Vortex Generators in a Two-Dimensional, External-Compression Supersonic Inlet

Ezgihan Baydar and Frank K. Lu

Aerodynamics Research Center, University of Texas – Arlington

and

John W. Slater

Inlets and Nozzles Branch, NASA Glenn Research Center

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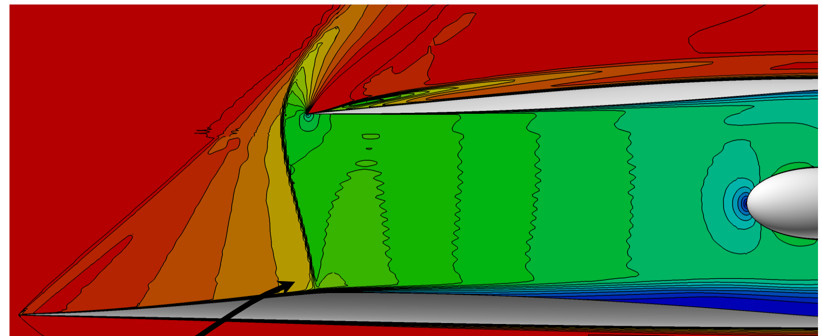
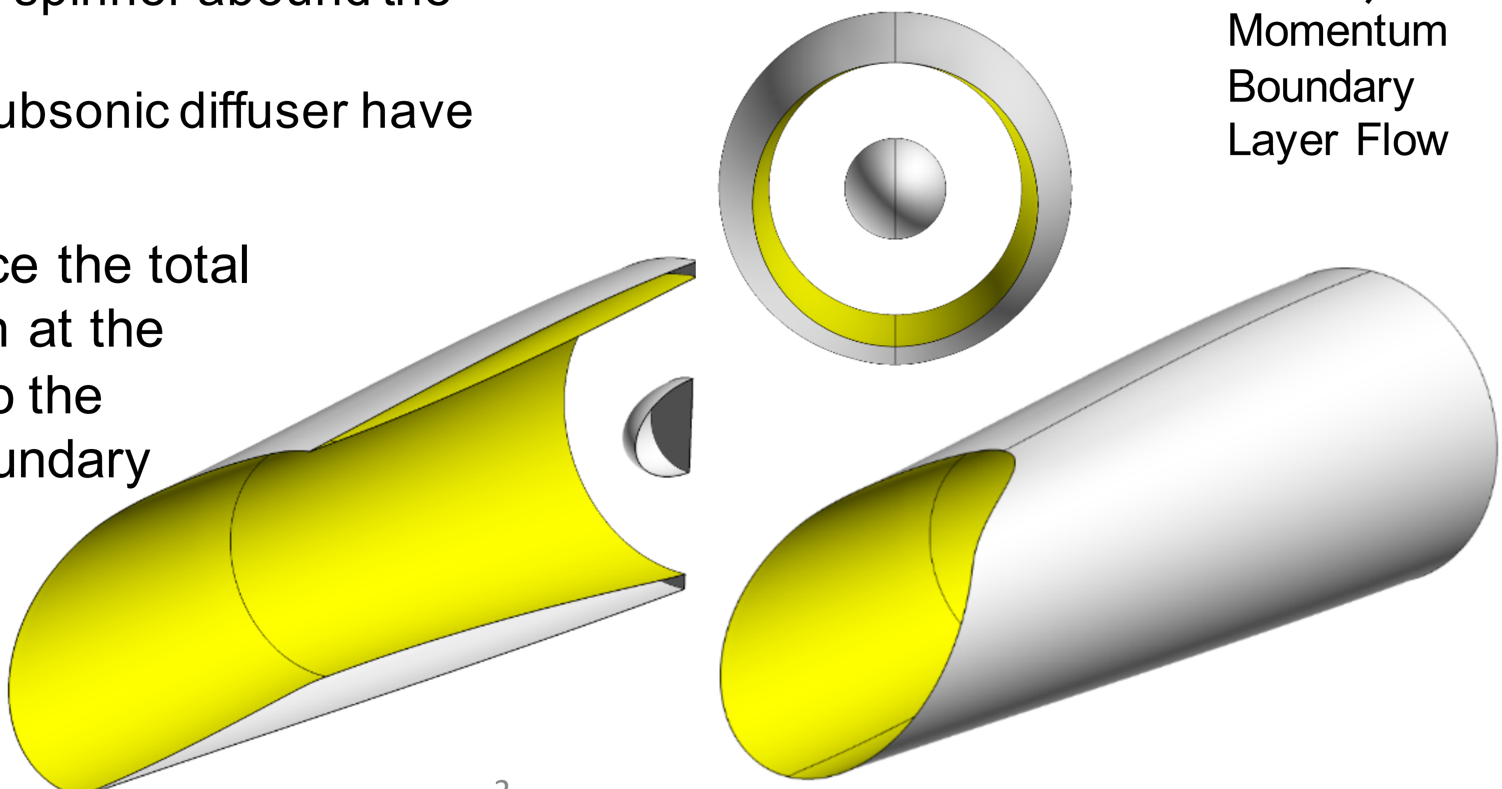
Streamline-Traced External-Compression (STEX) Inlet

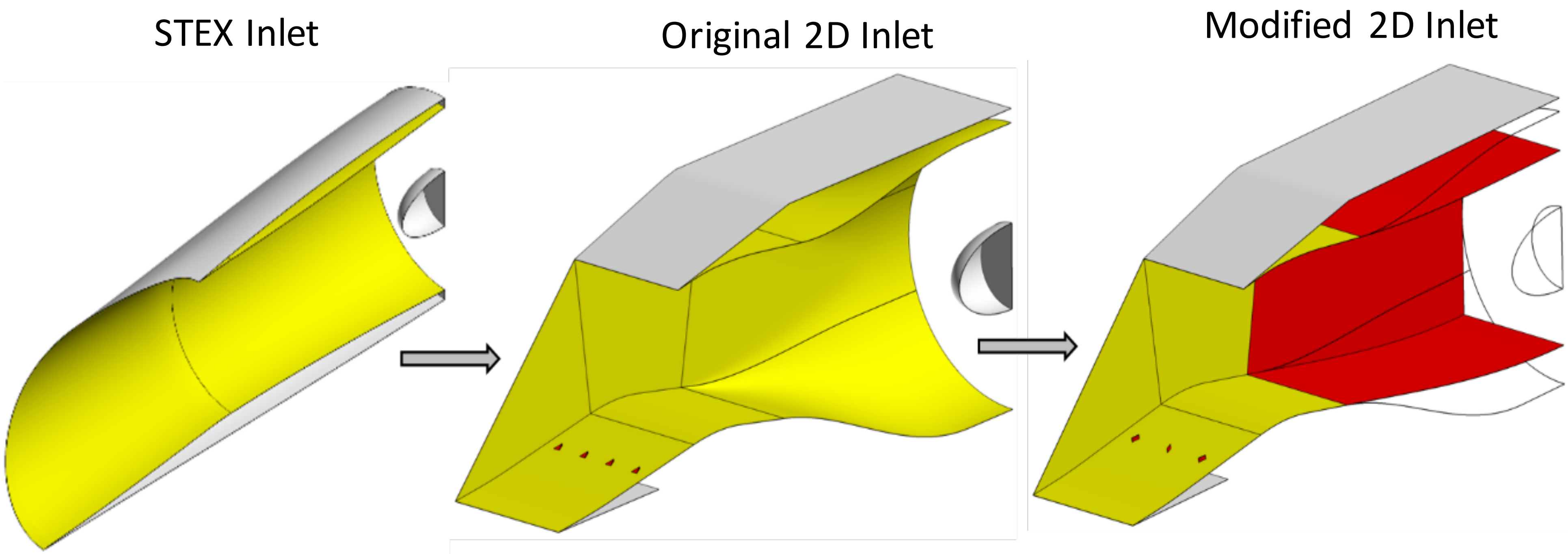
- Streamline-traced, inward-turning supersonic diffuser (decelerates and compresses flow)
- Terminal shock wave boundary layer interaction generates low-momentum flow in subsonic diffuser
- Subsonic diffuser consists of a circular engine face and a spinner abound the engine axis
- Supersonic and subsonic diffuser have no corner flows.



Objective: Reduce the total pressure distortion at the engine face due to the terminal shock/boundary layer interaction.



Simplification of the STEX inlet to the Simplified 2D inlet



- 2D rectangular supersonic diffuser
- 2D rectangular throat section
- Transitioning subsonic diffuser

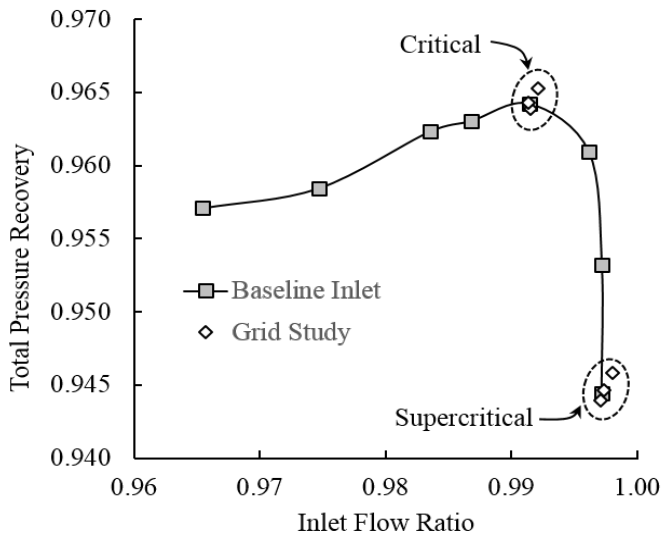
- Rectangular Subsonic Diffuser
- Inviscid Sidewalls
- No corner flows

Approach

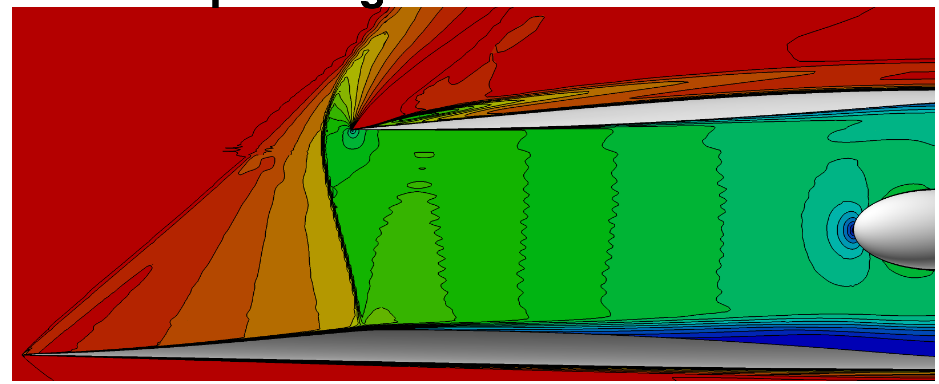
Approach: Incorporate passive devices (vortex generators) to generate vortices to mix the higher-momentum core flow with the low-momentum flow of the boundary layer.

Key Questions to Answer:

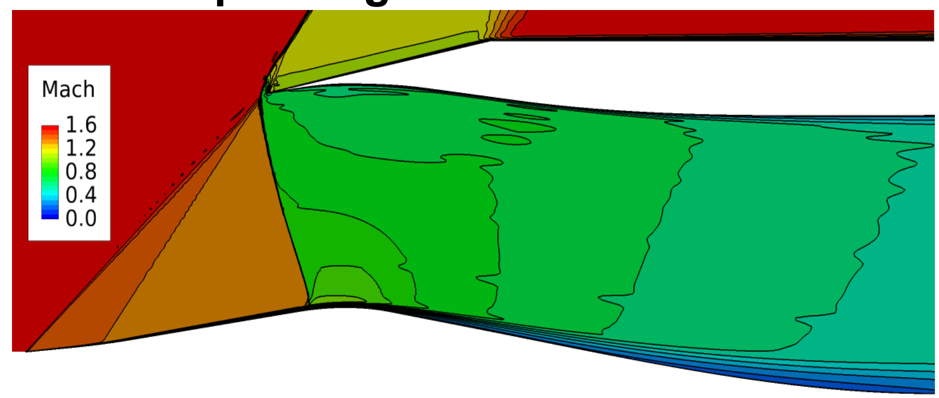
- What type of vortex generators work well for 2D inlets?
- What geometric properties of the vortex generators work well?
- How much can distortion be reduced with vortex generators?



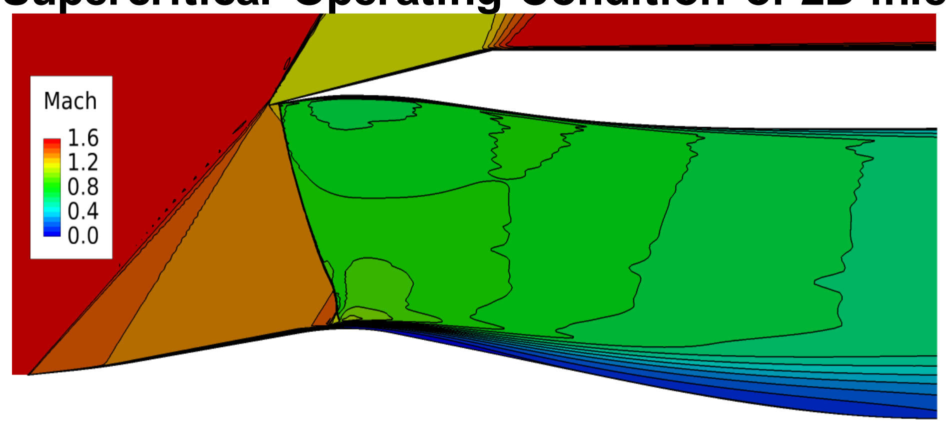
Critical Operating Condition of STEX inlet



Critical Operating Condition of 2D inlet



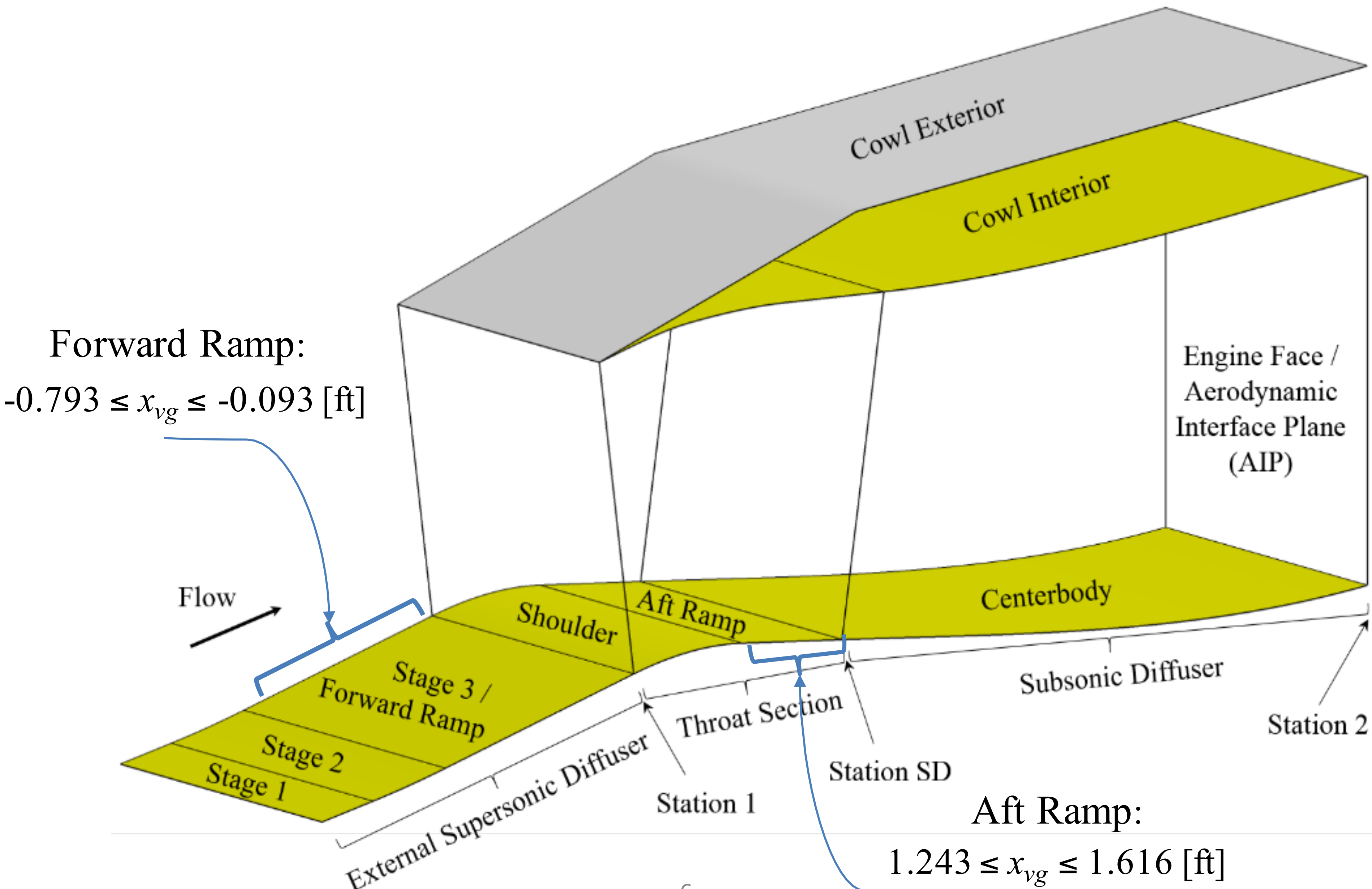
Supercritical Operating Condition of 2D inlet



Study of VGs in the 2D Inlet

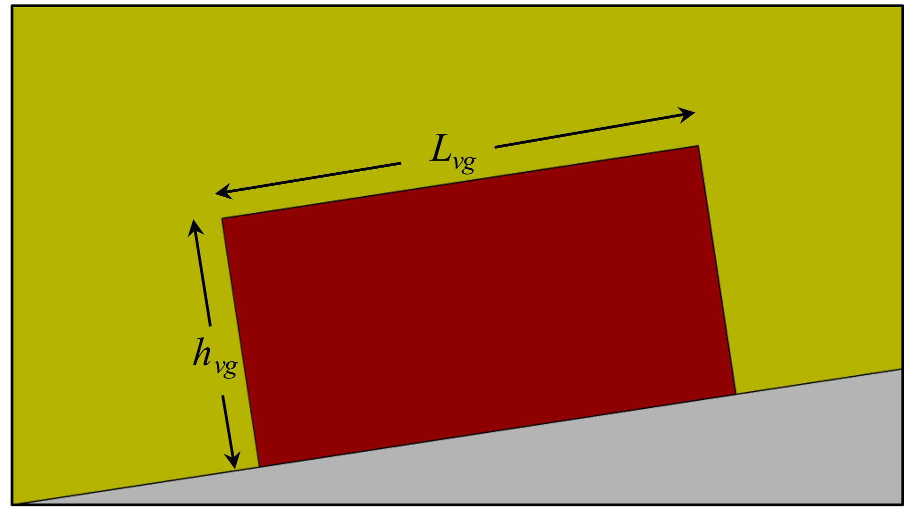
- Vane-type and ramp-type VGs were studied.
- Determine significant differences between upstream and downstream devices (ahead or downstream of the terminal shock).
- Determine significant differences between ramps and vanes.
- Quantify significant relationships between device geometry factors, such as height, length, spacing, and position.
- Incidence angle was fixed.

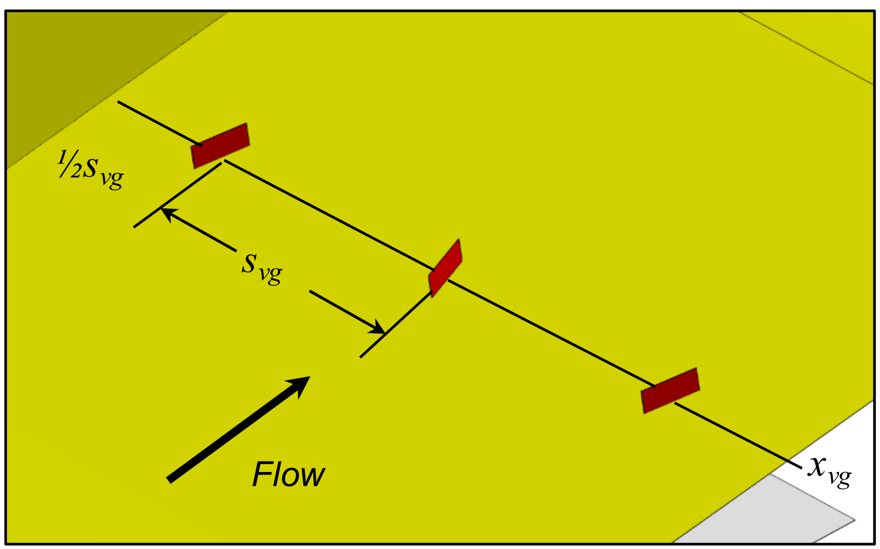
Axial Placement of Vortex Generators

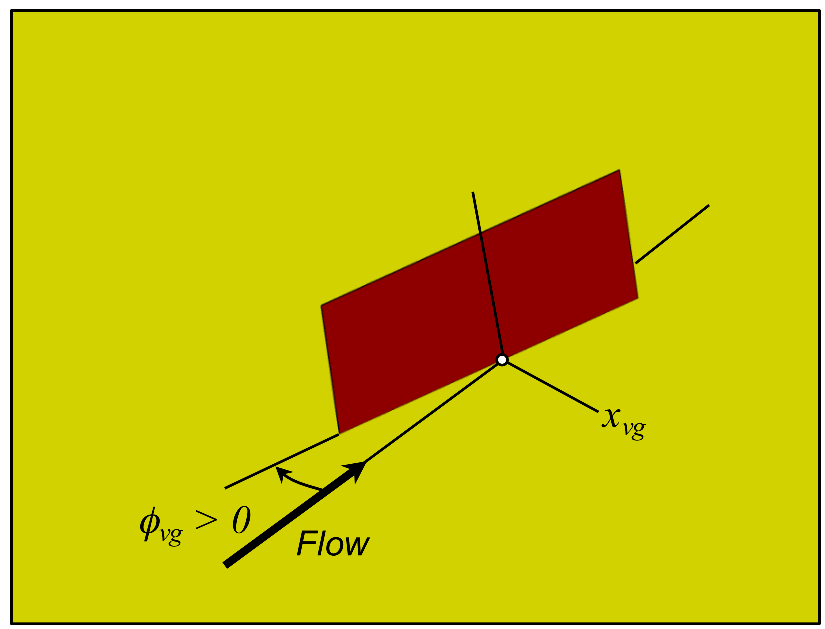


Vane-Type Vortex Generators

- L_{vg}, Length (ft), $0.25 \le h_{vg}/L_{vg} \le 0.50$
- h_{vg}, Height (ft), $0.25 \le h_{vg}/\delta \le 1.0$
- s_{vg}, Spacing (ft), $3.0 \le s_{vg}/h_{vg} \le 7.0$
- ϕ_{vg}, Angle of incidence, $\phi_{vg} = \pm\ 16$ degrees
- x_{vg}, Axial placement of vane center (ft)

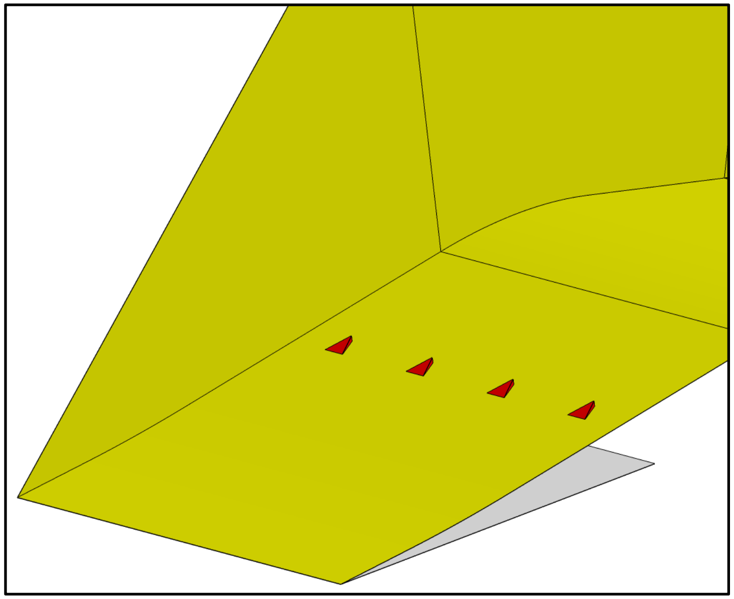


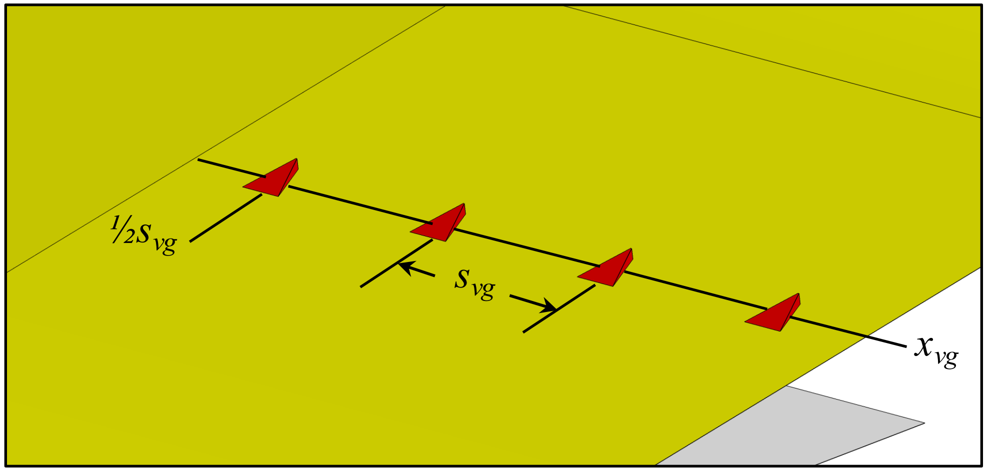


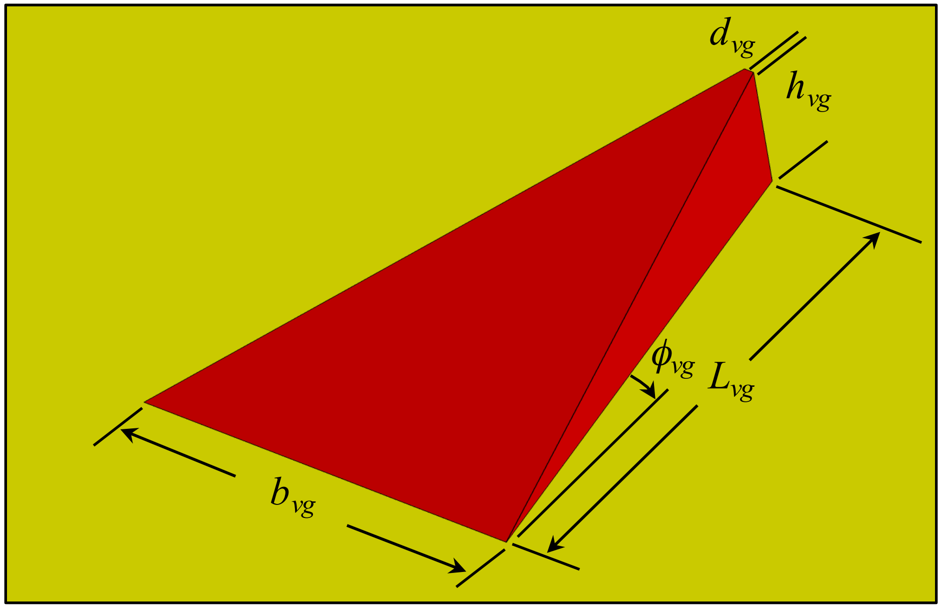


Ramp-Type Vortex Generators

- L_{vg}, Length (ft), $0.25 \leq h_{vg}/L_{vg} \leq 0.50$
- h_{vg}, Height (ft), $0.25 \leq h_{vg}/\delta \leq 1.0$
- s_{vg}, Spacing (ft), $3.0 \leq s_{vg}/h_{vg} \leq 7.0$
- ϕ_{vg}, Angle of incidence, $\phi_{vg} = 24$ degrees
- x_{vg}, Axial placement of vane center (ft)

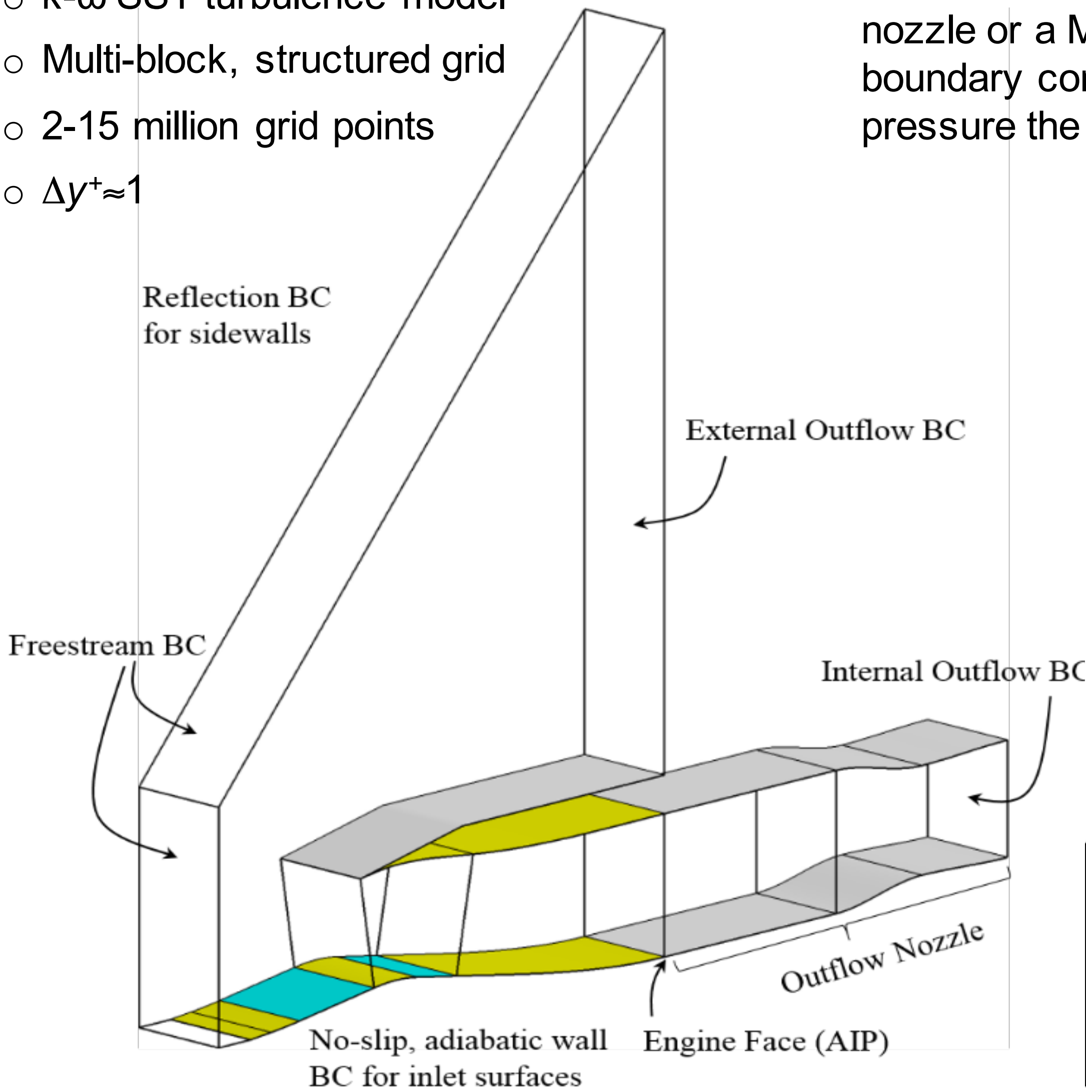




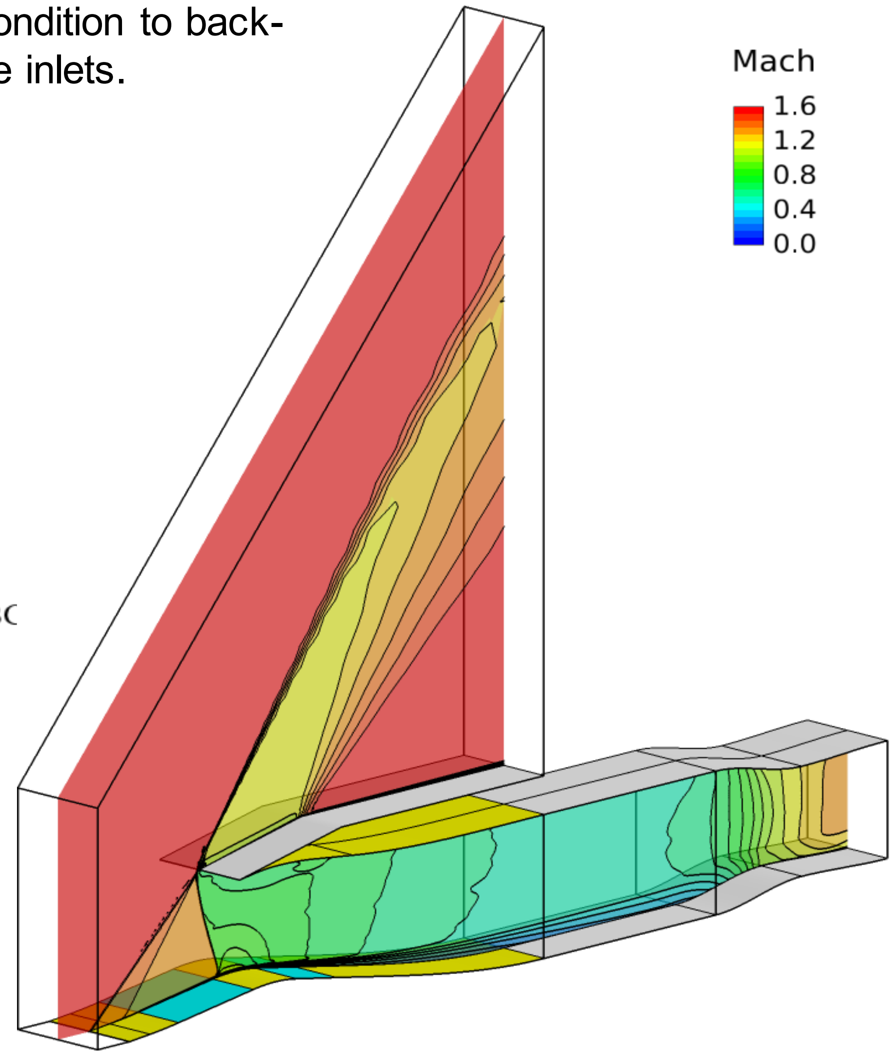


CFD Analysis

- Wind-US, steady-state RANS solver
- k-ω SST turbulence model
- Multi-block, structured grid
- 2-15 million grid points
- $\Delta y^{+} \approx 1$



- Outflow is modeled with an outflow converging-diverging nozzle or a Mach number boundary condition to back-pressure the inlets.

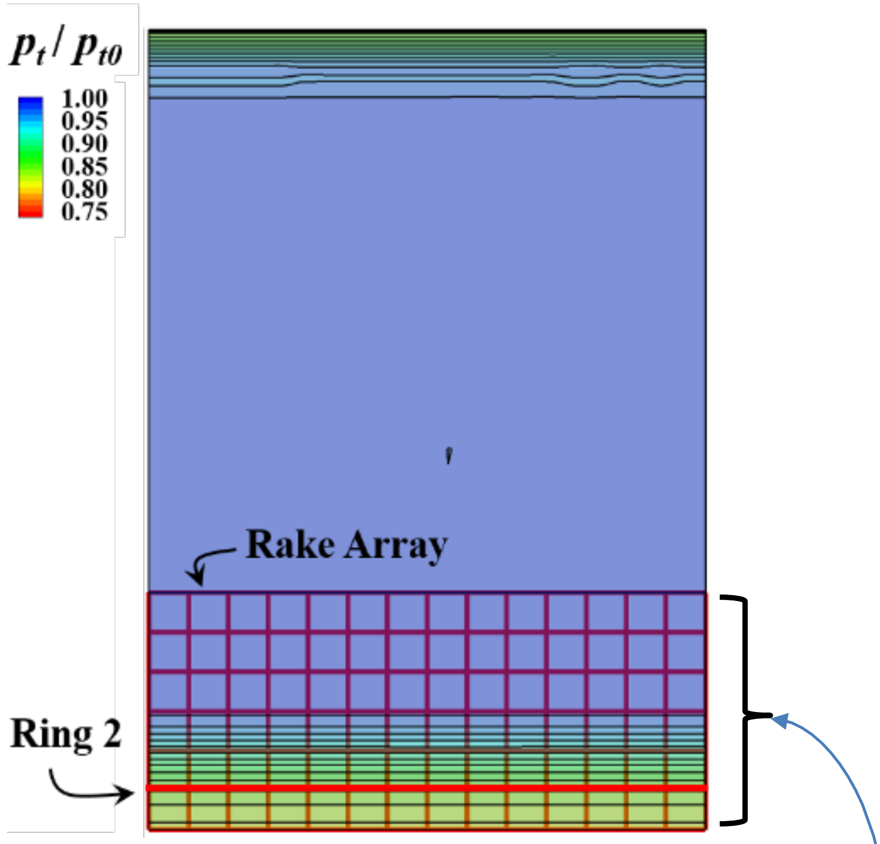


Inlet Performance Metrics

- Inlet Flow Ratio, W_2/W_{cap}
- Total Pressure Recovery, p_{t2}/p_{t0}
- Incompressible Shape Factor, H_i
- Circumferential Distortion, DPC/P
- Radial Distortion, DPR/P

Inlet Distortion Descriptors

- SAE ARP 1420 methods applied to compute distortion intensities.
- CFD solution was interpolated onto "probes" (intersection of the ring and rake lines).
- Circumferential distortion was computed in the horizontal direction among fifteen "rings".
- Radial distortion was computed in the vertical direction among seven "rings".
- Distortion intensities on Ring 2 were used to represent the inlet distortion.



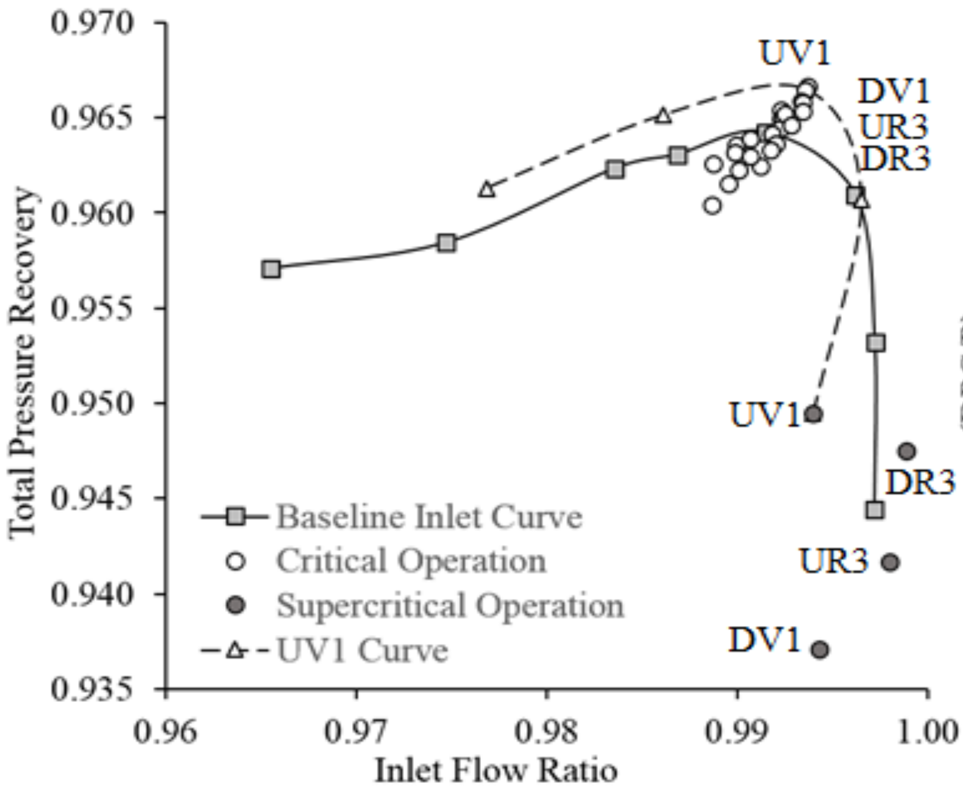
Rectangular rake array was configured to focus on the centerbody boundary layer

Vortex Generator Cases at the Critical Operating Condition

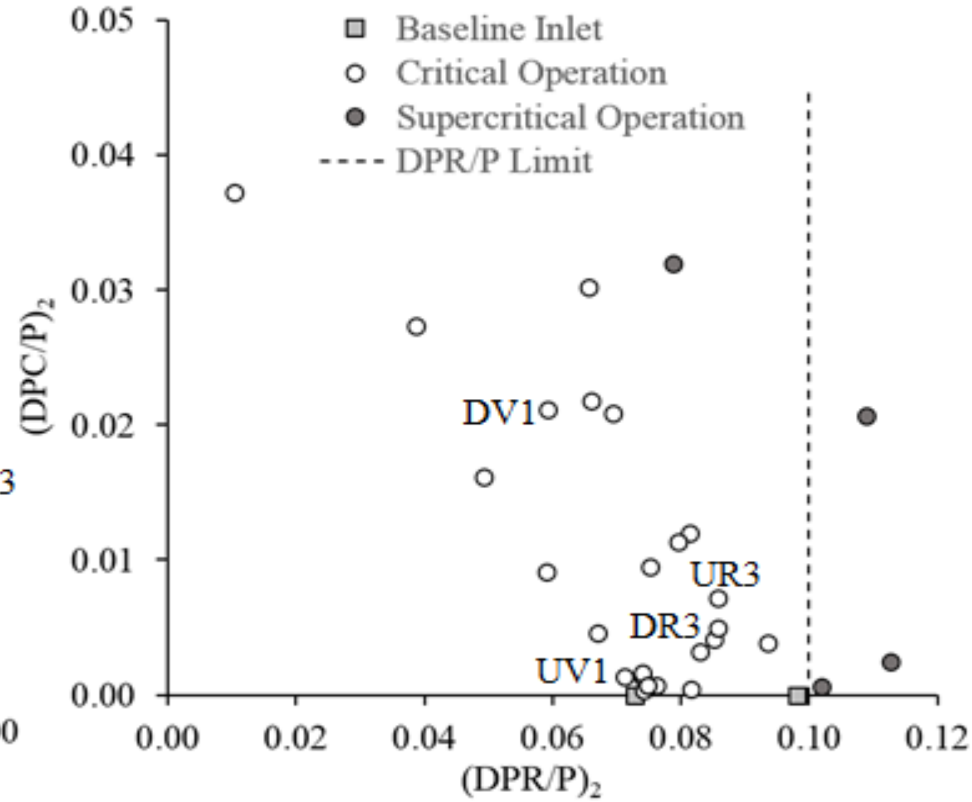
	Cases	x_{vg}(ft)	h_{vg} / δ	L_{vg} / h_{vg}	s_{vg} / h_{vg}	N_{vg}	W_2/W_{cap}	p_{t2}/p_{tL}	DPC/P_2	DPR/P_2	H_i
	Baseline	-	-	-	-	-	0.9922	0.9653	0.0000	0.0728	1.686
Downstream Vanes (*DV*)	DV1	1.24	0.429	3.75	8.34	6	0.9923	0.9654	0.0212	0.0592	1.604
	DV3	1.24	0.250	8.00	4.835	16	0.9923	0.9649	0.0013	0.0740	1.716
	DV4	1.20	0.645	2.00	6.00	10	0.9907	0.9639	0.0091	0.0590	1.523
	DV5	1.40	0.774	2.08	4.17	6	0.9900	0.9636	0.0274	0.0387	1.401
	DV6	1.24	0.500	4.00	4.835	8	0.9899	0.9632	0.0162	0.0493	1.452
	DV7	1.24	1.000	2.00	4.835	4	0.9887	0.9626	0.0373	0.0103	1.340
Downstream Ramps (*DR*)	DR1	1.40	0.36	5.47	13.39	4	0.9937	0.9666	0.0016	0.0740	1.754
	DR2	1.40	0.34	6.63	10.82	6	0.9923	0.9649	0.0003	0.0742	1.720
	DR3	1.43	0.50	7.20	7.74	5	0.9922	0.9644	0.0032	0.0829	1.777
	DR4	1.43	0.75	7.20	8.60	3	0.9895	0.9616	0.0095	0.0752	1.778
	DR5	1.43	1.00	7.20	9.68	2	0.9887	0.9604	0.0302	0.0656	1.716
Upstream Vanes (*UV*)	UV1	-0.50	0.31	2.00	12.50	12	0.9936	0.9665	0.0013	0.0712	1.727
	UV2	-0.50	0.46	2.08	12.50	8	0.9918	0.9642	0.0004	0.0815	1.766
	UV3	-0.79	0.43	3.75	19.81	6	0.9920	0.9636	0.0120	0.0814	1.848
	UV4	-0.44	0.43	3.75	19.81	6	0.9907	0.9630	0.0209	0.0694	1.679
	UV5	-0.50	0.40	11.60	8.30	14	0.9912	0.9625	0.0038	0.0935	1.982
	UV6	-0.09	0.43	3.75	19.81	6	0.9901	0.9623	0.0218	0.0660	1.633
Upstream Ramps (*UR*)	UR1	-0.50	0.36	4.29	25.30	5	0.9934	0.9659	0.0007	0.0748	1.760
	UR2	-0.50	0.75	7.19	20.39	3	0.9934	0.9658	0.0113	0.0796	1.809
	UR3	-0.44	0.50	7.20	7.65	12	0.9935	0.9654	0.0050	0.0858	1.945
	UR4	-0.50	0.49	5.47	31.25	3	0.9925	0.9652	0.0007	0.0762	1.724
	UR5	-0.44	0.75	7.20	7.65	8	0.9928	0.9647	0.0041	0.0852	1.930
	UR6	-0.44	1.00	7.20	7.65	6	0.9918	0.9633	0.0072	0.0857	1.930

Inlet Performance Plots

Total Pressure Recovery
VS. Inlet Flow Ratio



Circumferential Distortion
VS. Radial Distortion

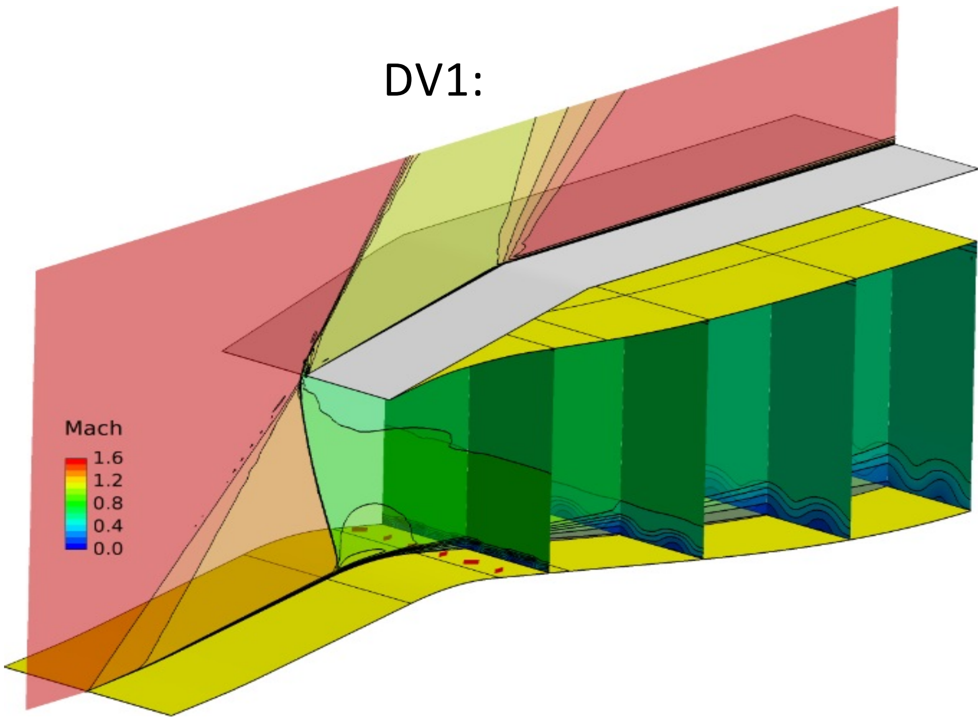


- Upstream devices are superior to downstream devices in increasing p_{t2}/p_{t0}.
- Overall *UV* cases are superior with 0.5% improvement in p_{t2}/p_{t0}.
- Vanes are superior to ramps in reducing DPR/P, which fall far left of dashed distortion indicator for the baseline inlet.

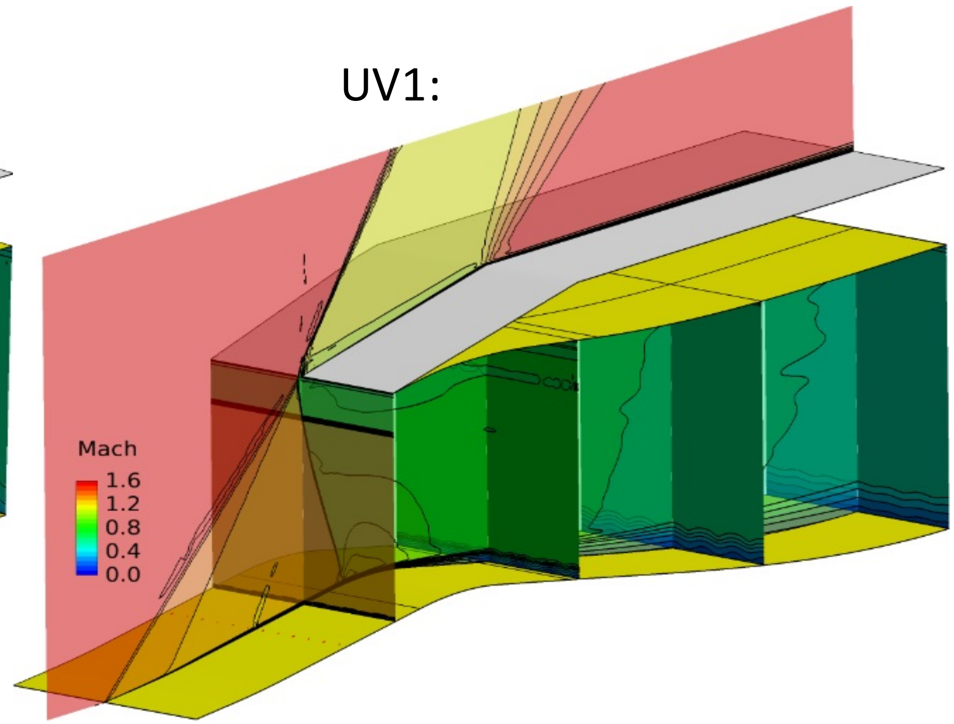
Vortex Generator Cases at Critical Operating Condition

- **Downstream Vanes** did not show improvement in total pressure recovery; however larger device heights had impact on local flow effects, such as Case *DV1*
- **Upstream Vanes** shows the most improvement in total performance metrics with smaller heights, such as Case *UV1*
- **Ramps** did not show any improvement in total performance metrics.

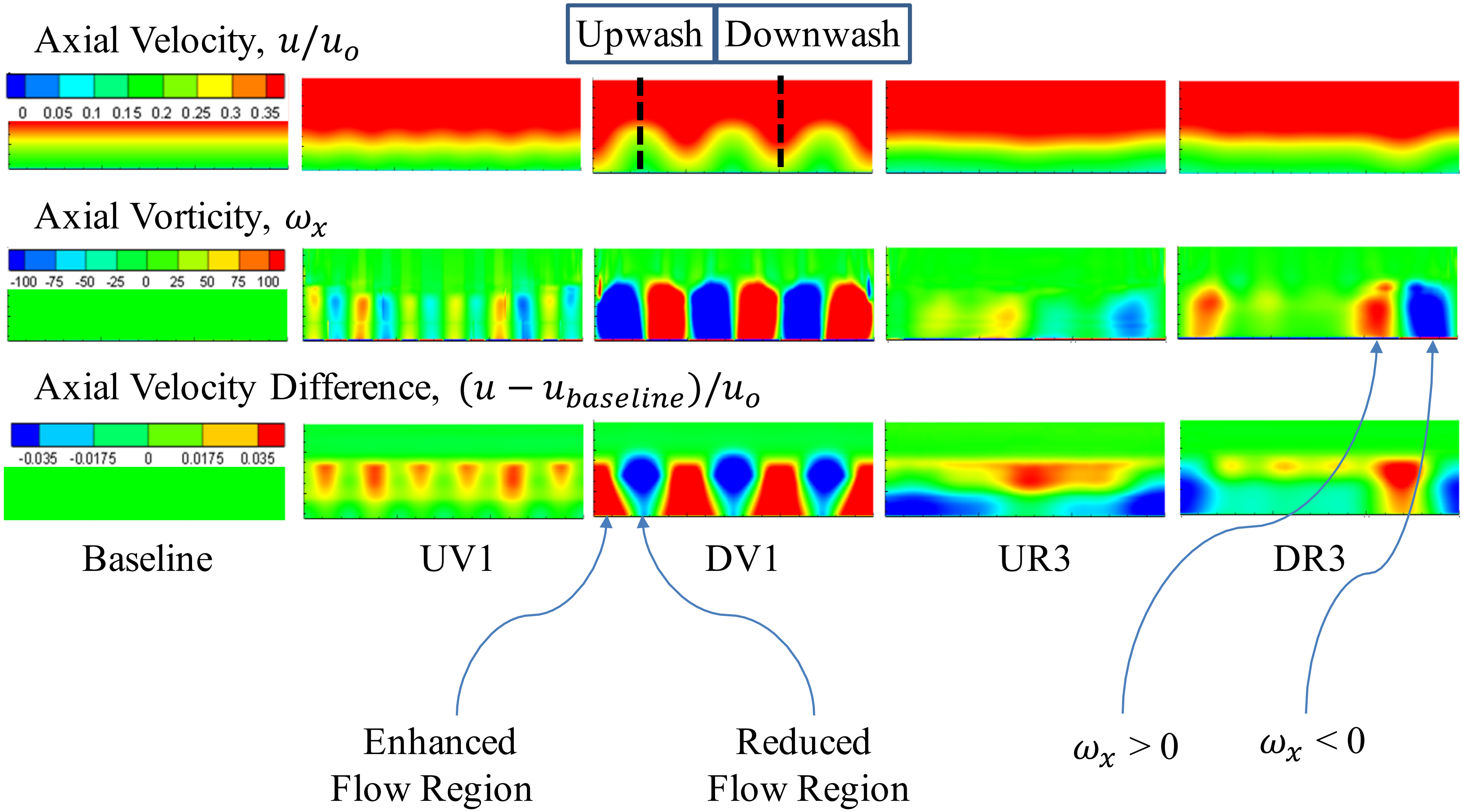
DV1:



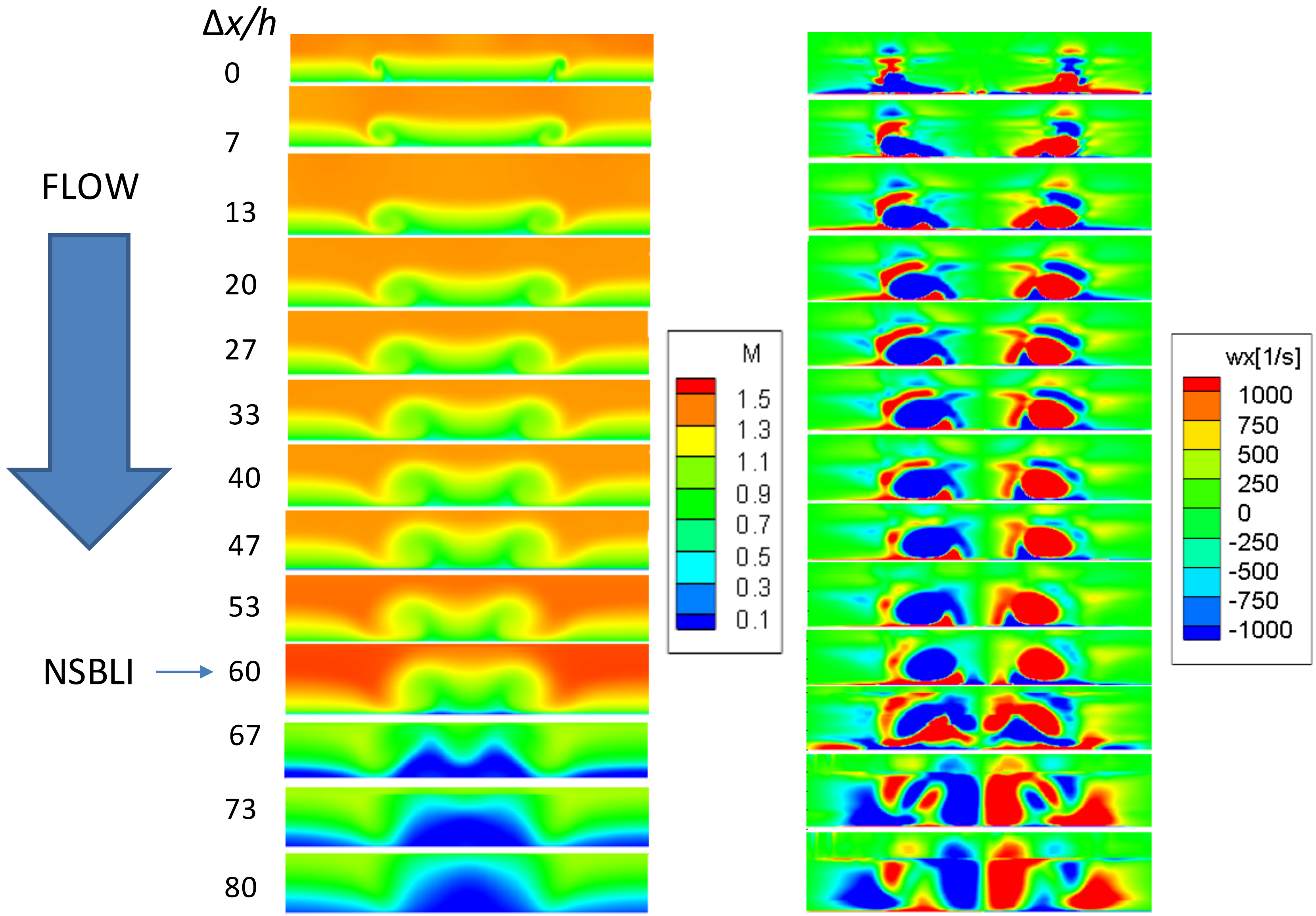
UV1:



Spanwise AIP Contours

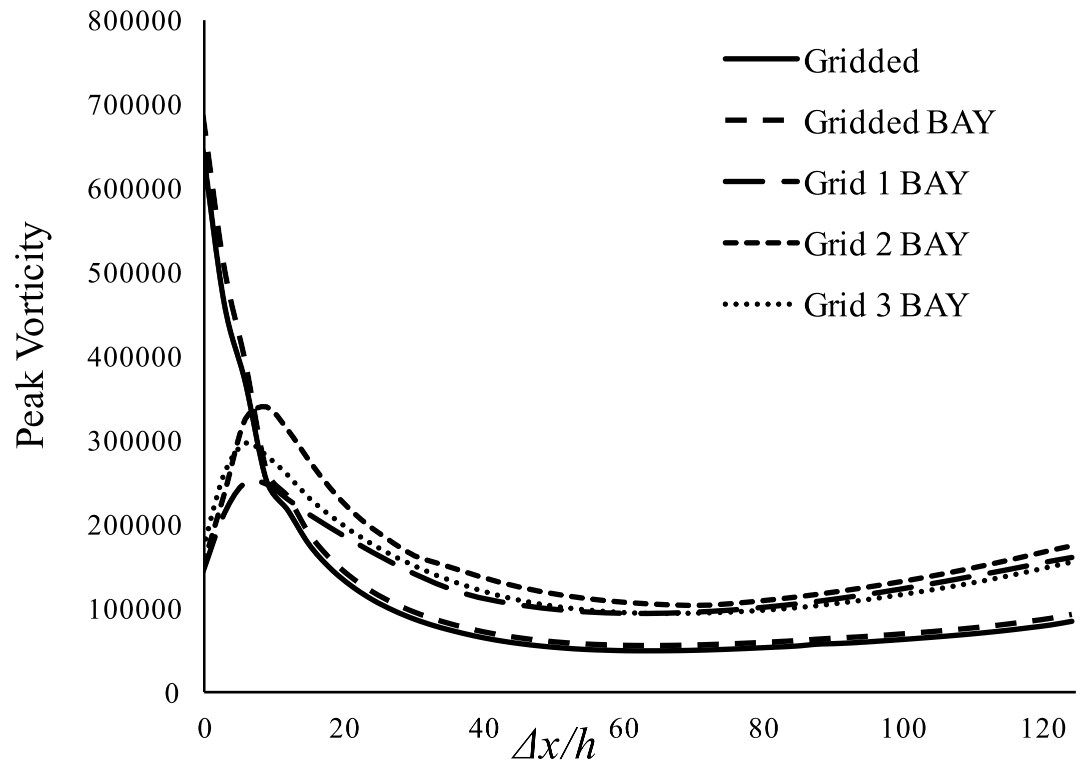


Upstream Vane Study on 2D inlet



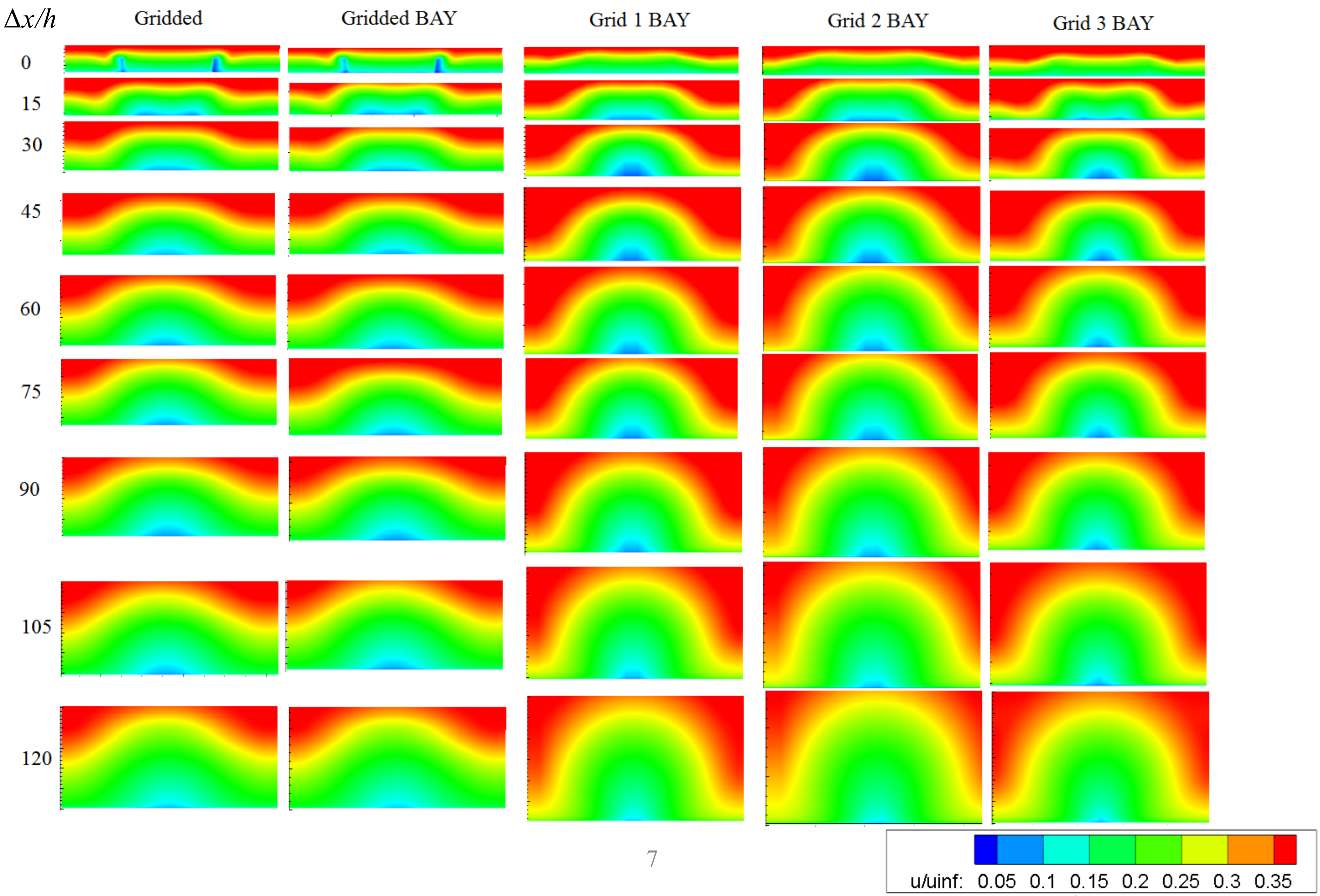
Comparison of *DS* gridded vanes with use of BAY model

- BAY model imposes lifting-force source term.
- Aligns the local flow velocity with the vane incidence.
- Generates vortices downstream of vane placement (without physically gridding vanes).
- Includes the following inputs:
  - Grid range of vane
  - Angle-of-incidence of vane
  - Planform area of vane



Simulations	$N_{i\text{-}vg}$	$N_{i\text{-}sub}$	$N_{k\text{-}sub}$	W_2/W_{cap}	p_{t2}/p_{t0}	$(DPC/P)_2$	$(DPR/P)_2$	H_i
Baseline	-	152	73	0.9922	0.9653	0.0000	0.0728	1.686
Gridded	15	71	549	0.9924	0.9653	0.0173	0.0657	1.660
Gridded BAY	15	71	549	0.9923	0.9653	0.0239	0.0539	1.637
Grid 1 BAY	3	54	27	0.9905	0.9634	0.0239	0.0539	1.540
Grid 2 BAY	5	109	53	0.9901	0.9639	0.0295	0.0437	1.453
Grid 3 BAY	7	152	73	0.9901	0.9643	0.0321	0.0401	1.436

Comparison of *DS* gridded vanes with use of BAY models



Conclusions and Future Plans

- **Upstream and downstream devices** can be used to improve the flow at the engine face.
- **Smaller devices** perform better than larger devices at improving the flow at the engine face. In each study, lower h_{vg}/δ values indicate higher total pressure.
- **Downstream vanes** are the best performing devices in terms of reducing radial distortion and improving the boundary layer. Radial distortion resulted in 23% improvement.
- **Upstream vanes** resulted in the most improvement in total pressure recovery by 0.12%.
- **Ramps** were not as effective in reducing radial distortion compared to **vanes**.

Future Work:

- Study VGs in the STEX inlet.
- Conduct a formal DOE to the STEX inlet to statistically determine the interactions between all VG factors, such as height, aspect ratio, and spacing for one nozzle setting.
- Prepare paper for AIAA Aerospace Sciences Meeting.

Questions?