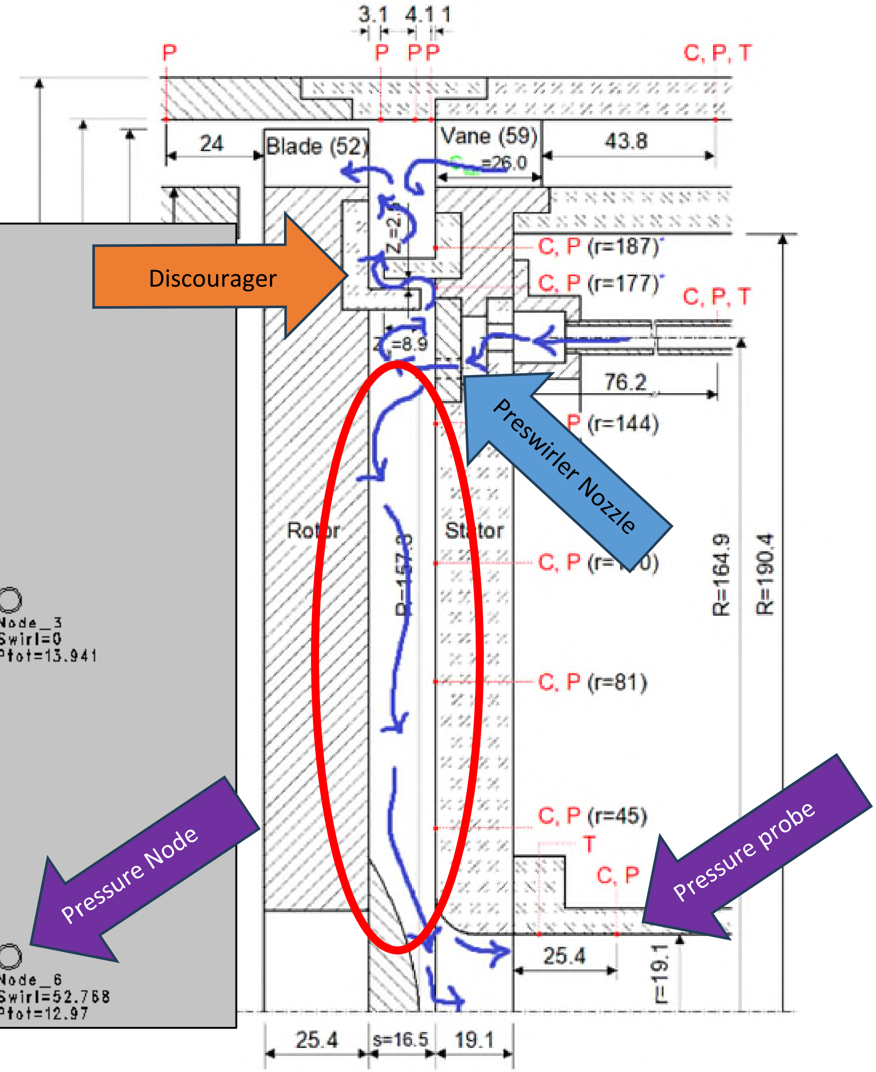


Finesse: 1D Flow Network Code

- A fundamental tool for designing complex flow systems
  - For gas turbines, it is used to design secondary flow systems with emphasis on heat transfer and component cooling







* Circumferentially 5 locations over one vane pitch All dimensions in mm

Fig. 5 ASU Disk Cavity diagram with static pressure tap, thermocouple, and concentration tap locations.

Arizona State University Disk Cavity Research Rig

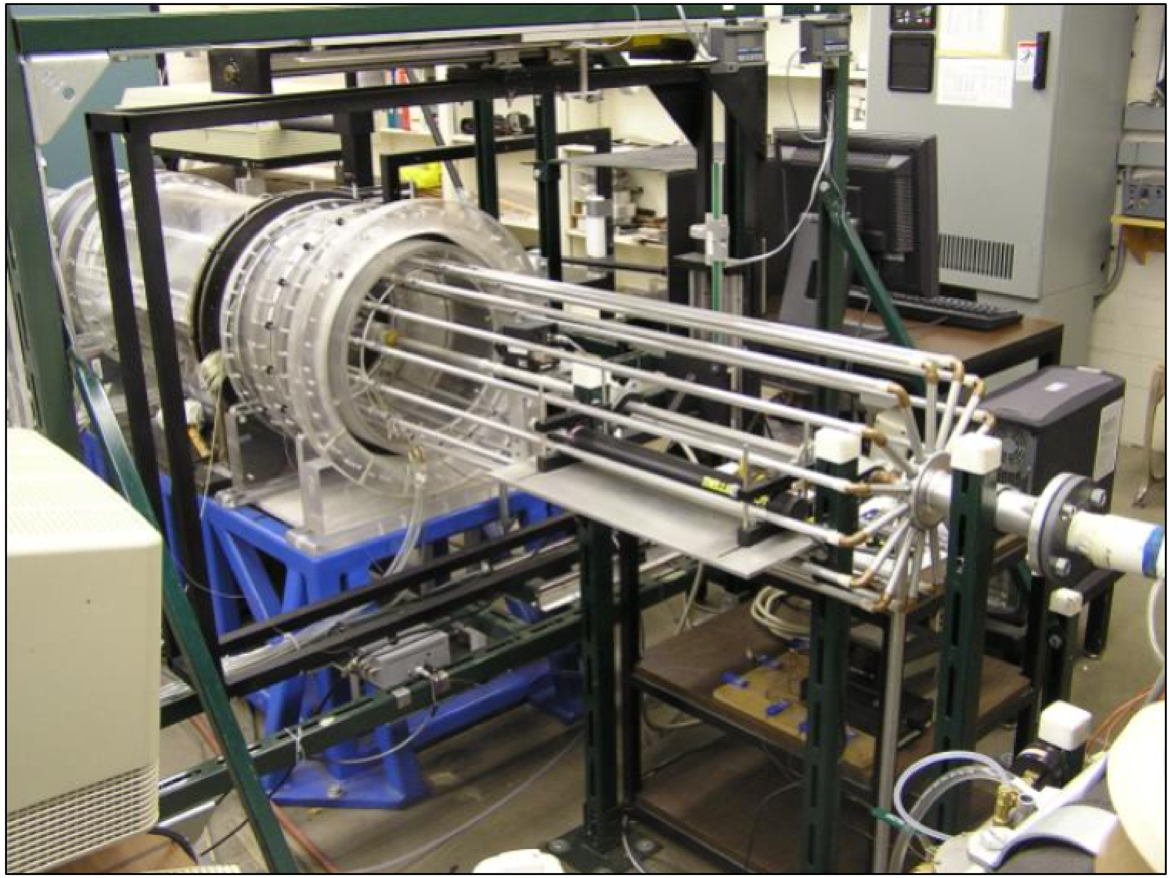


Fig. 2 ASU Disk Cavity research rig

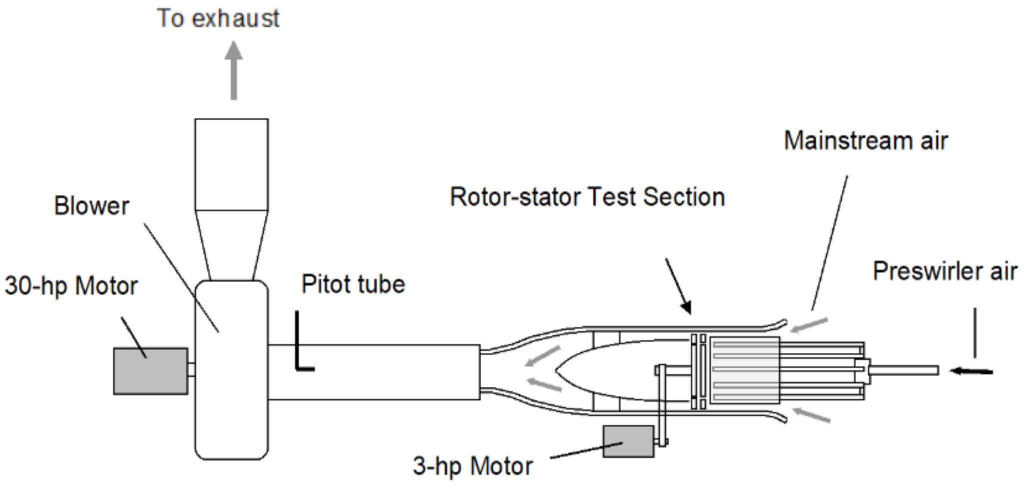


Fig. 3 ASU Disk Cavity research rig diagram

- In the ASU rig, the 15 tubes pictured on the left provides air to the preswirler plenum

ASU Rig DCAT Modeling

What ASU Reports:

- Mass flow through purge and hub
- Preswirler tangential exit velocity (swirl)
- DCAT Tape 8 Output

Table 3 Swirl ratio for the experimental conditions

Re_ϕ (Ω)	c_w (Q_{purge})	Diameter of pre-swirl holes (")	Area of pre-swirl holes (m^2)	No. of pre-swirl holes	Pre-swirl air V_{exit}(m/s)	Pre-swirl air V_{tang}(m/s)	$V_{rotor,local}$ (m/s)	Swirl Ratio (V_{tang}/ $V_{rotor,local}$)
7.57×10^5 (2600 rpm)	1602 (10cfm)	0.1875	1.781×10^{-5}	30	8.8	8.6	42.8	0.2017
	4005 (25cfm)	0.1875	1.781×10^{-5}	30	22.1	21.6	42.8	0.5044
	6569 (41 cfm)	0.1875	1.781×10^{-5}	30	36.2	35.4	42.8	0.8271
	11063 (69.1 cfm)	0.1875	1.781×10^{-5}	30	60.9	59.6	42.8	1.3931
8.74×10^5 (3000 rpm)	1923 (12 cfm)	0.1875	1.781×10^{-5}	30	10.6	10.4	49.4	0.2098
	4806 (30 cfm)	0.1875	1.781×10^{-5}	30	26.5	25.9	49.4	0.5245
	7370 (46 cfm)	0.1875	1.781×10^{-5}	30	40.6	39.7	49.4	0.8043
	12404 (77.4 cfm)	0.1875	1.781×10^{-5}	30	68.4	66.9	49.4	1.3538

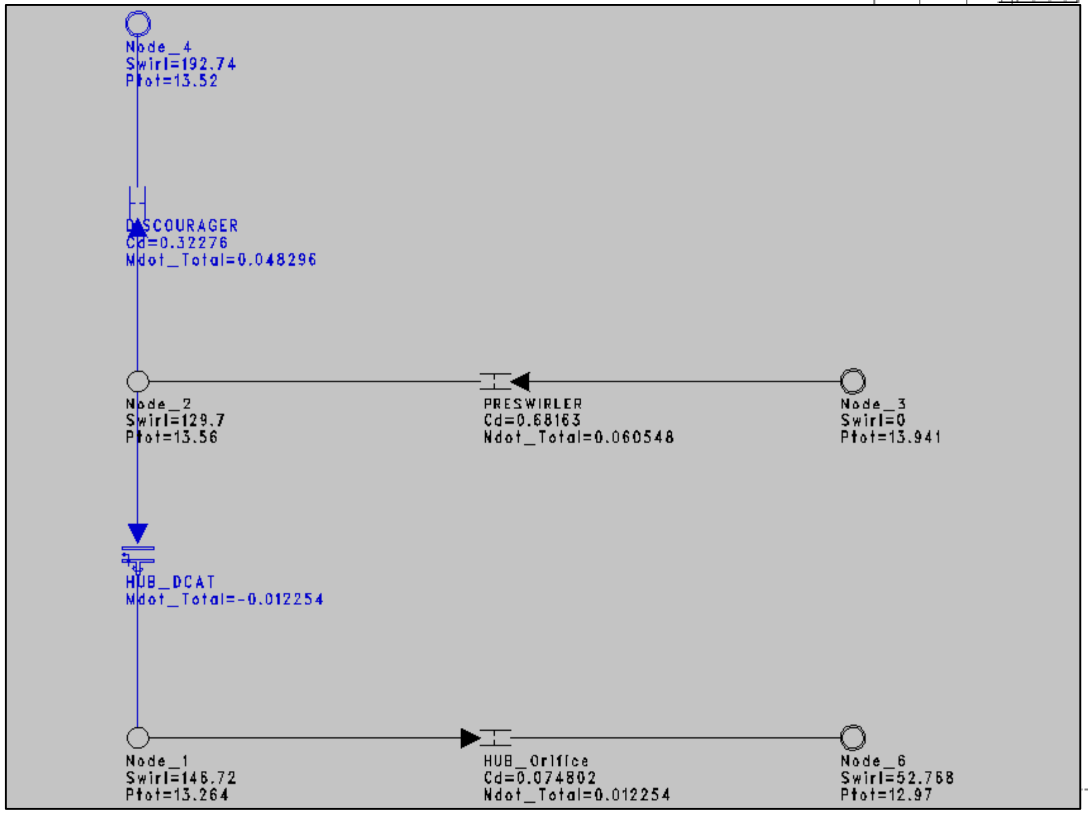
APPENDIX B

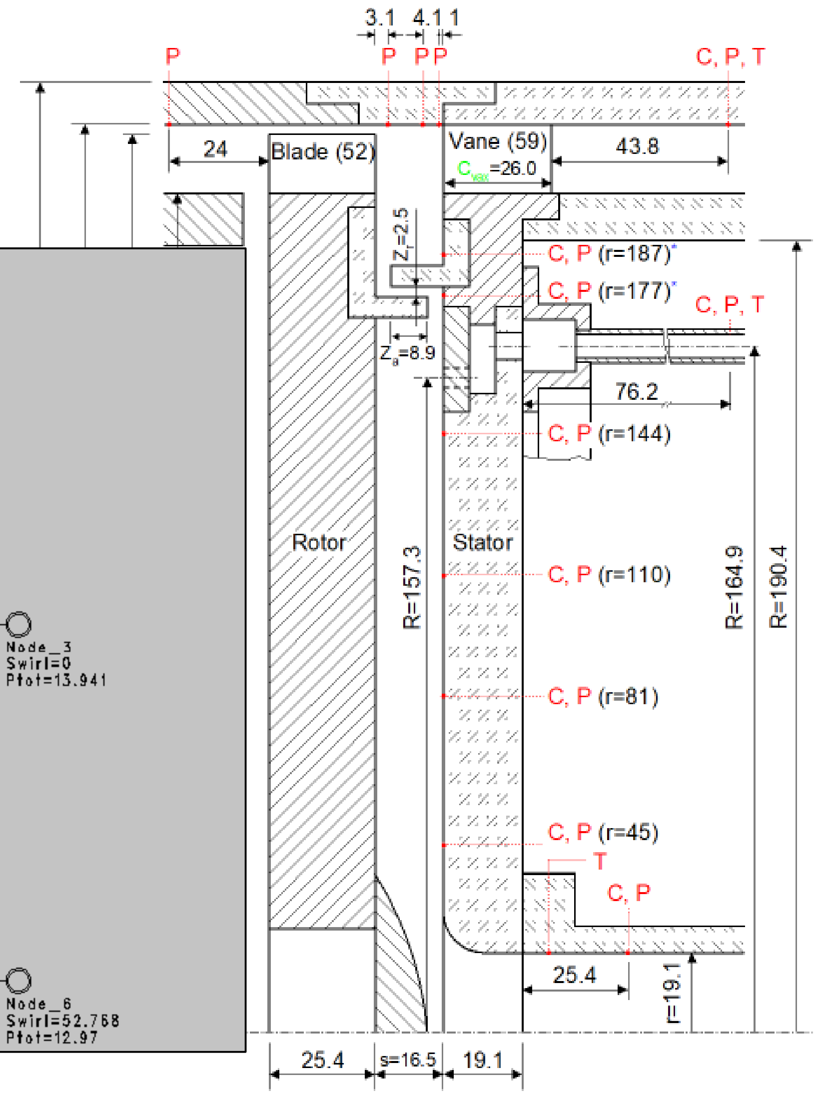
Set I - $Q_{hub\ exit}$ = 2.1 cfm

```
Pstat=            13.65 ,    Tin=  79.0  , Vt=  28.        2
Rotor     Sp        eed =    2600.0 Rpm
Stator    Sp        eed =    0.0 Rpm
flow r    ate              0 0239 Lbm/s
```

Rad	X	Gap	Dmr	Dms	Tmetd	Tmets	
5.67		0.1	0.65	1	1	82	82	1
4.33		0.1	0.65	1	1	82	82	2
3.19		0.1	0.65	1	1	82	82	3
1.77		0.1	0.65	1	1	82	82	4
1.49		0.1	0.4	1	1	82	82	5
1.04		0.1	0.4	1	1	82	82	6

```
Rad      Gap      Trel      Tmetd Tawd Tt  Taws  Tmets    Ps       Htcd  Vd    Vt    Vs    Htcs  Vrad Vrc  Qgen
in       in       F         F     F    F   F     F        (psia)   ft/s        ft/s  ft/s        ft/s ft/s Btu/s
5.670 0        0.650  80.   82.   80   .   79.   79  .  82.   13.65 16.6  128.6 28.2  0.0   6.2   0.2  0.2  0.0000
5.000 0        0.650  81.   82.   81   .   81.   81  .  82.   13.65 10.2  113.4 59.1  0.0   10.9  0.2  0.2  0.0011
4.330 0        0.650  82.   82.   82   .   82.   82  .  82.   13.64 9.0   98.2  52.1  0.0   9.9   0.3  0.3  0.0015
3.760 0        0.650  82.   82.   82   .   82.   82  .  82.   13.64 7.9   85.3  46.2  0.0   9.0   0.3  0.3  0.0018
3.190 0        0.650  82.   82.   82   .   82.   82  .  82.   13.63 6.7   72.4  40.9  0.0   8.2   0.4  0.4  0.0019
2.480 0        0.650  82.   82.   82   .   82.   82  .  82.   13.63 4.8   56.3  35.5  0.0   7.3   0.5  0.5  0.0019
1.770 0        0.650  82.   82.   82   .   82.   82  .  82.   13.62 2.0   40.2  32.9  0.0   6.9   0.7  0.7  0.0019
1.630 0        0.525  82.   82.   82   .   82.   82  .  82.   13.62 1.2   37.0  32.1  0.0   7.1   0.9  0.9  0.0019
```





* Circumferentially 5 locations over one vane pitch

All dimensions in mm

Preswirler Modeling & Adjustments

- Why model the preswirler?
  - to provide the correct inlet condition for the radial in-flow cavity (match conditions such as inlet swirl with a 10° shallow injection angle)
- How do we model the preswirler?
  - Need to adjust the *Cd* to match the measured flow rate in the rig *(Cd = Coefficient of Discharge)*

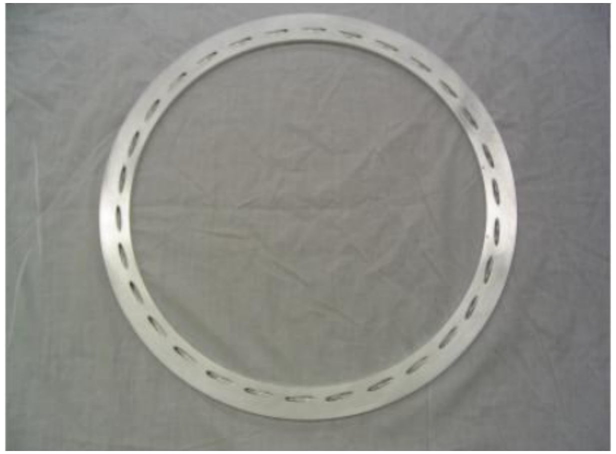
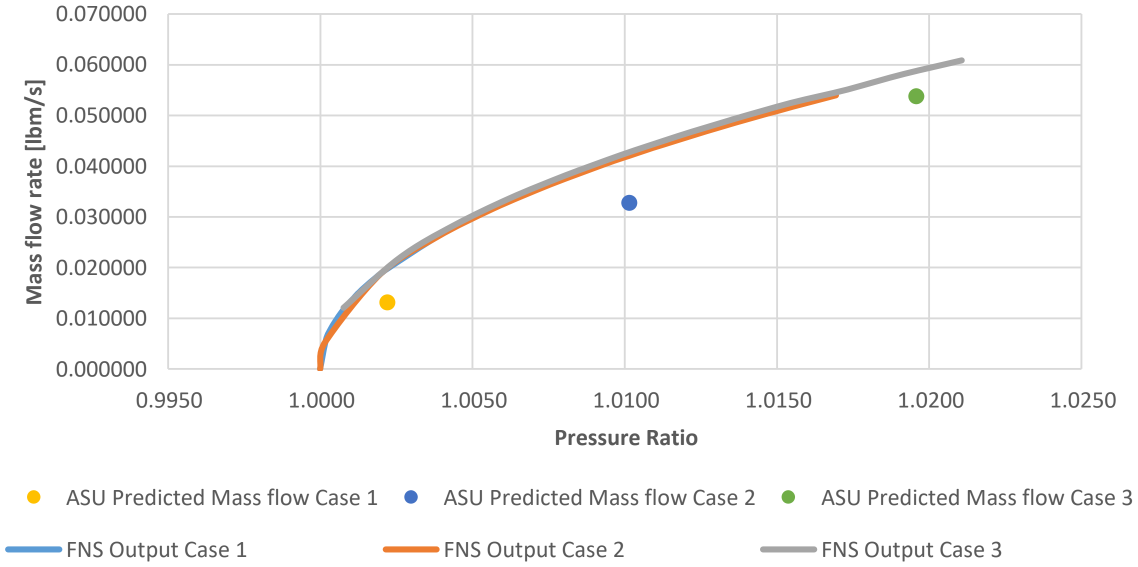


Fig. 8 Preswirler ring with shallow, discreet injection holes.



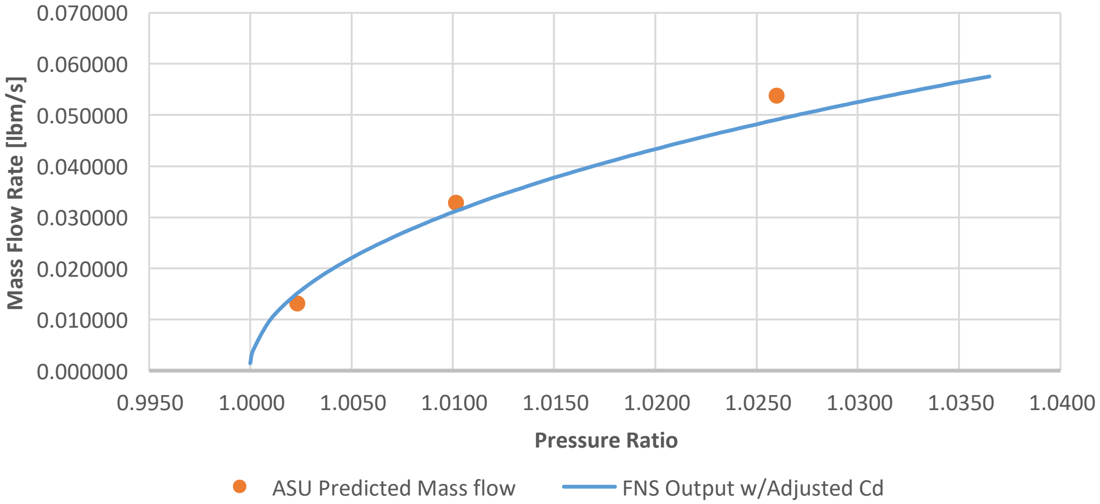
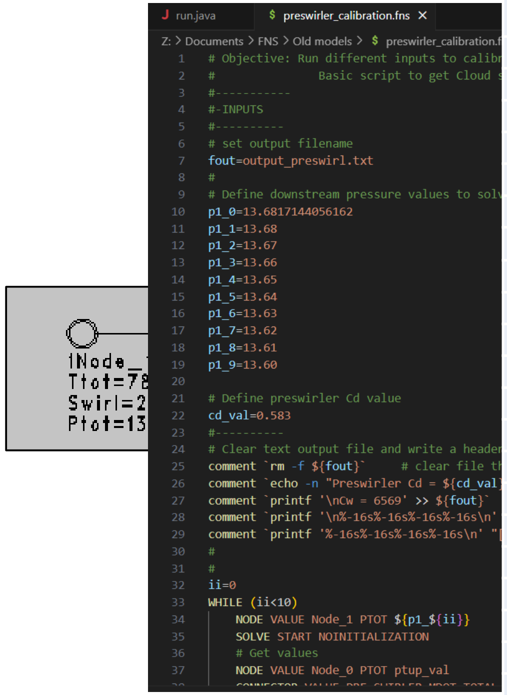


Fig. 9 The preswirler prediction for mass flow rate before and after adjusting the discharge coefficient.

Preswirler Discharge Coefficient Adjustment



Expt. Set 1: Test 1 | Cw = 1602, Cd = 0.583, PSE = 0.861

	Node 0 [psi]	Node 1 [psi]	P0/P1	mdot_tot [lbm/s]	Swirl [ft/s]
1	13.682	13.682	1.0000	0.0014	3.0704
2	13.682	13.680	1.0001	0.0038	8.1255
3	13.682	13.670	1.0009	0.0093	19.9058
4	13.682	13.660	1.0016	0.0125	26.9561
5	13.682	13.650	1.0023	0.0151	32.5146
6	13.682	13.640	1.0031	0.0173	37.2550
7	13.682	13.630	1.0038	0.0192	41.4589
8	13.682	13.620	1.0045	0.0210	45.2761
9	13.682	13.610	1.0053	0.0226	48.7974
10	13.682	13.600	1.0060	0.0241	52.0828
11	13.682	13.590	1.0067	0.0255	55.1744
12	13.682	13.580	1.0075	0.0269	58.1033
13	13.682	13.570	1.0082	0.0282	60.8930
14	13.682	13.560	1.0090	0.0294	63.5616
15	13.682	13.550	1.0097	0.0306	66.1240
16	13.682	13.540	1.0105	0.0317	68.5920
17	13.682	13.530	1.0112	0.0328	70.9755
18	13.682	13.520	1.0120	0.0338	73.2827
19	13.682	13.510	1.0127	0.0348	75.5205
20	13.682	13.500	1.0135	0.0358	77.6951
21	13.682	13.490	1.0142	0.0368	79.8116
22	13.682	13.480	1.0150	0.0377	81.8745
23	13.682	13.470	1.0157	0.0386	83.8877
24	13.682	13.460	1.0165	0.0395	85.8547
25	13.682	13.450	1.0172	0.0403	87.7787

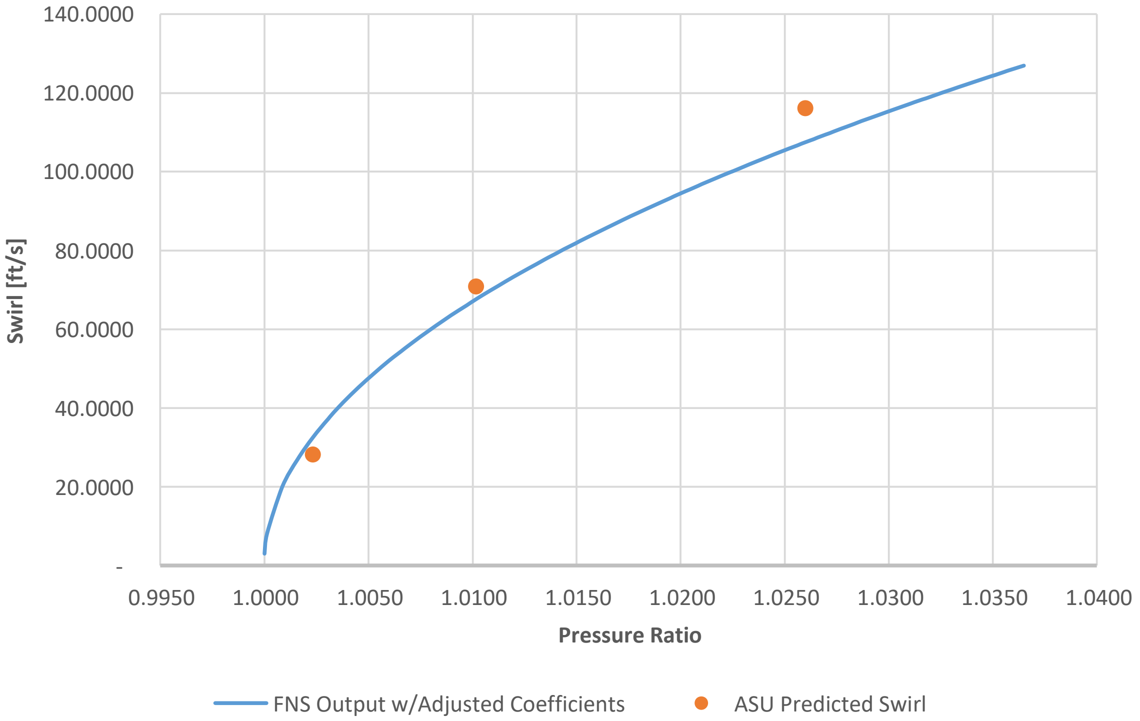
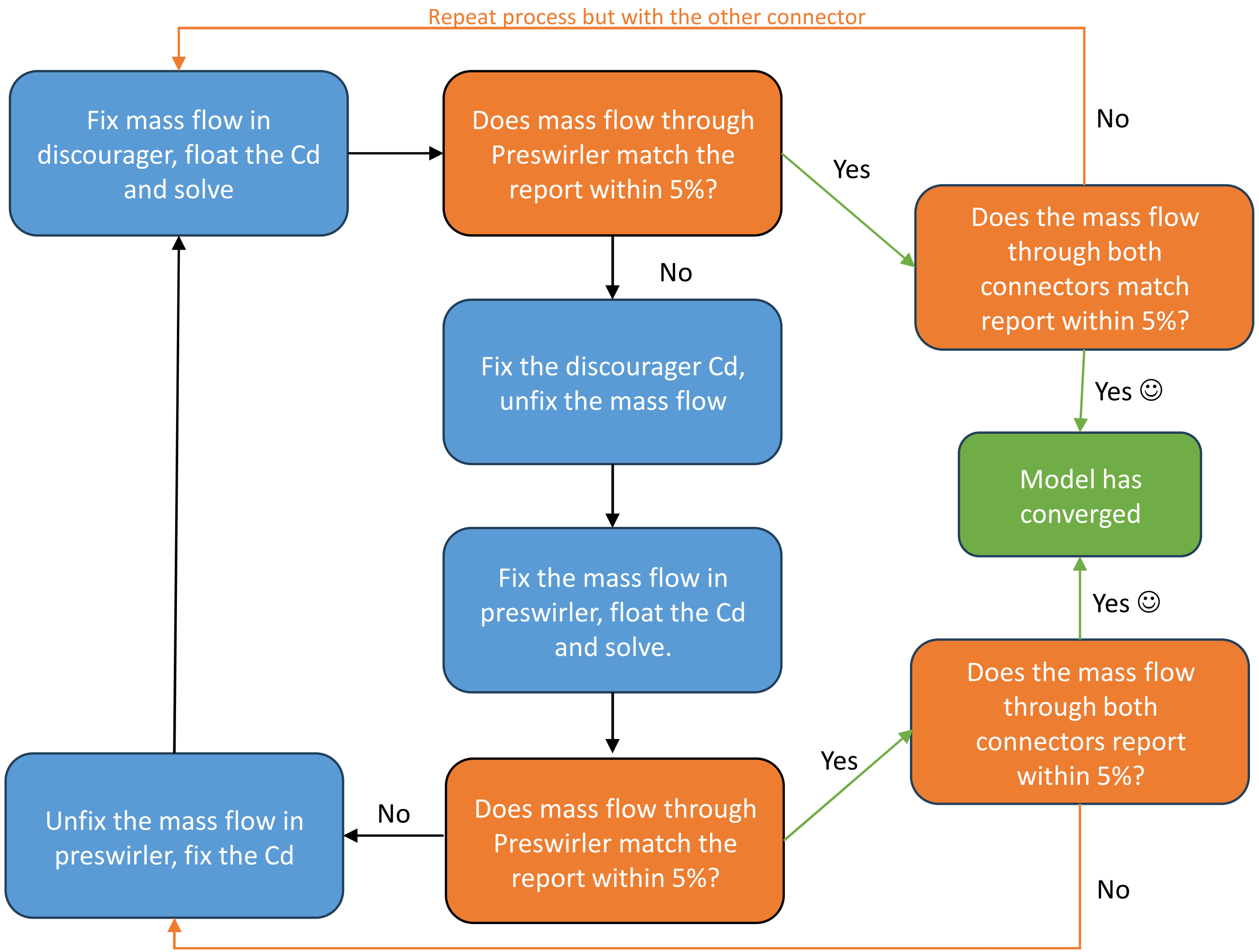


Fig. 11 The tangential velocity exiting the preswirler after adjusting the discharge coefficient and preswirler effectiveness.

Mass Flow Balancing to Match Rig Flow Rates



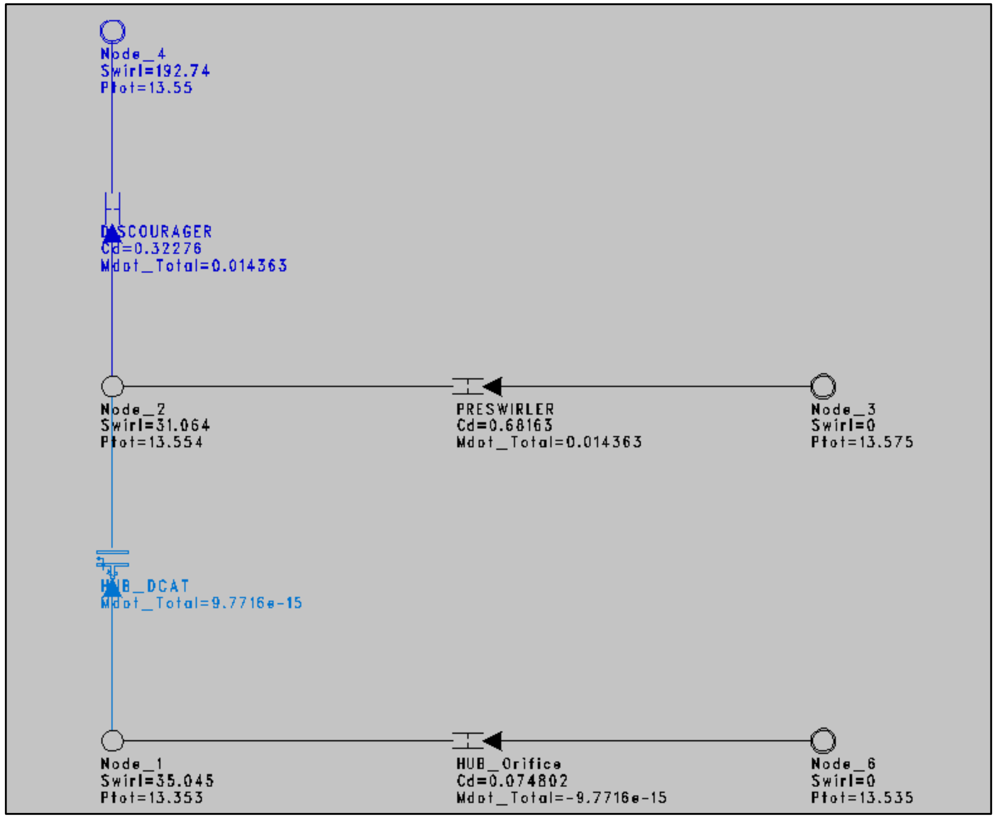
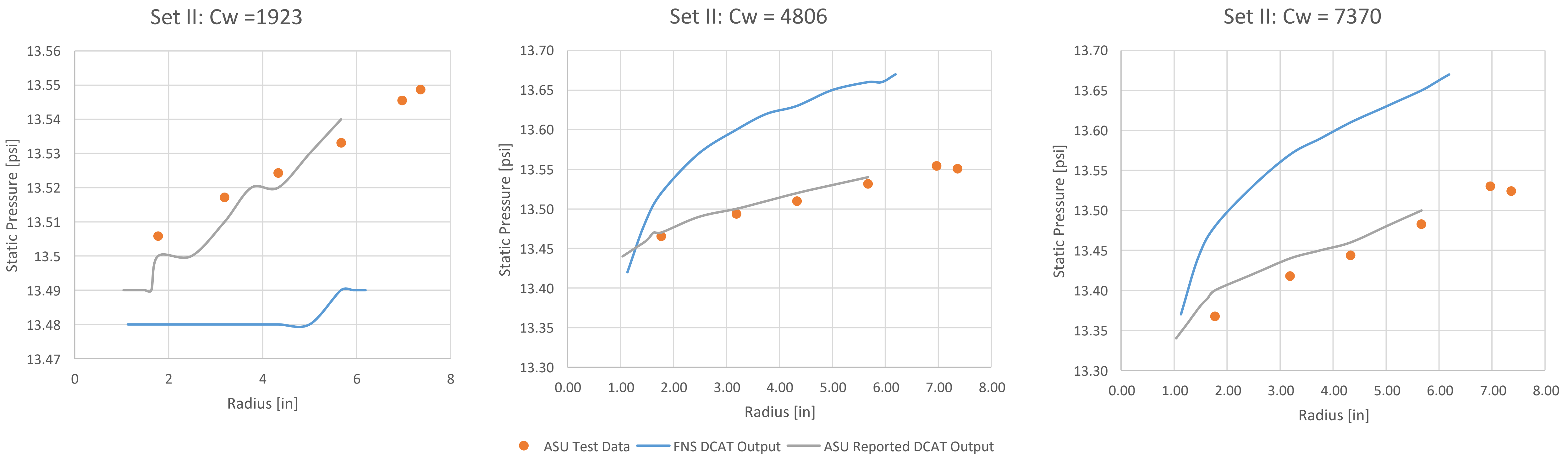


Fig. 13 The current model with unresolved mass flow through the DCAT for the lowest flow rate case.

Mass flow predictions

$$c_w = \frac{\dot{m}_{air}}{\mu b}$$

Cw = nondimensionalized flow rate
b = rotor disk outer radius



At this point . . . we were about halfway through my internship, and I had crashed enough FNS models and stumped Grant, so he sent me away to learn CFD while we contemplated the inaccuracies of my FNS model.

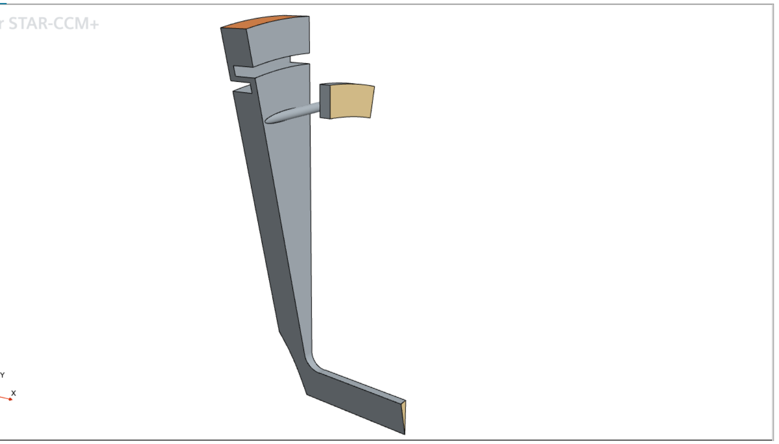
AGENDA

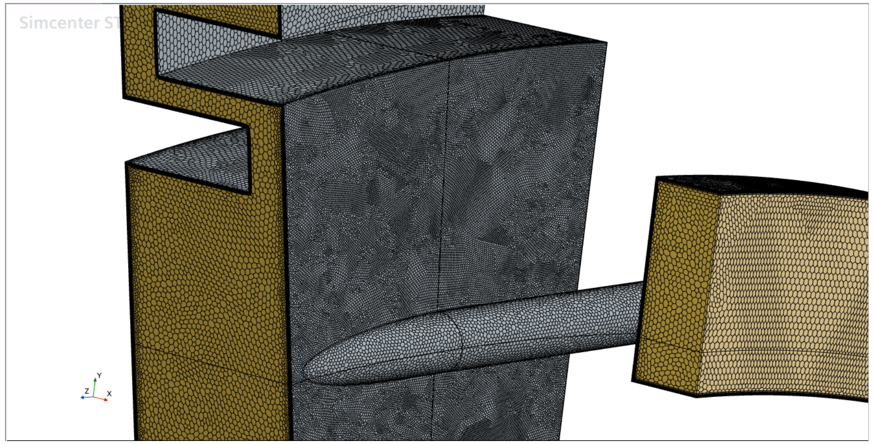
1. About me & Background
2. Projects
   - ASU DCAT Modeling in Finesse
   - CFD Analysis
     - Complete STARCCM+ training
     - Construct geometry from schematic
     - Mesh refinement study
     - Run CFD and postprocess
3. Takeaways
4. Solar Summer
5. Acknowledgements

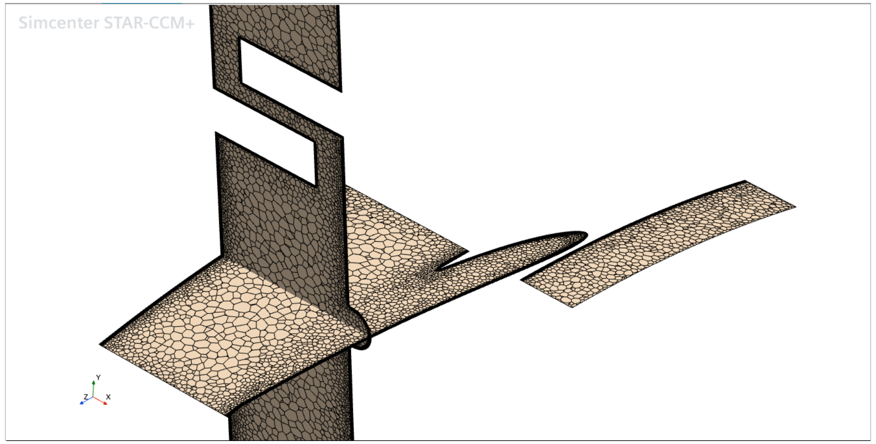
CFD Analysis

First Steps:

- Complete the STAR-CCM+ training manual
  - By itself was somewhat of a challenge due to having 19.02 which was incompatible with the HPC







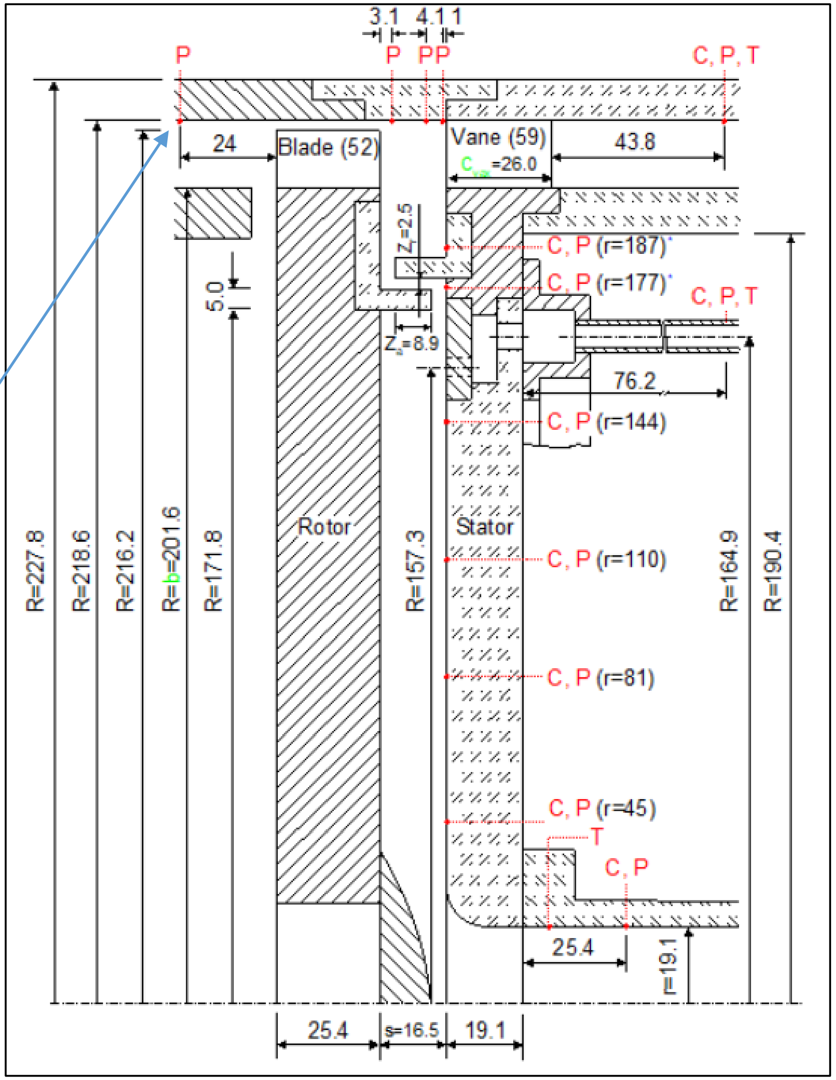
Boundary Conditions

- Boundary conditions are extracted from tables within the ASU Rig report
- Purge is a mass flow inlet, mainstream is a pressure outlet
- Hub outlet is a mass flow inlet to fully control the mass flow through the cavity

Static pressure measurements in Solar test rig, single rim seal

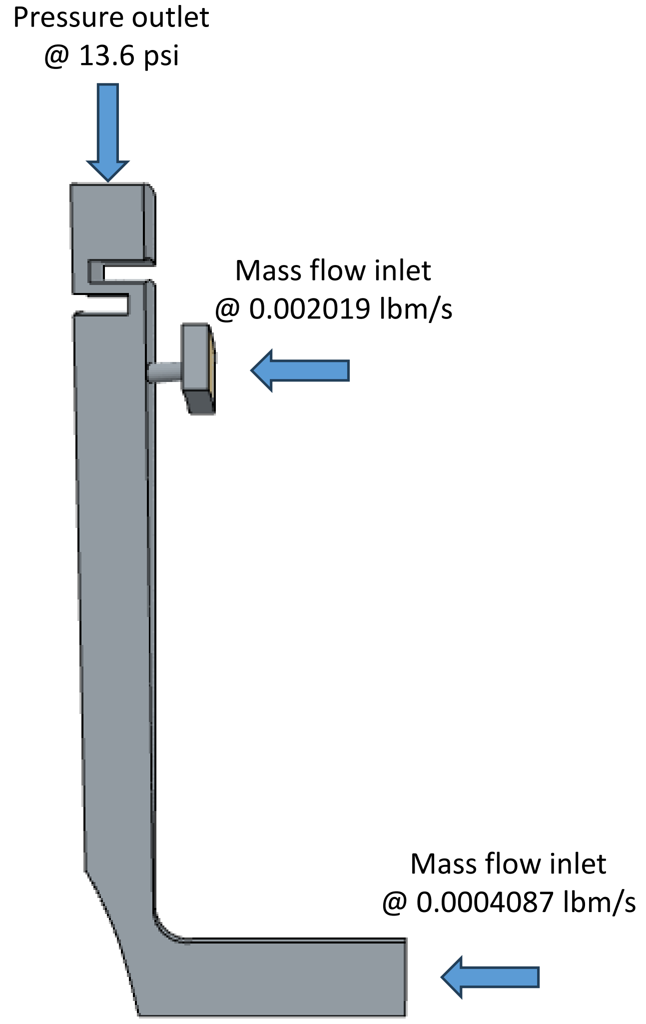
Date: 02/11/05 Expt. No. P-05-006

Lab ambient pressure	0.974 bar
Rotor speed	3000 rpm ($Re_\phi = 8.74\times10^5$)
Main air flow rate	1900 cfm ($Re_{vax} = 7.11\times10^4$)
Purge air flow rate	**46cfm ($c_w = 7370$)**
Radial exit flow rate	36.7cfm
Hub exit flow rate	9.3 cfm
Main air inlet pressure	-1347.9Pa
Main air inlet temperature	25.8°C (78.4°F)
Purge air inlet pressure	-1278.3 Pa
Purge air inlet temperature	27.3°C (81.2°F)
Hub exit pressure	-6429.9 Pa
Hub exit temperature	27.7°C (81.9°F)
Static gage pressure 24mm downstream of rotor blade	-4033.4 Pa



Boundary Conditions

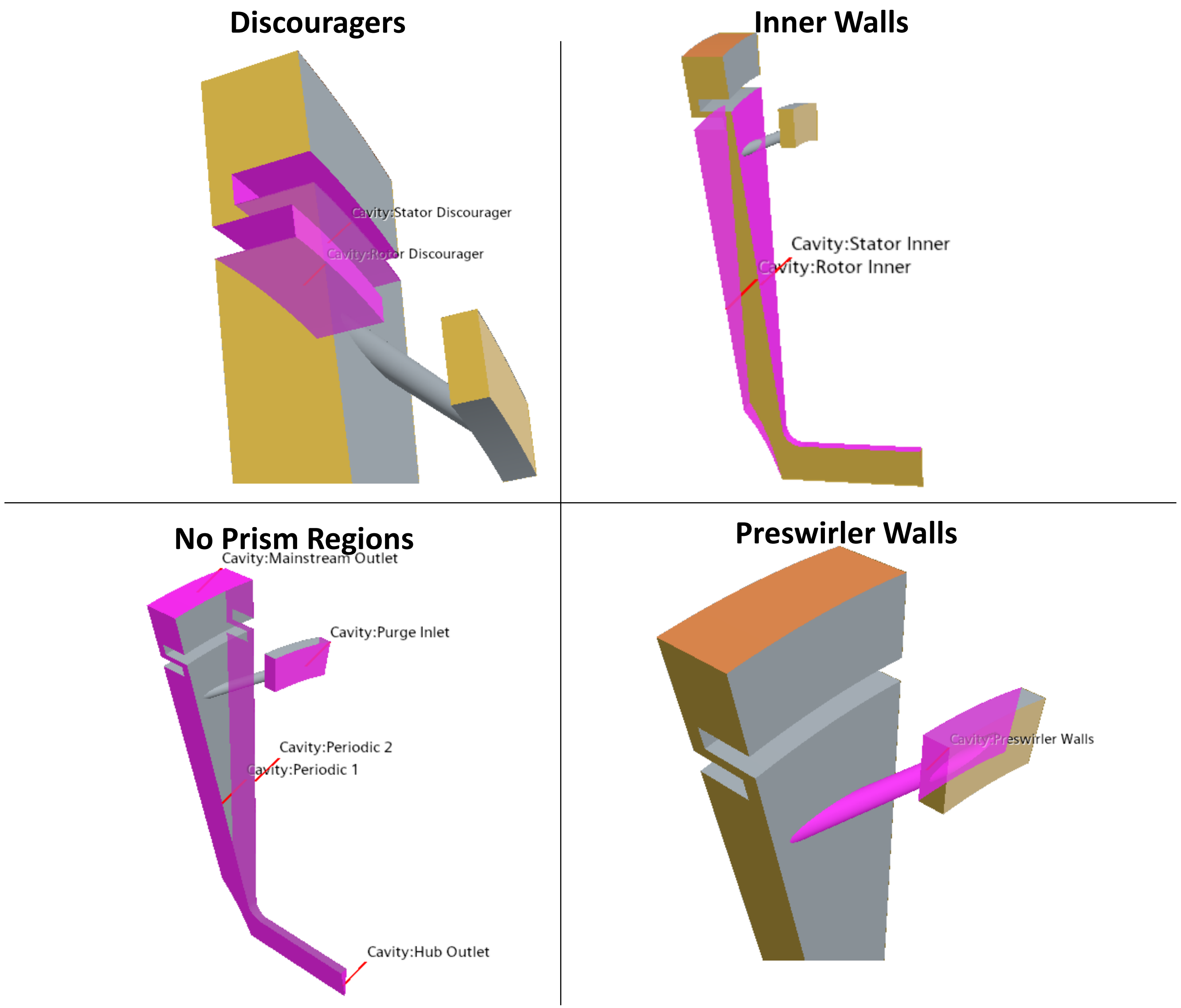
GP Speed = 3000 rpm
Purge $\dot{m}_{total}$ = 0.06058 lbm/s



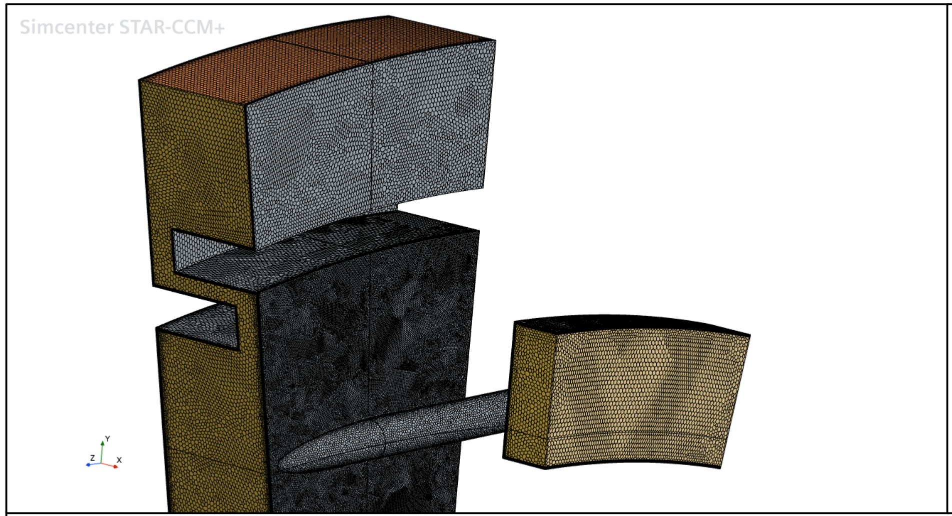
Mesh Sizing

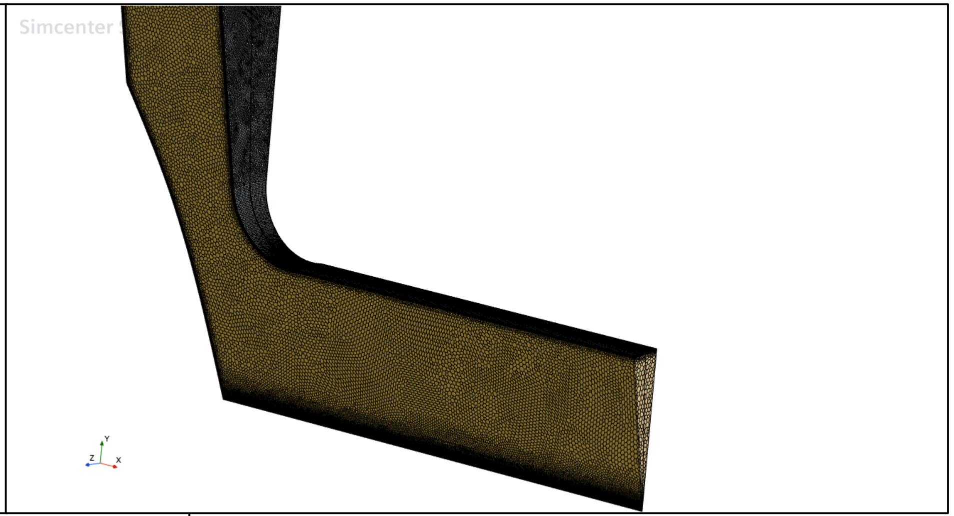
Mesh Custom Controls

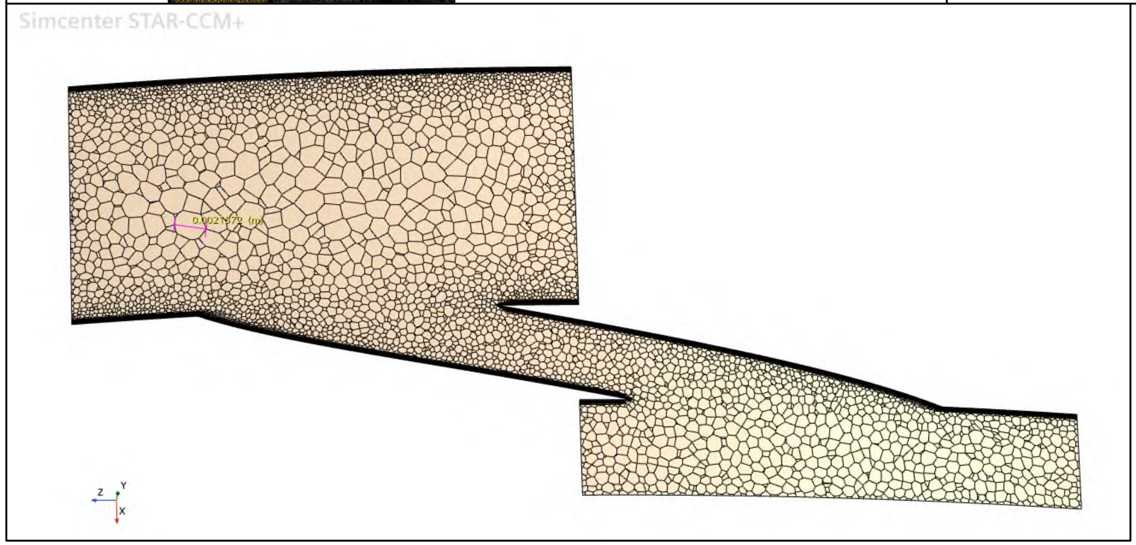
	Target Surface Size	Number of Prism Layers	Minimum Surface Size
Discourager	50%	12	10%
Inner Walls (rotor and stator inner walls	20%	16	10%
No Prism (periodic surfaces, inlets, outlets)	100%	-	10%
Preswirler Walls	33.33%	12	10%



Mesh Sensitivity Study







Core region with cell size up to 2mm in diameter (200% base size, 400% target size)

Mesh Sensitivity Study

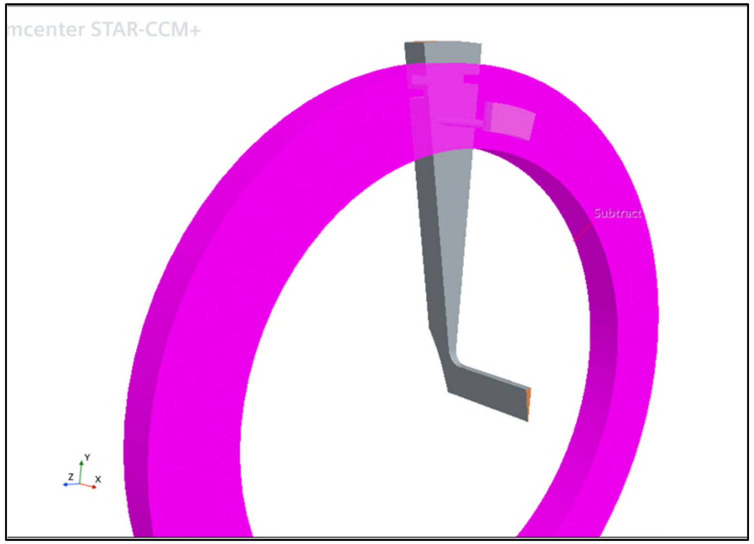
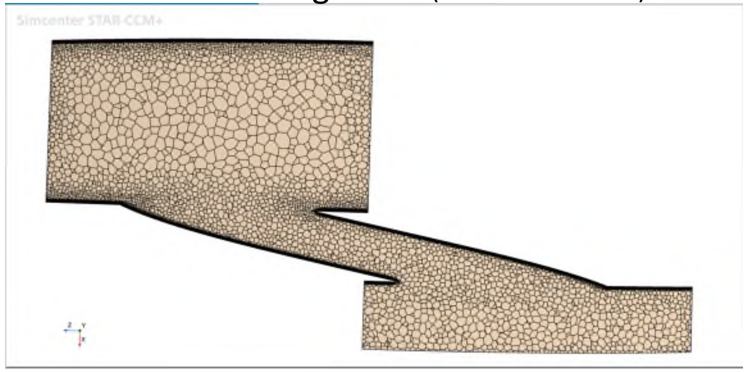
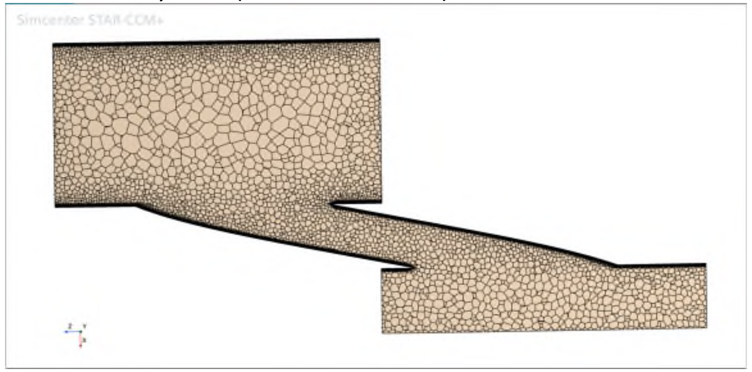


Fig. 24 Volume control focused on refining preswirler region

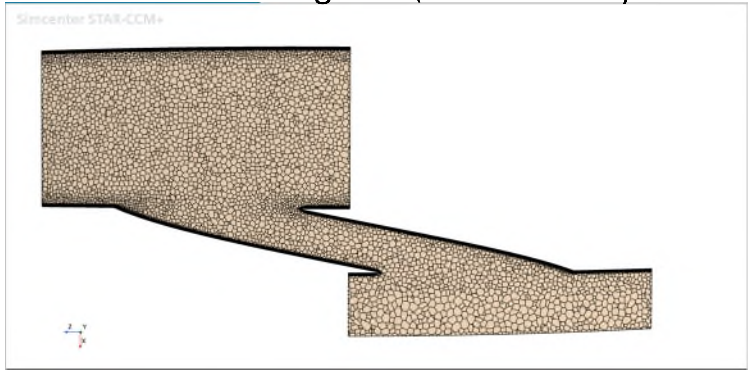
Volume control sizing 100% (4.56 million cells)



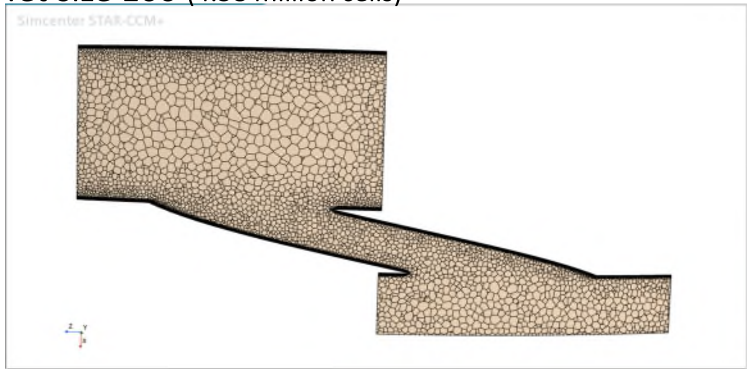
Tet size 10,000 (4.56 million cells)



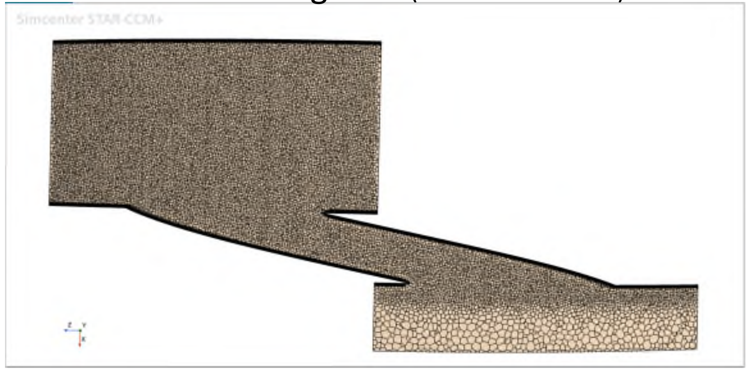
Volume control sizing 50% (4.67 million cells)



Tet size 100 (4.58 million cells)

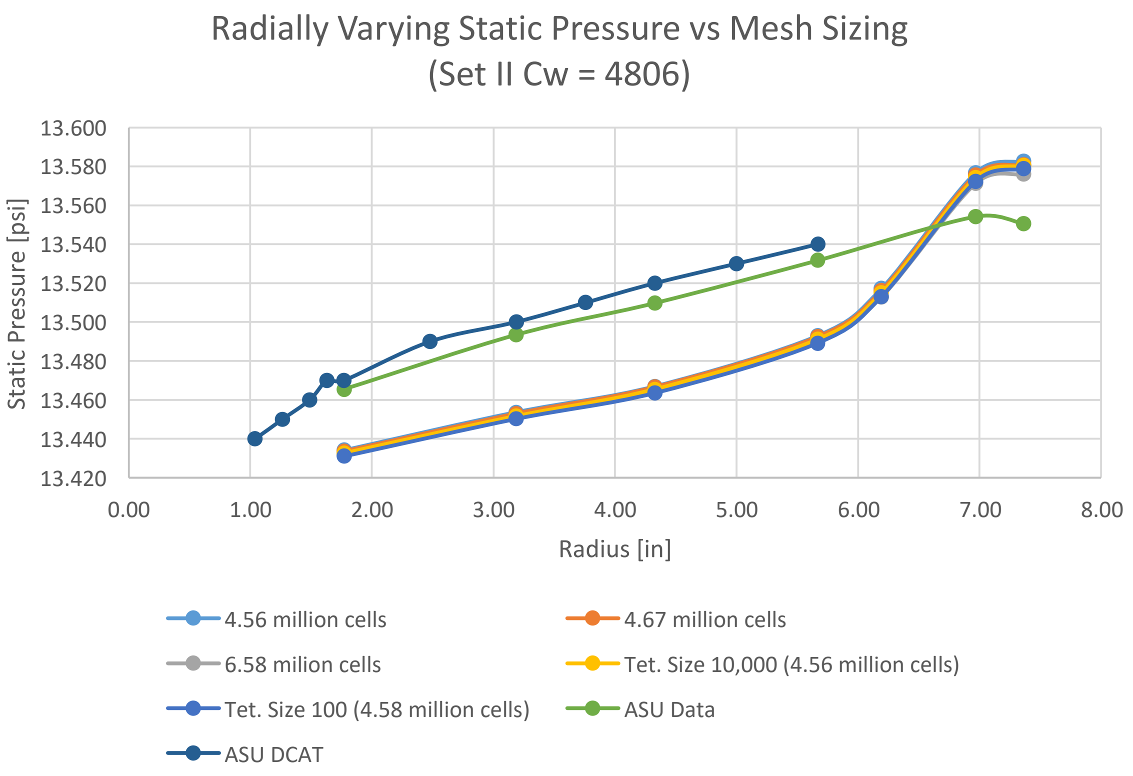


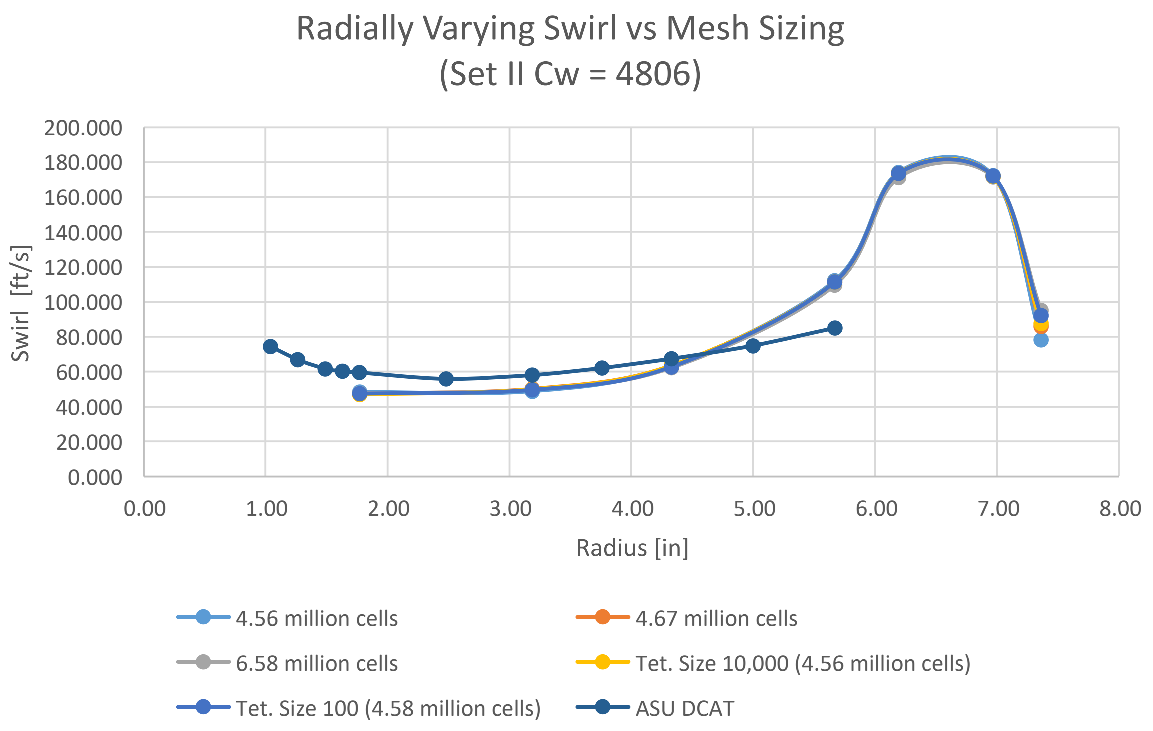
Volume control sizing 20% (6.58 million cells)



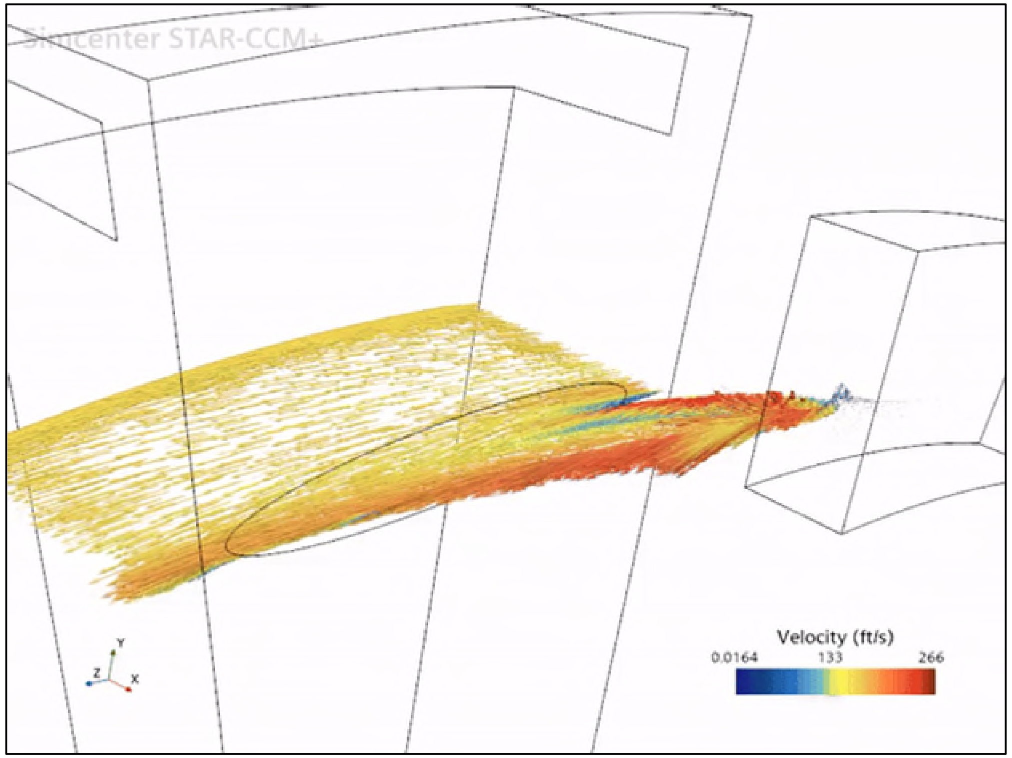
Mesh Sensitivity Study Results

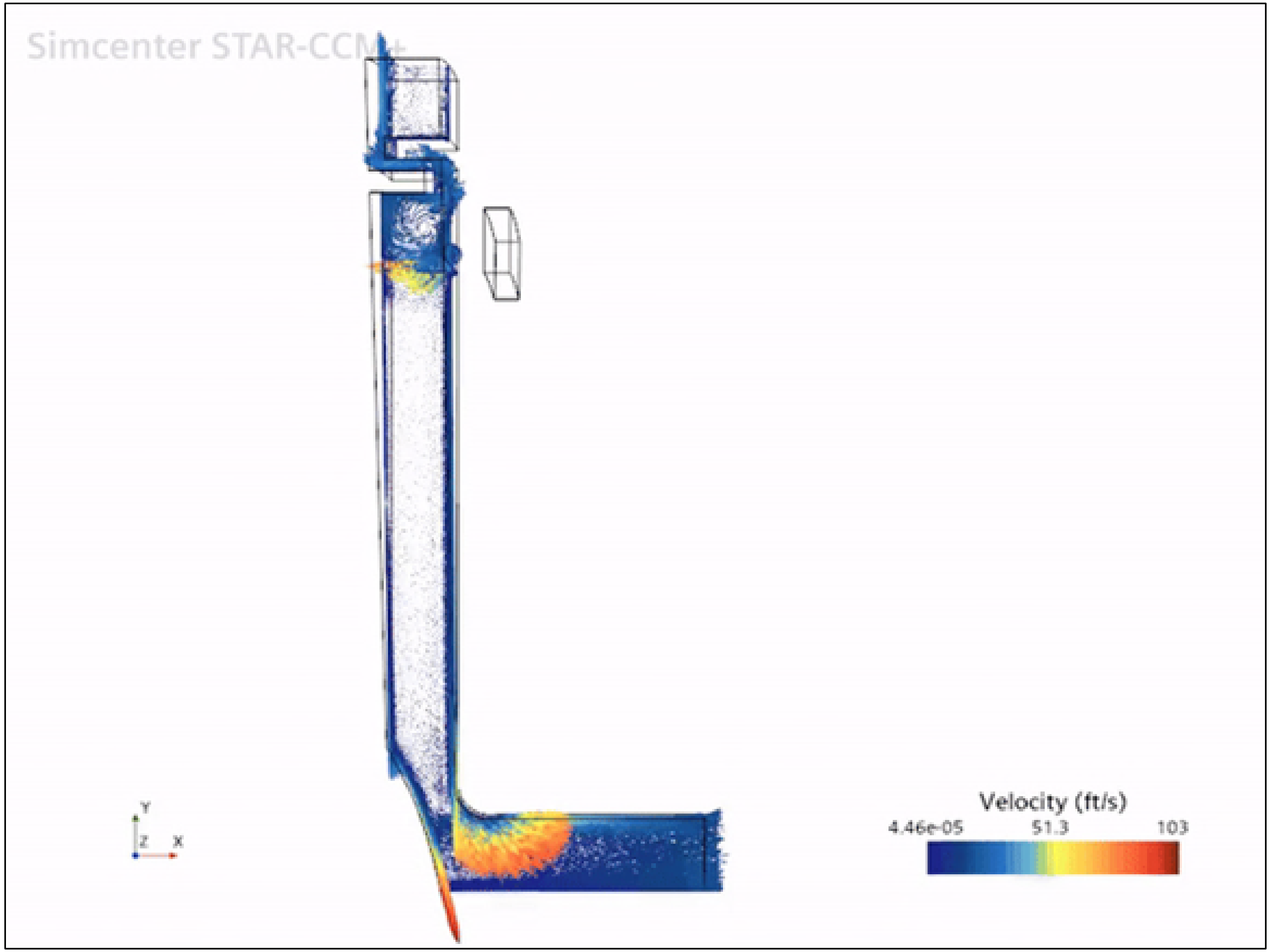
- The mesh is not an issue as all meshes produced pressures and swirls with percent differences below 0.05%
- The 100% Volume control mesh is selected to reduce computational power required to simulate the models



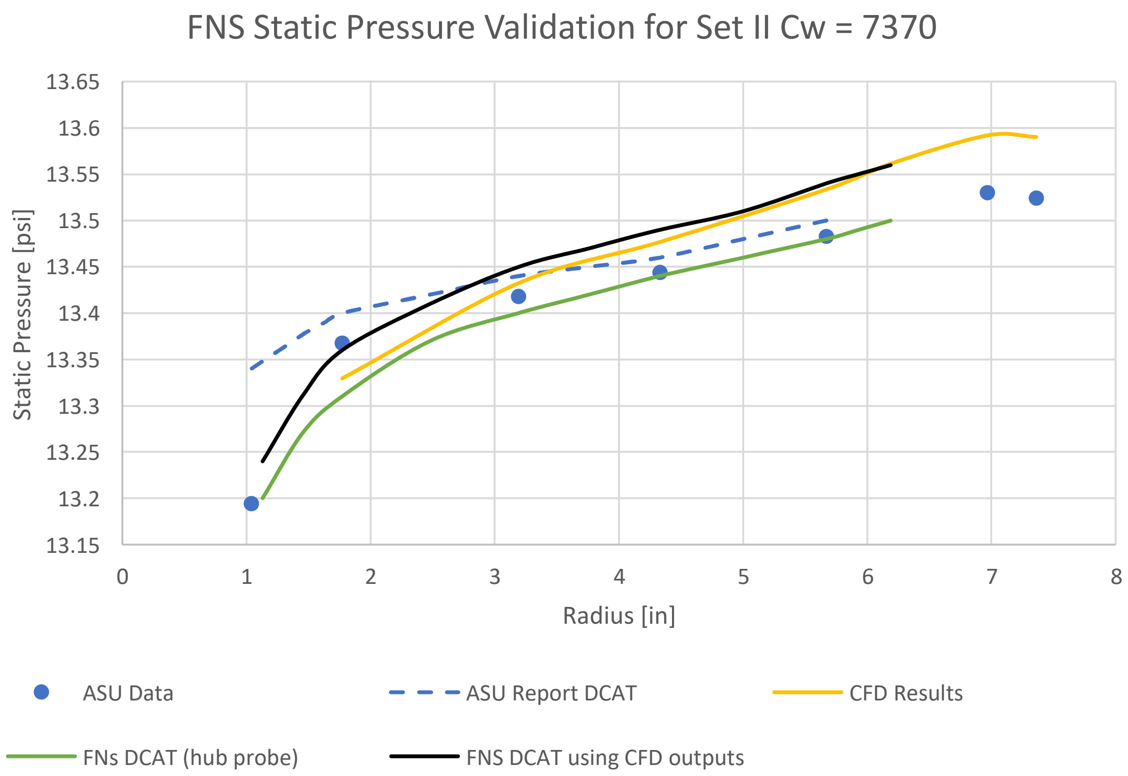


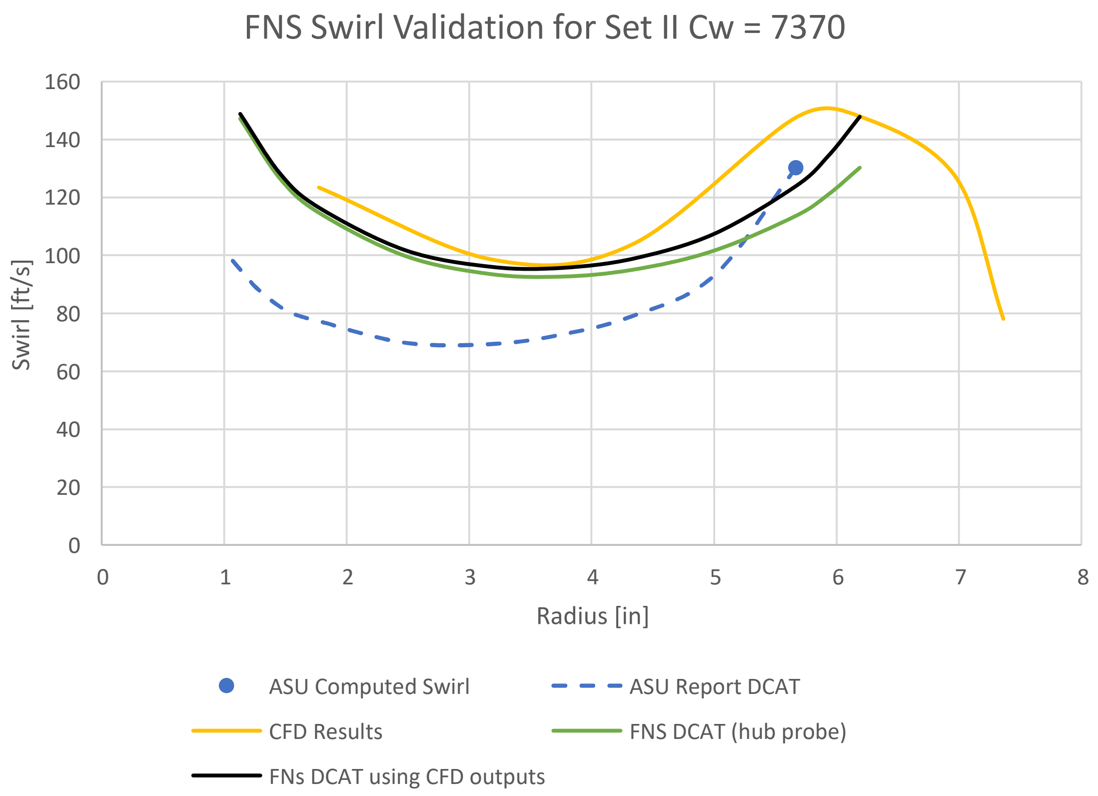
CFD Analysis





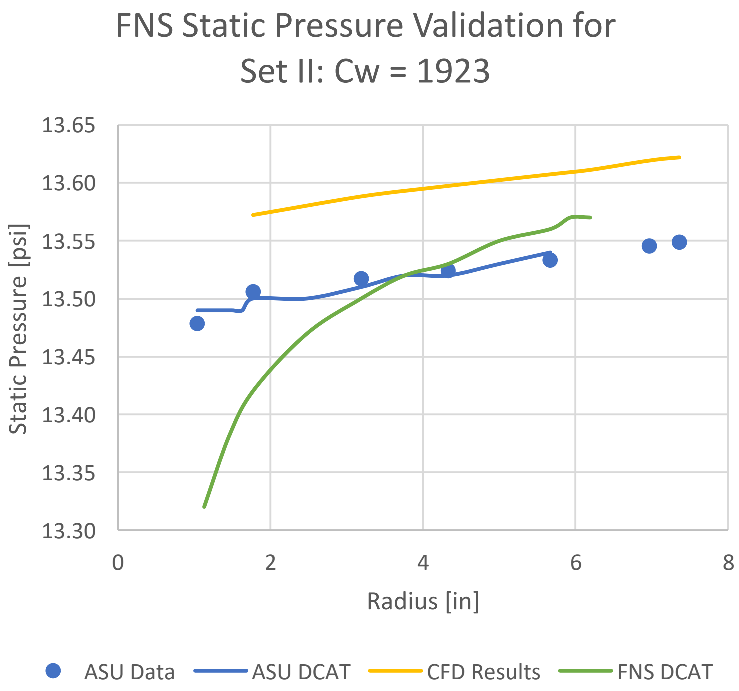
Back to Finesse



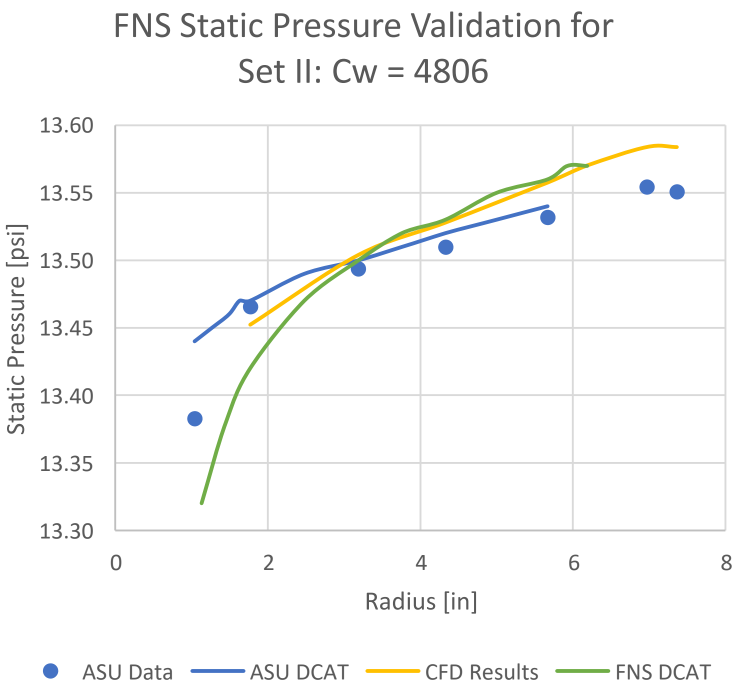


<u>What</u>: Let’s revisit FNS model
<u>Why</u>: figure out why the model doesn’t converge by comparing it to CFD results
<u>How</u>: plug CFD outputs (hub outlet pressure & swirl) and see how accurately they match

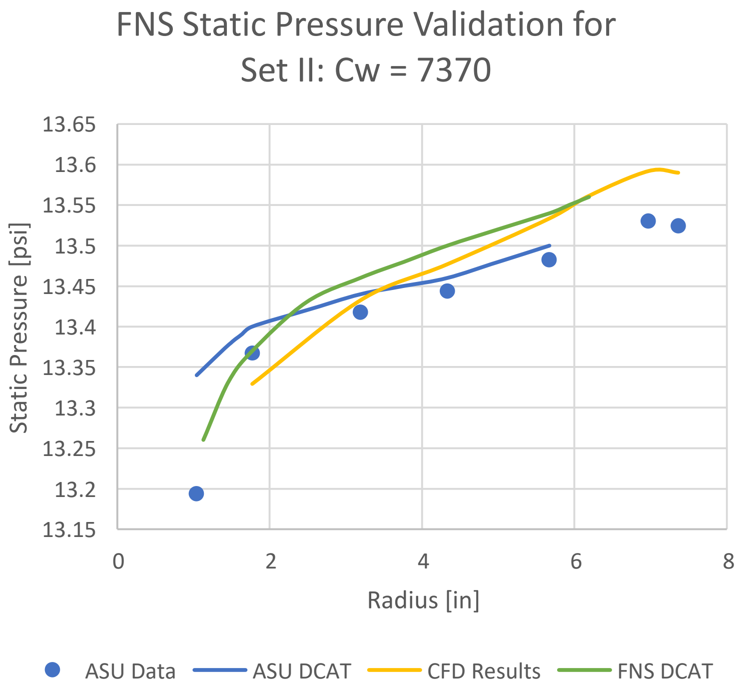
Results



FNS Static Pressure Validation for
Set II: Cw = 1923
Static Pressure [psi]
13.65
13.60
13.55
13.50
13.45
13.40
13.35
13.30
0
2
4
6
8
Radius [in]
ASU Data
ASU DCAT
CFD Results
FNS DCAT

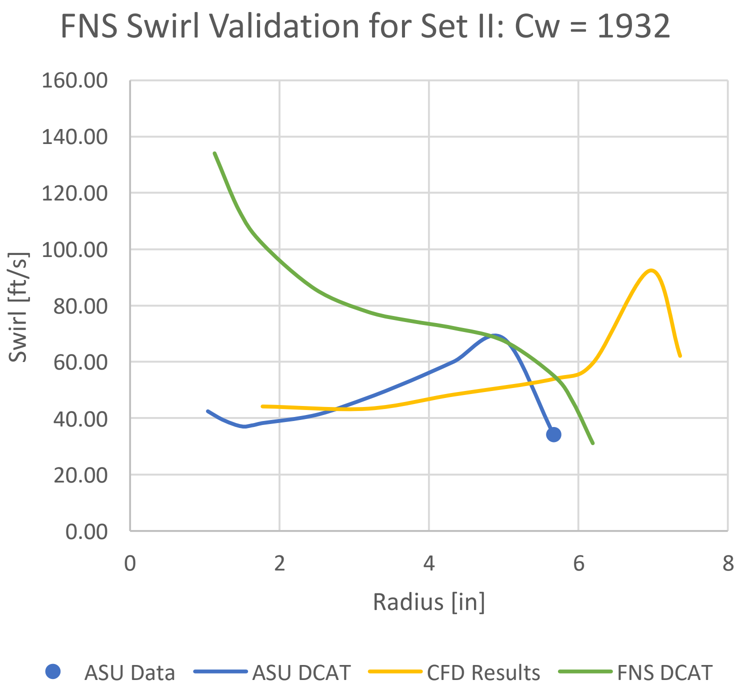


FNS Static Pressure Validation for
Set II: Cw = 4806
Static Pressure [psi]
13.60
13.55
13.50
13.45
13.40
13.35
13.30
0
2
4
6
8
Radius [in]
ASU Data
ASU DCAT
CFD Results
FNS DCAT

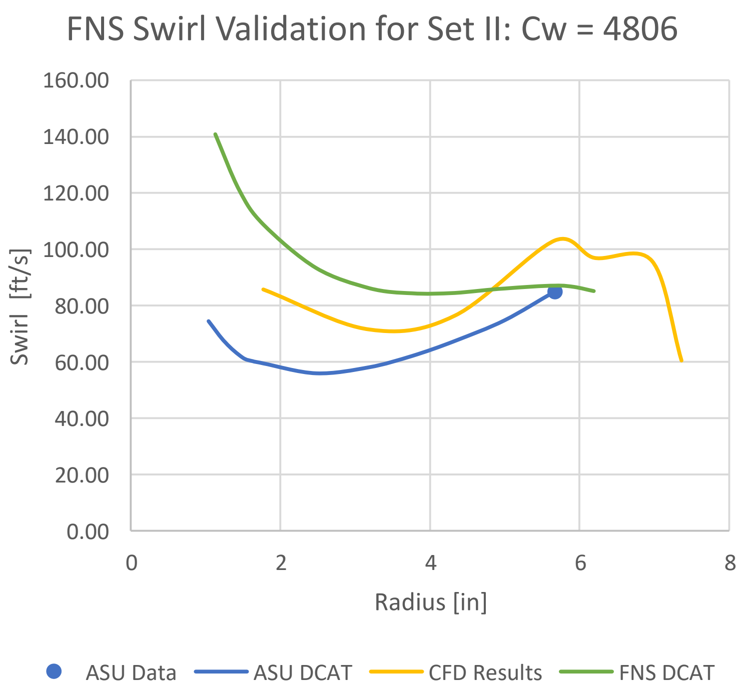


FNS Static Pressure Validation for
Set II: Cw = 7370
Static Pressure [psi]
13.65
13.6
13.55
13.5
13.45
13.4
13.35
13.3
13.25
13.2
13.15
0
2
4
6
8
Radius [in]
ASU Data
ASU DCAT
CFD Results
FNS DCAT

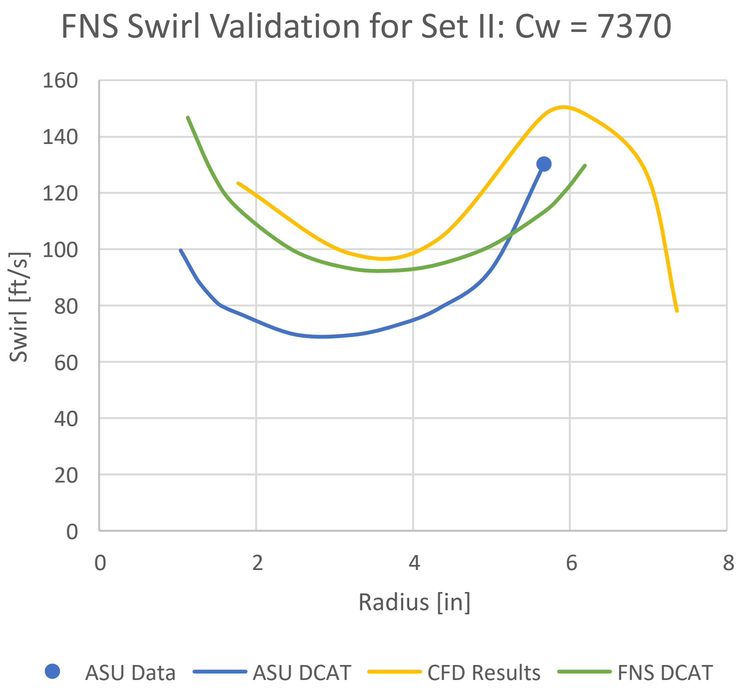
Results



FNS Swirl Validation for Set II: Cw = 1932
Swirl [ft/s]
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
2
4
6
8
Radius [in]
ASU Data
ASU DCAT
CFD Results
FNS DCAT



FNS Swirl Validation for Set II: Cw = 4806
Swirl [ft/s]
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
2
4
6
8
Radius [in]
ASU Data
ASU DCAT
CFD Results
FNS DCAT



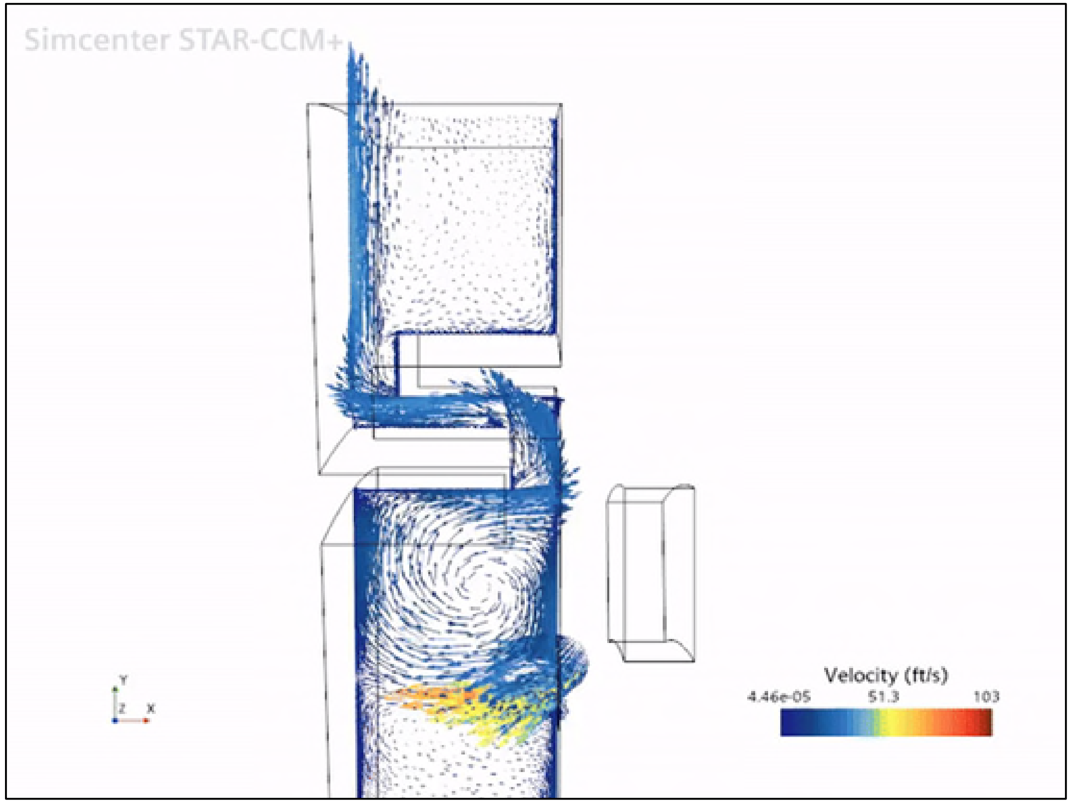
FNS Swirl Validation for Set II: Cw = 7370
Swirl [ft/s]
160
140
120
100
80
60
40
20
0
0
2
4
6
8
Radius [in]
ASU Data
ASU DCAT
CFD Results
FNS DCAT

AGENDA

1. About me & Background
2. Projects
   - ASU DCAT Modeling in Finesse
   - Preswirler Calibration
   - CFD Analysis
   - Results
3. Takeaways
4. Solar Summer
5. Acknowledgements

Takeaways

- Uncertainty in the ASU reported pressures and lack of information near the preswirler makes it difficult to accurately model
- Low flow cases need to be investigated more to understand underlying issues regarding convergence and mass flow
- FNS's DCAT connector tends to under predict static pressure at radially inboard locations, and over predict at radially outboard locations
- FNS's DCAT connector generally is over predicting swirl radially inboard of the preswirler.



Personal takeaways:

- You can never check enough times your BCs and calculations
- You must prioritize your own growth by not being afraid to ask questions (even if you think they're not worth ask)

Recommendations

- Continue the investigation of low flow cases and achieve some convergence to be compared with each case to verify whether the discrepancies are real or mistakes in the design of model
- Run the higher flow test cases to see if the trend extends (we expect that with higher flow rates that FNS DCAT becomes more accurate with less convergence issues
- Run a similar study on a different geometry (preferably a real geometry)

AGENDA

1. About me & Background
2. Projects
   - ASU DCAT Modeling in Finesse
   - Preswirler Calibration
   - CFD Analysis
   - Results
3. Takeaways
4. Solar Summer
5. Acknowledgements

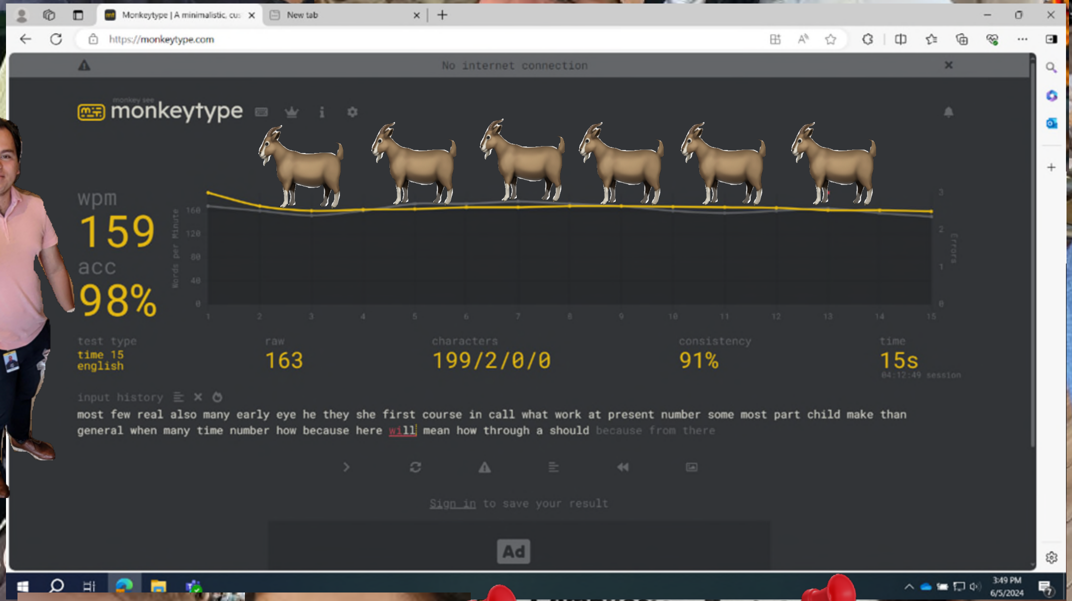

eal T250 compared to cloud


Interns working hard
So locked in


8-3 btw
L Padres


Ana
Eoin
Ashley
Anusha
Jehimi
Sunmerry Bakery
after first KM visit


DRY CLEANING
#1 Ice cream in the
U.S. An's Gelato


monkeytype
wpm
159
acc
98%
test type
time 15
english
raw
163
characters
199/2/0/0
consistency
91%
time
15s
input history
most few real also many early eye he they she first course in call what work at present number some most part child make than
general when many time number how because here will mean how through a should because from there
Sign in to save your result
Ad


FOGO DE CHAO SPOTTED


Combustion Test Center
THE T350!!
:OOO

AGENDA

1. About me & Background
2. Projects
   - ASU DCAT Modeling in Finesse
   - Preswirler Calibration
   - CFD Analysis
   - Results
3. Takeaways
4. Solar Summer
5. Acknowledgements

THANK YOU

Solar Turbines
A Caterpillar Company

Heat Transfer

Yong Kim
Grant Musgrove
Hans Hamm
James Chang
Hasan Nasir

Management

Geoffrey Potts
Michael Fox
Miller Robison

IT Support

Edward Gonzales
Aidan Kelly

UTSR & SDSU

Gustaaf Jacobs
Dorothea Martinez

Intern Coordinators

Aadit Pujara
John Strollo
Garret Herbst
Alison Ramsland

Interns

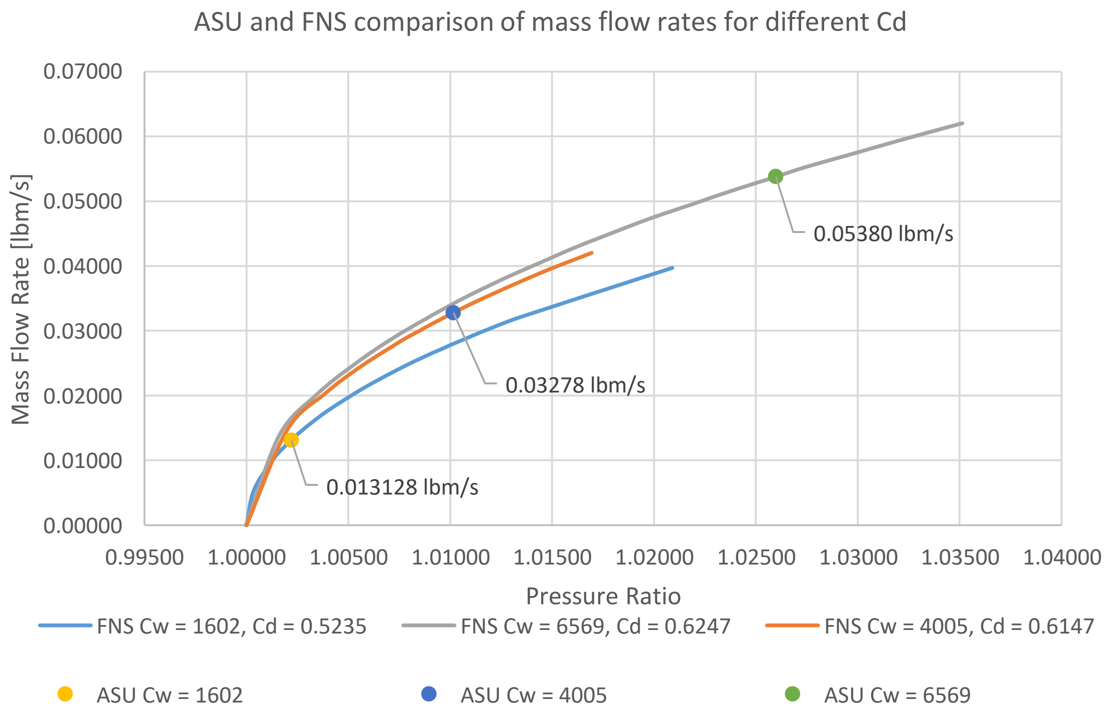
Kingsley Essuman Atomboh
Jazmine Blanchard
Ashley Campbell
Miro Garrett
Juan Felipe Guevara
Anusha Gupta
Malcolm Overbaugh
Eoin Lenham
Anders Liesse
Ana Strahm
Christina Sturgeon
Edward Wang
Jehimi Zuniga-Umana

Q & A

Solar Turbines
A Caterpillar Company

Backup Slides

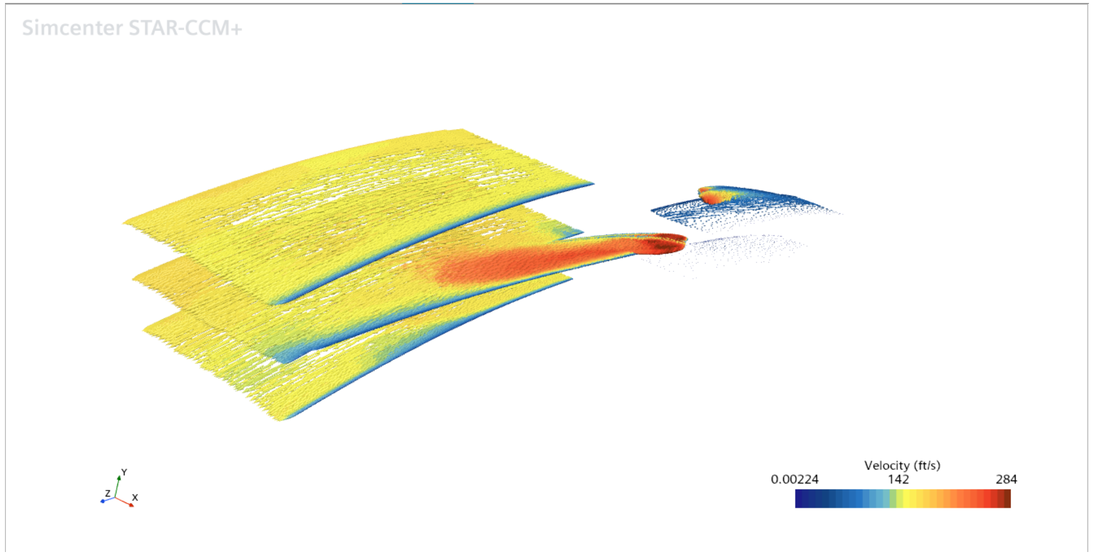
Preswirler Calibration

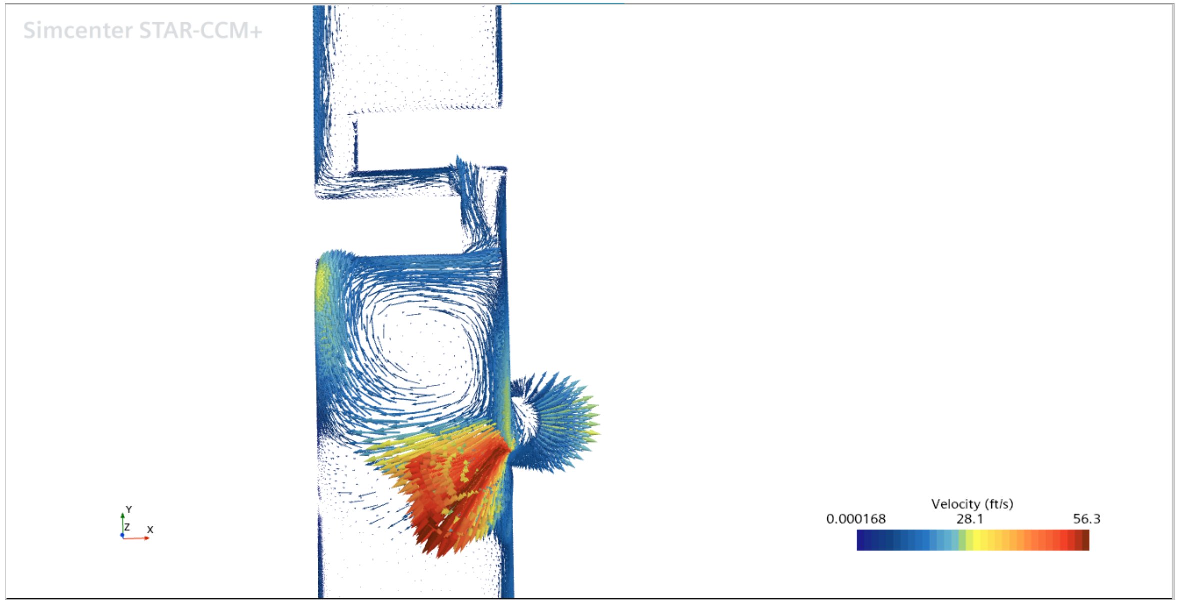


Average			ASU			Middle	
mdot	swirl		mdot	swirl		mdot	swirl
0.01510	32.5146		0.013127	28.22		0.01592	34.1633
0.03167	68.5920		0.032775	70.87		0.0334	72.0703
0.04945	108.2949		0.053800	116.14		0.05214	113.7865
Error						Error	
15.03	15.2387					21.2747147	21.08205
3.37	3.2089					1.90707391	1.699405
8.09	6.7557					3.08531226	2.027277
26.48	25.2032					26.2671008	24.80873

The calibrated pre-swirler uses a Cd and PSE that is actually the average between the Cd and PSE that perfectly match each flow rate. i.e. for Cw = 1602, the ideal Cd = 0.5068, and for higher Cw, the Cd and PSE is also higher. There could be an argument made to just use the Cd and PSE from the middle test case, and upon checking the percent difference, it is only about 2% better than using the average. So, it won't matter too much which one you choose to use.

CFD Blunder





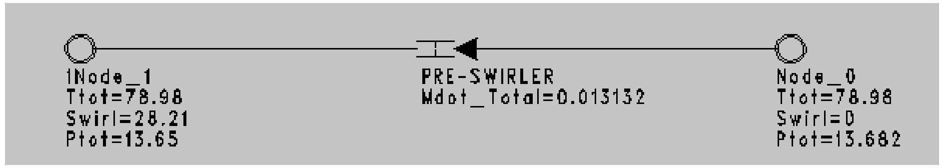
One issue I encountered while running the simulations is that my results showed a huge spike in the preswirler exit velocity—nearly twice the expected value.

It turns out it was injecting the swirl from a rotating frame of reference, essentially adding more swirl to an already high velocity swirling fluid and increasing the relative total pressure instead of being added from the lab frame to reduce the relative total as much as possible.

Preswirler Modeling

- The current model had difficulty converging as the mass flow reported by ASU were simply not achievable through each branch of the model
  - Test and calibrate the pre-swirler for one set of data to check if that was an issue

- Use the reported data and calibrate an isolated preswirler to calibrate a Cd and pre-swirler effectiveness
  - Then using one pre-swirler configuration, apply to each test case



Additional issues encountered: Even after we determine the necessary coefficients, the pressure at the exit node was highly influenced by the rest of the model. ASU did not have experimental data of the pressure at that location (r = 157.3 mm) so while the effectiveness remained, the flow rate was subject to change as other parts changed and was later recalibrated.

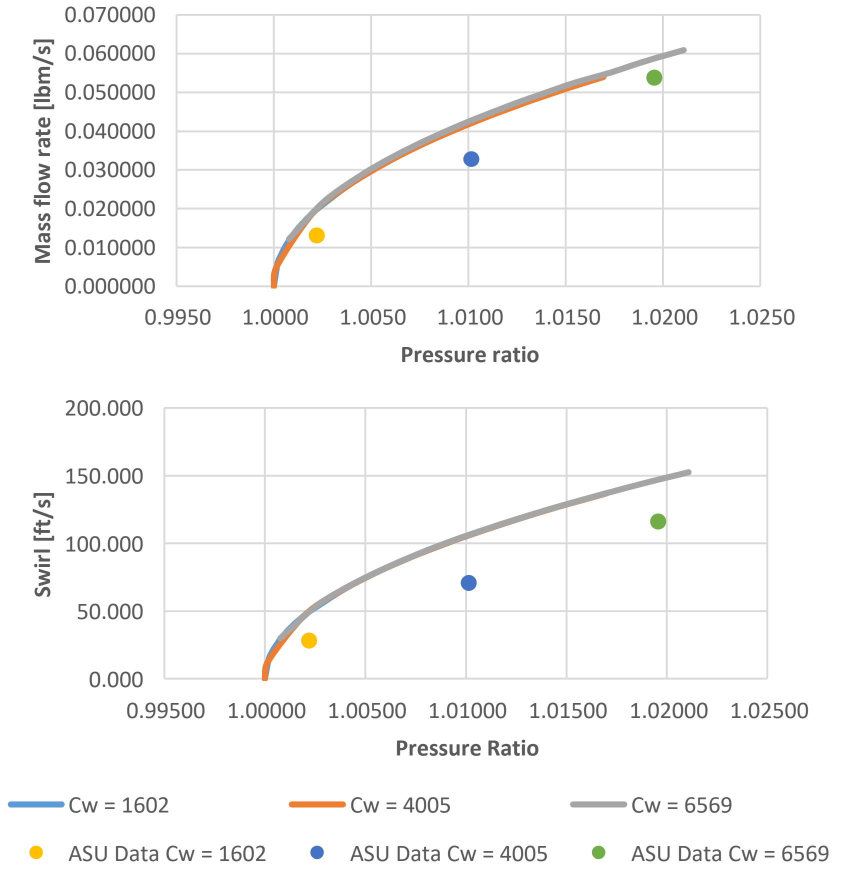


Fig. 4 The preswirler prediction for mass flow rate and swirl without calibration

Mass Flow Balancing to Match Rig Flow Rates (Written)

1. Purge flow rate is the input, hub flow is the outlet (Node_6) , and the difference is the mass traveling towards the mainstream (Node_5 = downstream).
2. So we fix the flow exiting the DCAT downstream by taking the difference between hub and purge flow rate and setting that as the discourager mdot.
3. We know the output, so we fix that orifice's mdot but we float the Cd to solve for the Cd instead.
4. Solving on optimized flow imbalance will calculate a Cd and will also determine the flow through the preswirler, which if already calibrated will yield the correct mdot.
5. Switch between solving the Cd of the discourager and the Cd for the preswirler to obtain mass flow as close to the report as possible (it will take a couple of manual solving for the values to settle).

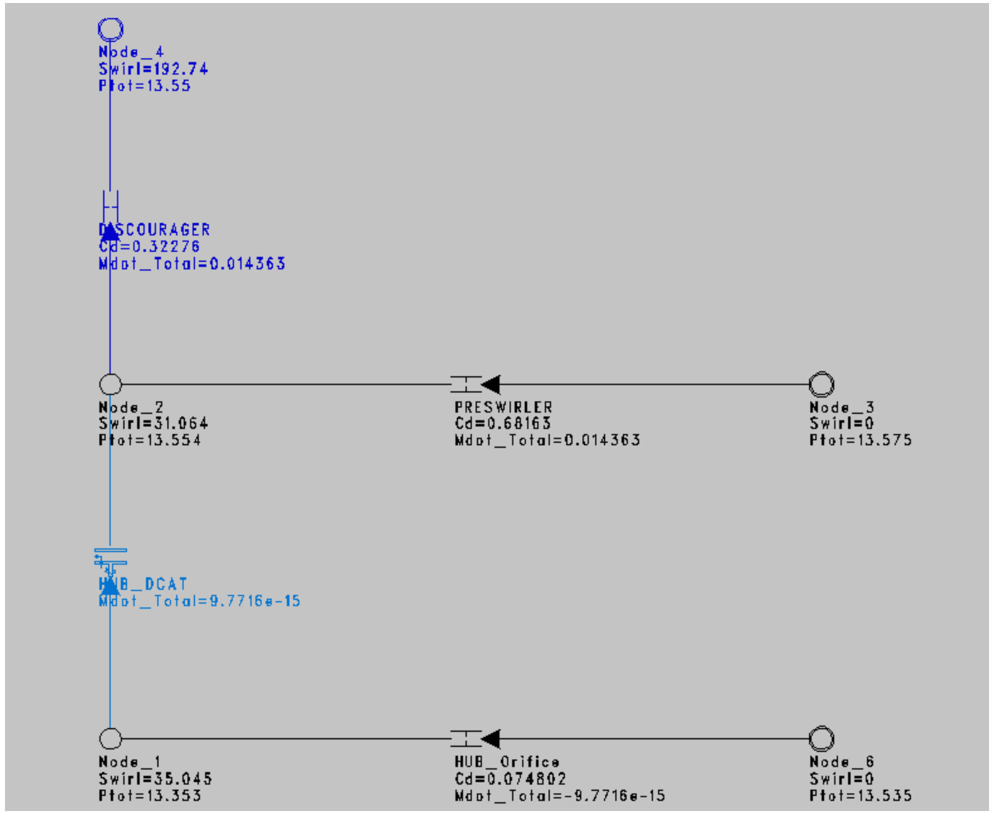
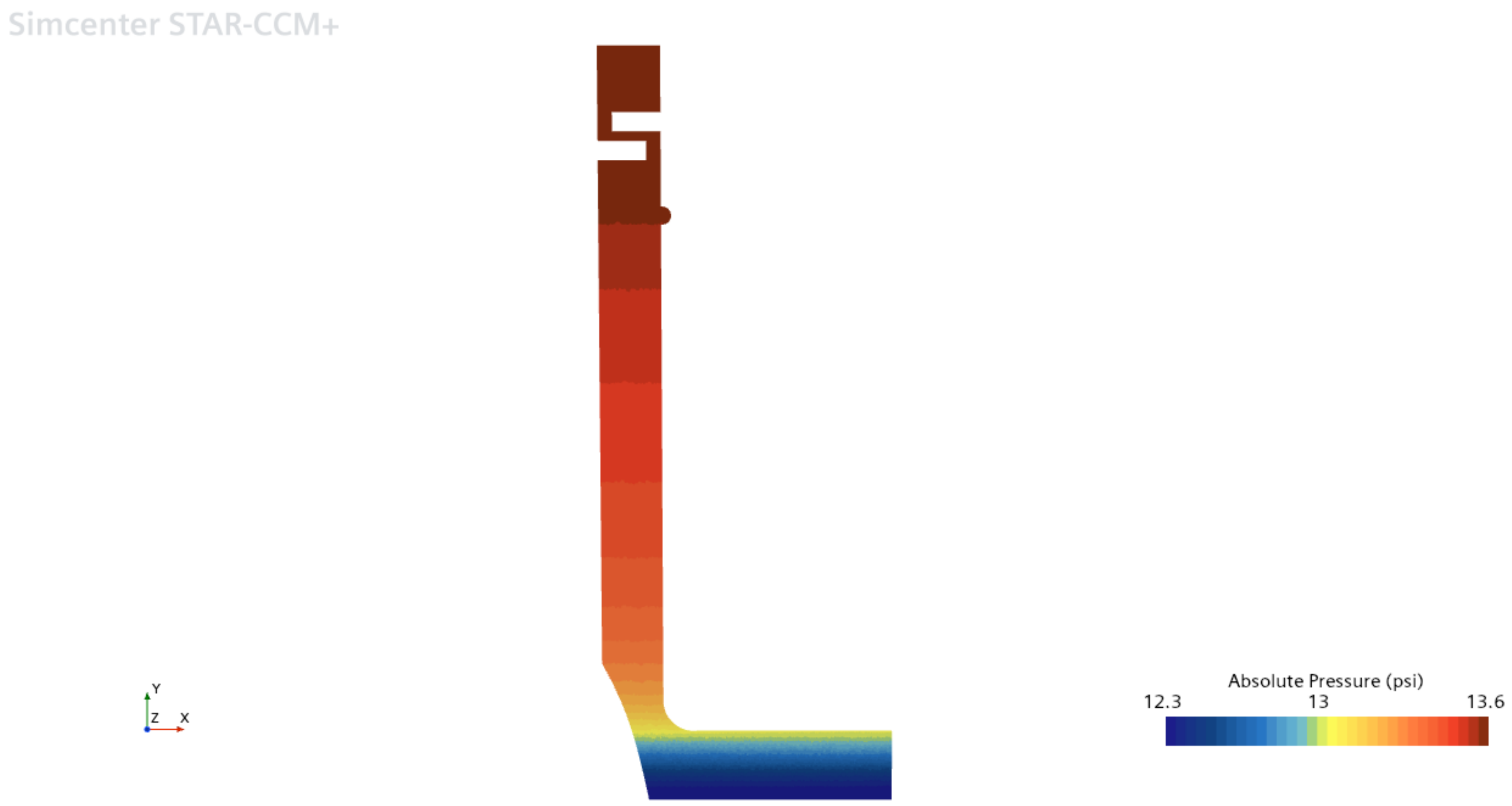


Fig. 7 The current model being solved with unresolved mass flow through the DCAT (Set II: Cw = 1923) .

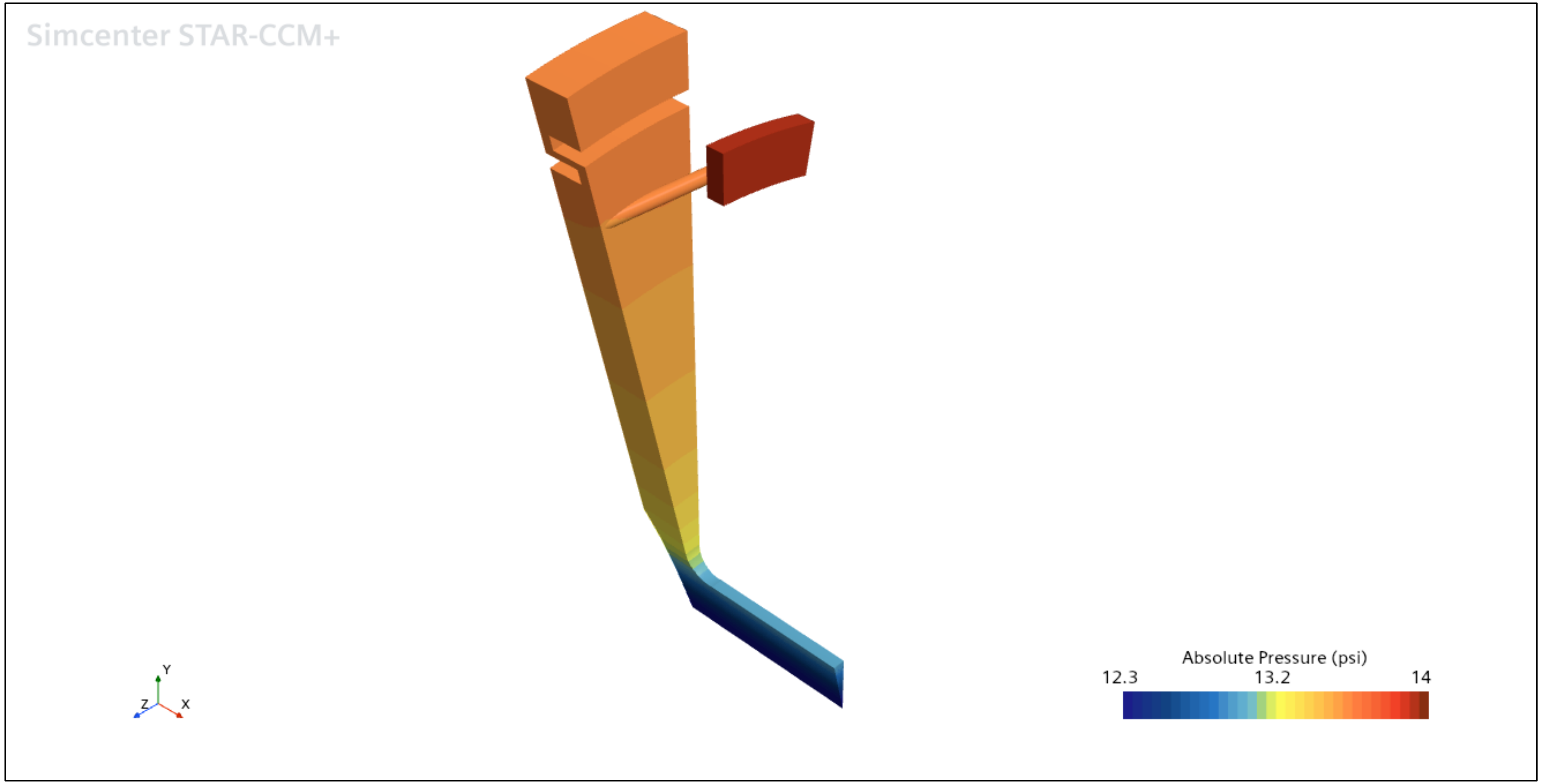
Boundary Conditions

Expt. No.	c_w (purge)	Rotor speed	Pressure				Temperature			Mass Flow Rate			Swirl
			Ambient	Mainstream	Purge Inlet	Hub exit	Mainstream	Purge Inlet	Hub exit	Mainstream	Purge Inlet	Hub exit	
	-	[rpm]	[psia]	[psig]	[psig]	[psig]	[°F]	[°F]	[°F]	[cfm]	[lbm/s]	[lbm/s]	[ft/s]
P-04-001	1602	2600	14.272	14.08	13.68	13.61	76.46	78.98	79.88	1900	0.01313	0.00276	28.22
P-04-002	4005	2600	14.098	13.90	13.63	13.36	76.28	78.08	79.16	1900	0.03277	0.00657	70.87
P-04-003	6569	2600	14.185	13.99	13.92	13.30	76.28	78.62	78.98	1900	0.05380	0.01077	116.14
P-05-001	1923	3000	14.156	13.96	13.58	13.48	81.50	82.04	84.38	1900	0.01583	0.00277	34.12
P-05-002	4806	3000	14.156	13.96	13.73	13.38	78.08	79.70	80.24	1900	0.03942	0.00789	84.97
P-05-003	7370	3000	14.127	13.93	13.94	13.19	78.44	81.14	81.86	1900	0.06058	0.01226	130.25
P-05-004	1923	3000	14.141	13.90	13.42	13.33	75.56	78.98	79.52	2100	0.01576	0.00316	34.12
P-05-005	4806	3000	14.156	13.92	13.60	13.24	80.42	81.50	83.84	2100	0.03953	0.00793	84.97
P-05-006	7370	3000	14.098	13.86	13.78	13.07	80.06	80.96	81.14	2100	0.06057	0.01224	130.25
P-05-007	2083	3400	14.127	13.89	13.40	13.29	79.34	80.60	84.74	2100	0.01711	0.00344	36.75
P-05-008	4806	3400	14.156	13.91	13.59	13.22	80.42	81.50	83.12	2100	0.03953	0.00792	84.97
P-05-009	8171	3400	14.098	13.86	13.88	13.07	81.50	81.50	84.92	2100	0.06720	0.01351	144.36

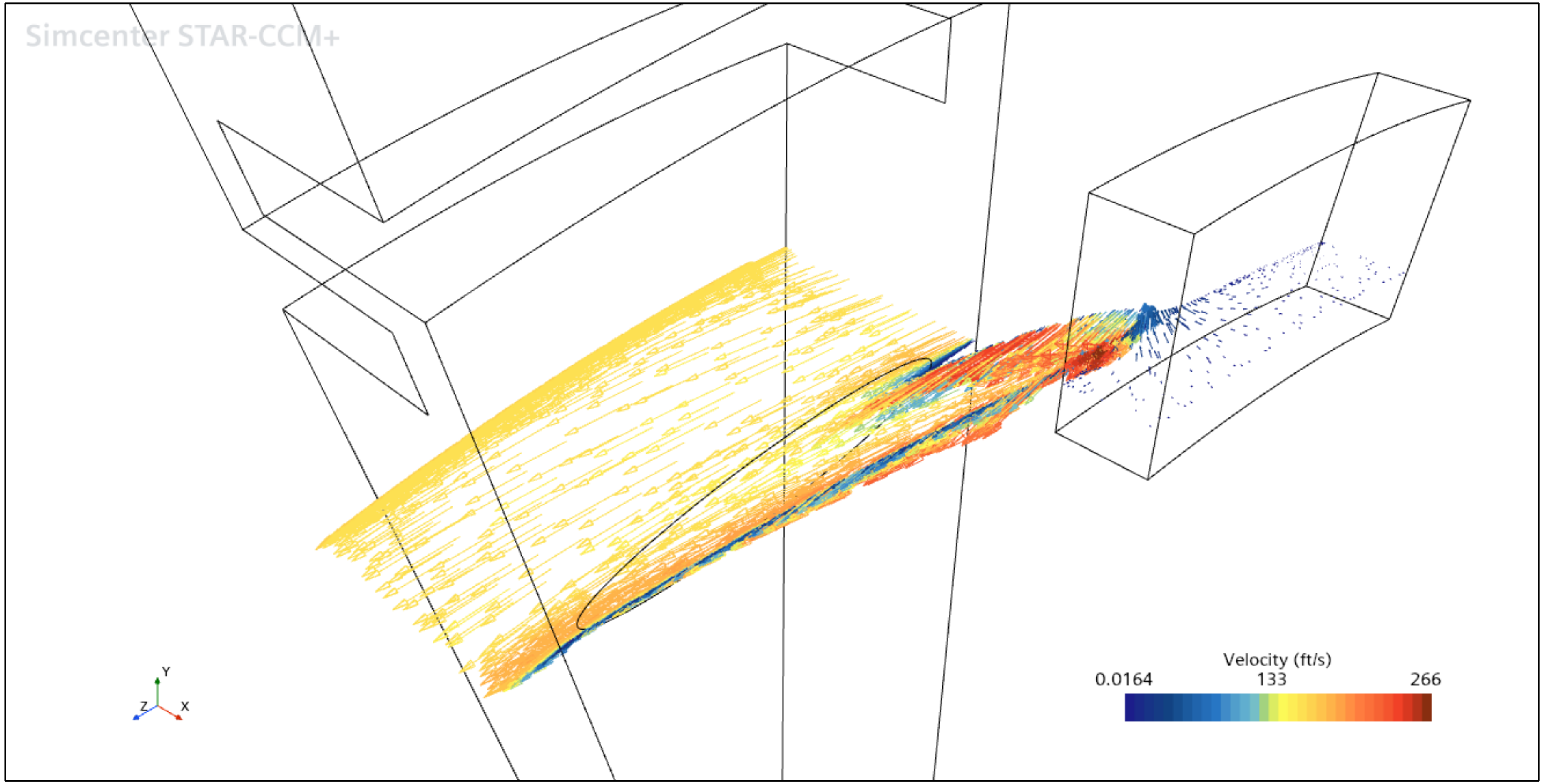
Notes: The report provides flow rates in scfm, however, the non-dimensional flow rate was used to determine the mass flow rates for the purge inlet and hub exit. Secondly, the mainstream pressure provided is the main air inlet as reported by ASU, however depending on how the model's pressure outlet is defined, a different measurement may be considered



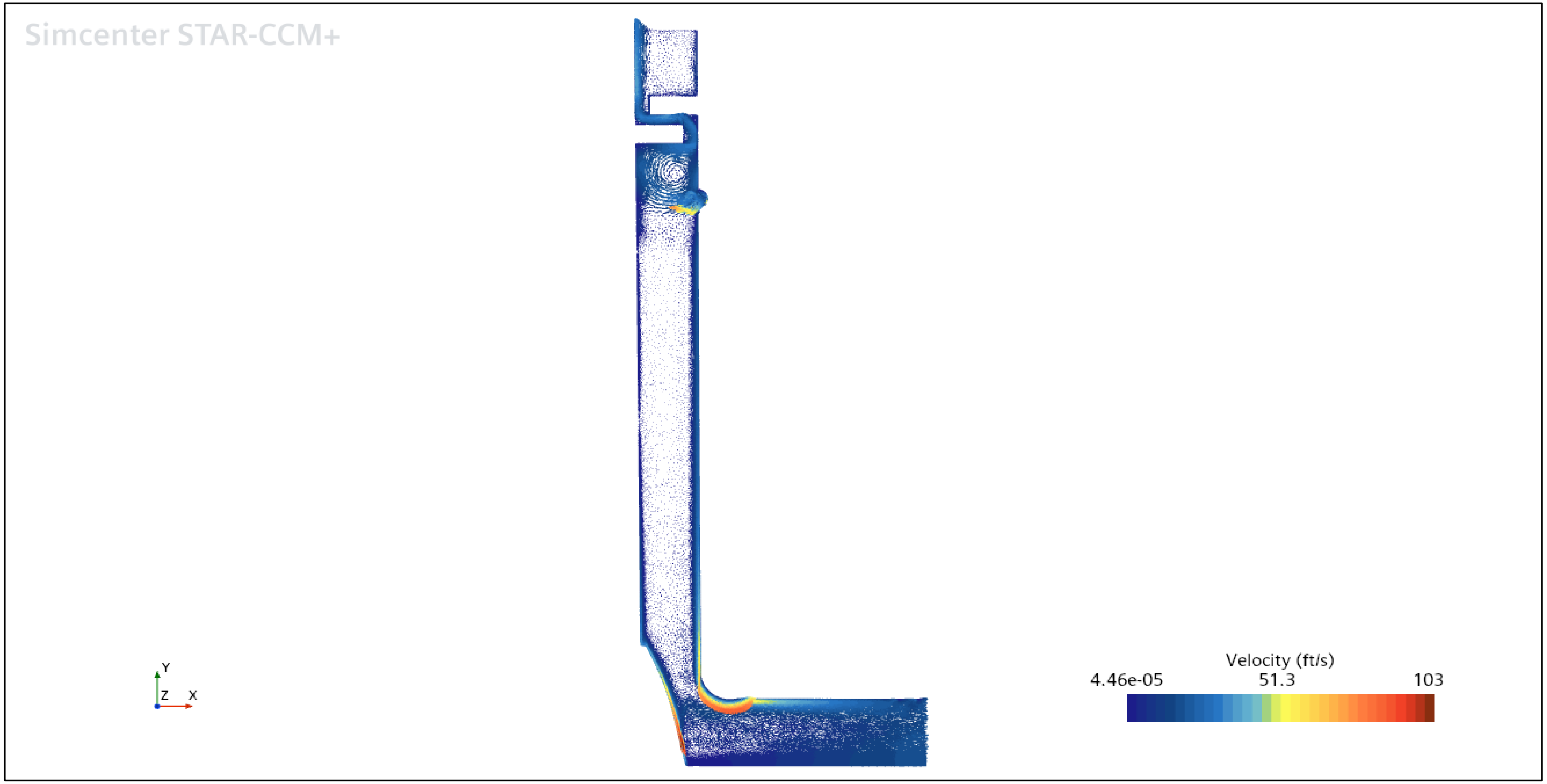
Absolute Pressure mid plane



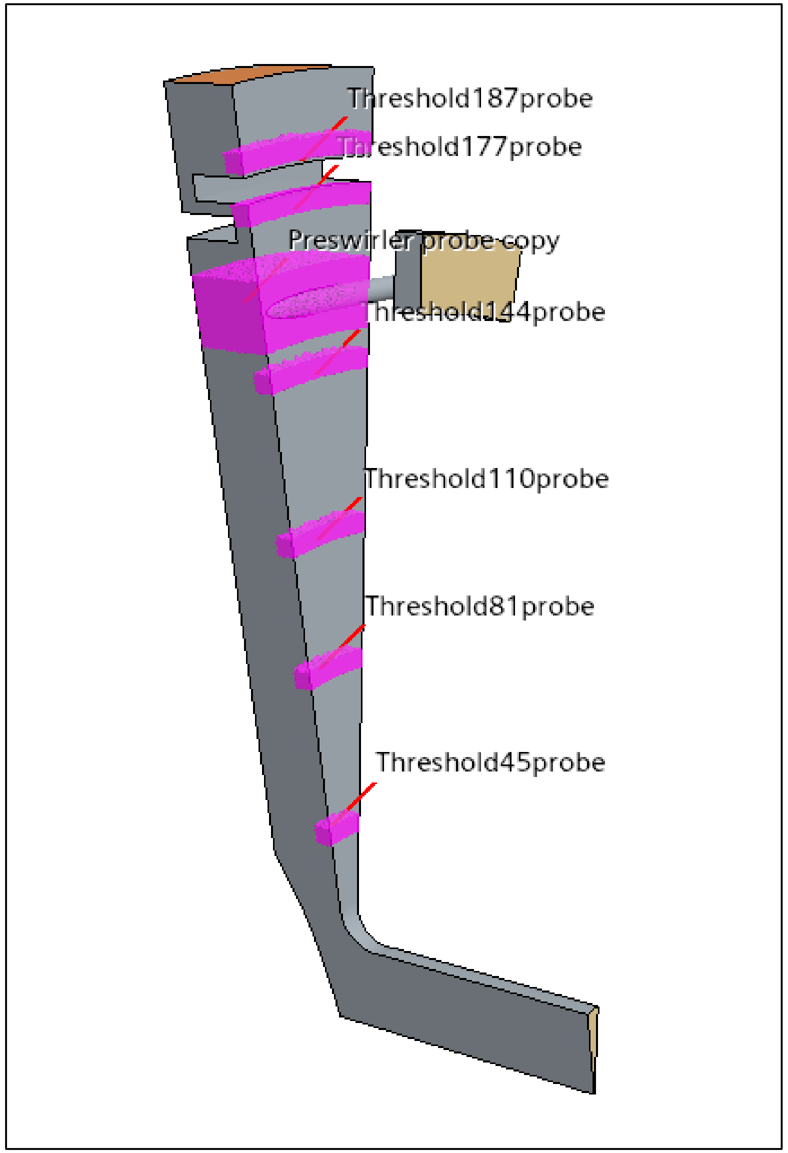
Absolute pressure contour



Velocity (lab frame)



Velocity: Tangential projection, lab frame velocity



All pressure probe locations including preswirler region