Use of Vortex Generators to Reduce Distortion for Mach 1.6 Streamline-Traced Supersonic Inlets

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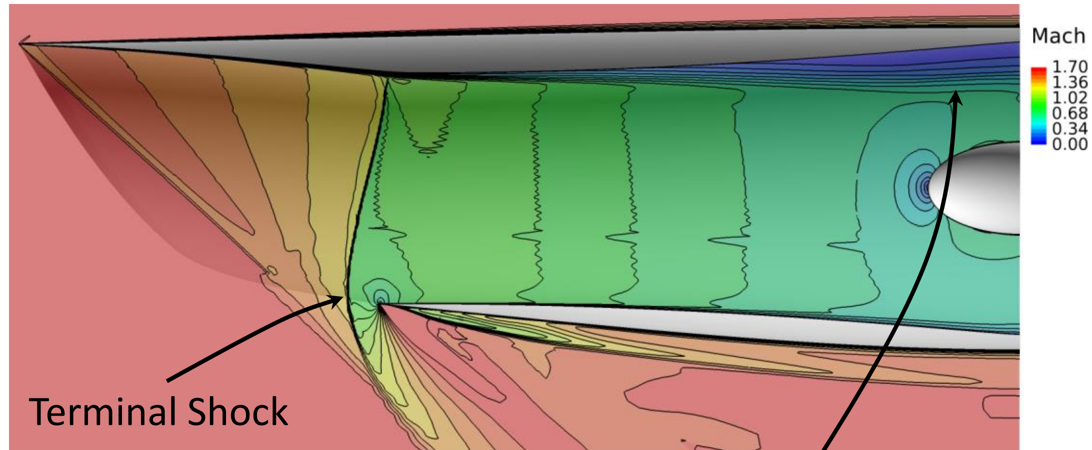
Objectives

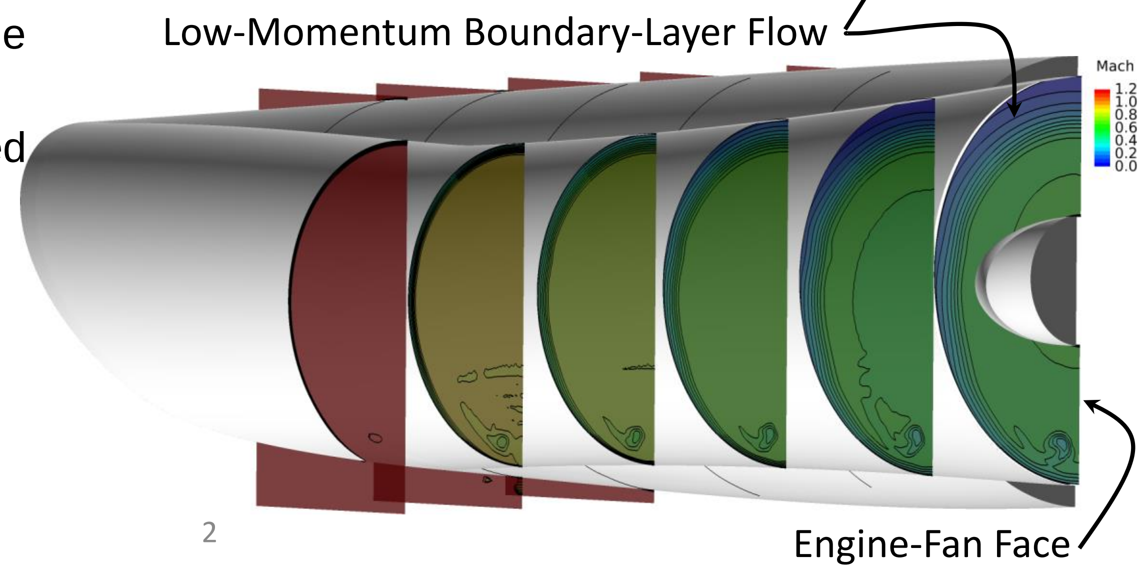
Main Objective: Reduce the total pressure distortion at the engine-fan face due to low-momentum flow caused by the interaction of an external terminal shock at the turbulent boundary layer along a streamline-traced external-compression (STEX) inlet for Mach 1.6.

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:

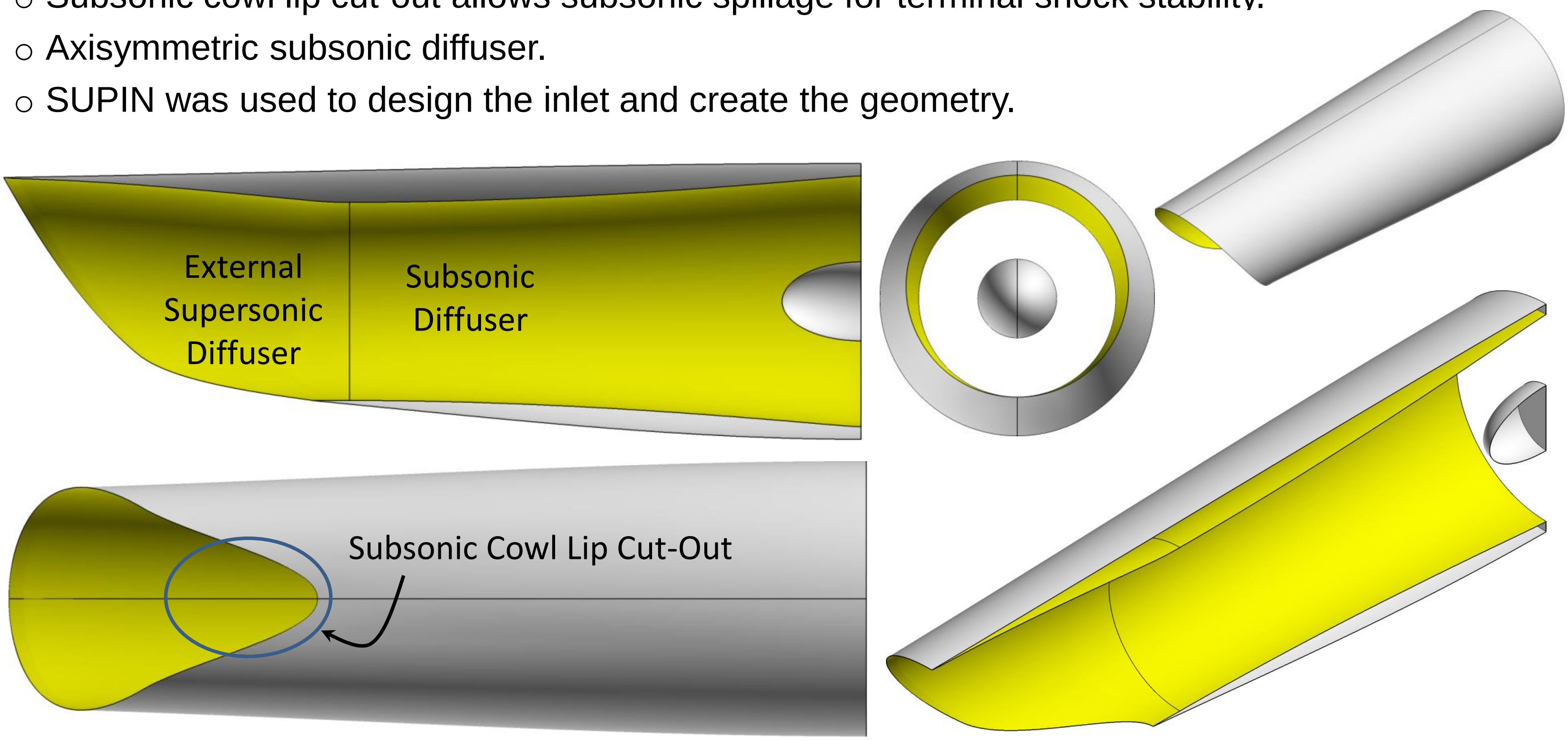
- What type of vortex generators work well for STEX inlets?
- What geometric properties of the vortex generators work well?
- How much can distortion reduced with vortex generators?





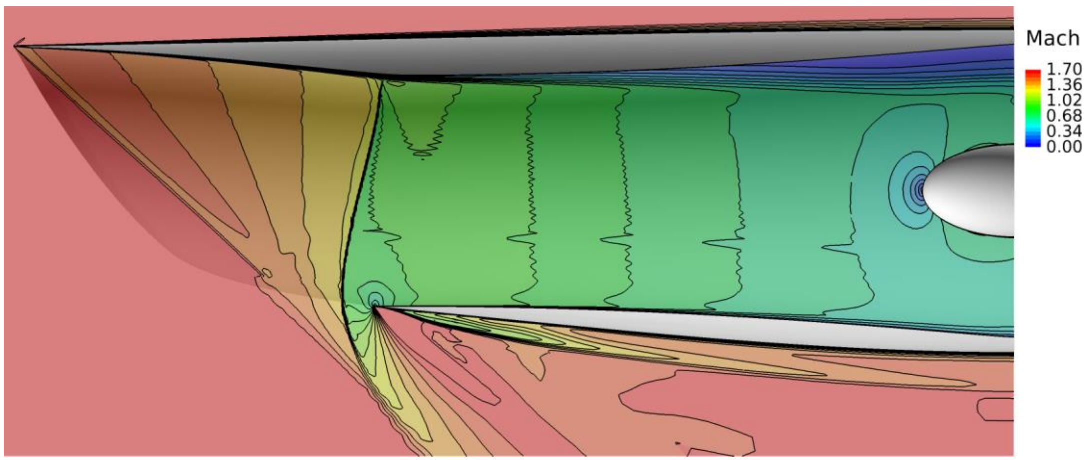
STEX Inlet Design

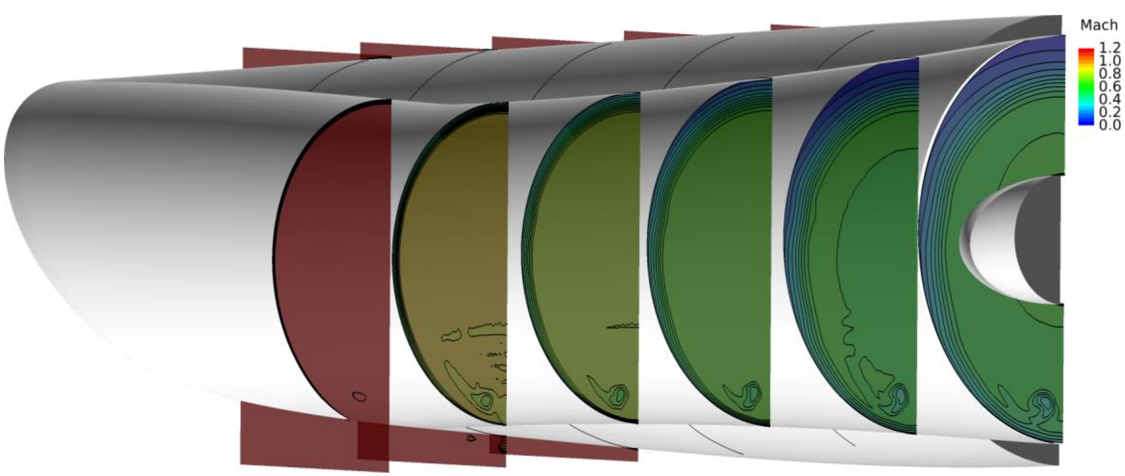
- Freestream of Mach 1.664 corresponds to NASA Glenn 8x6-foot wind tunnel condition.
- Engine-fan face of diameter D_2 = 0.9793 feet with a spinner and Mach number of M_2 = 0.4776 based on scaled GE F404 engine.
- Supersonic diffuser created by streamline-tracing of a circular cross-section through an axisymmetric, inward-turning, Otto-ICFA-Busemann flowfield with an outflow of Mach 0.90.
- Subsonic cowl lip cut-out allows subsonic spillage for terminal shock stability.
- Axisymmetric subsonic diffuser.
- SUPIN was used to design the inlet and create the geometry.

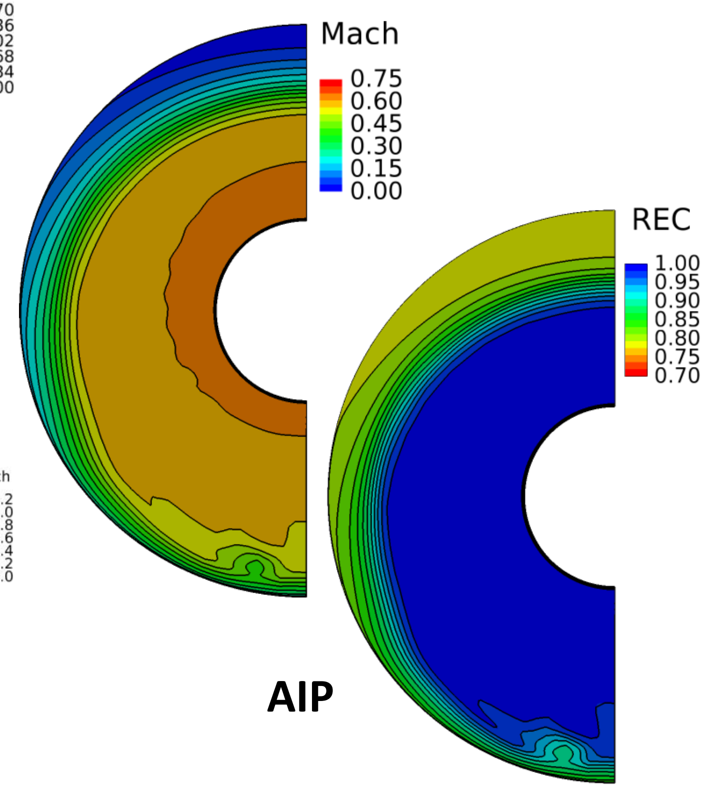


Baseline STEX Inlet Performance

- At Mach 1.664, MIL-E-5008B estimates total pressure recovery at p_{t2}/p_{t0} = 0.9521.
- SUPIN: p_{t2}/p_{t0} = 0.9336, W_2/W_0 = 1.0000, C_{Dwave} = 0.0162.
- Wind-US: p_{t2}/p_{t0} = 0.9339, W_2/W_0 = 0.9717, C_{Dwave} = 0.03627, IDC = 0.0851, IDR = 0.1036

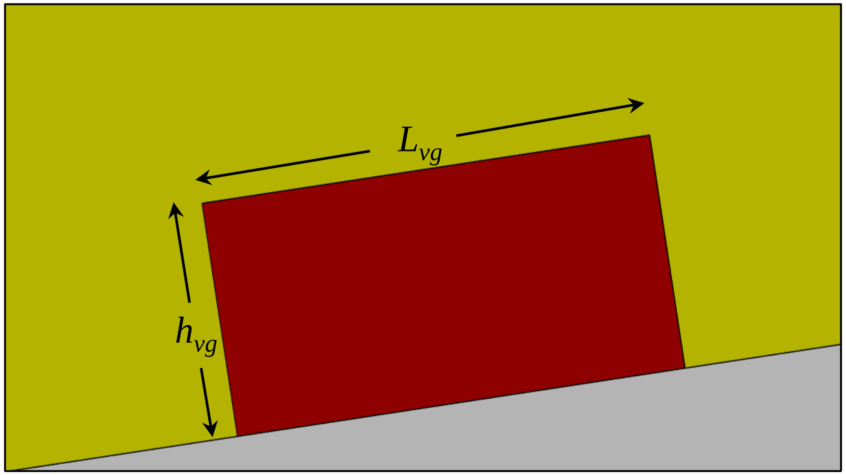


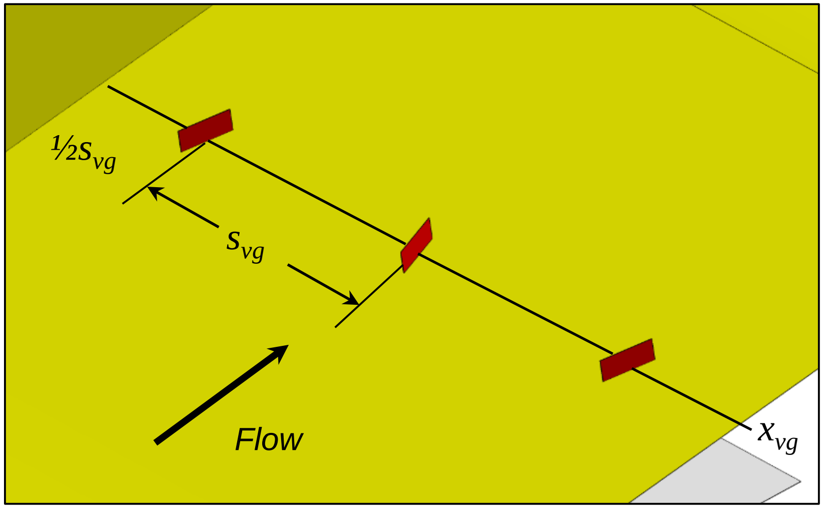


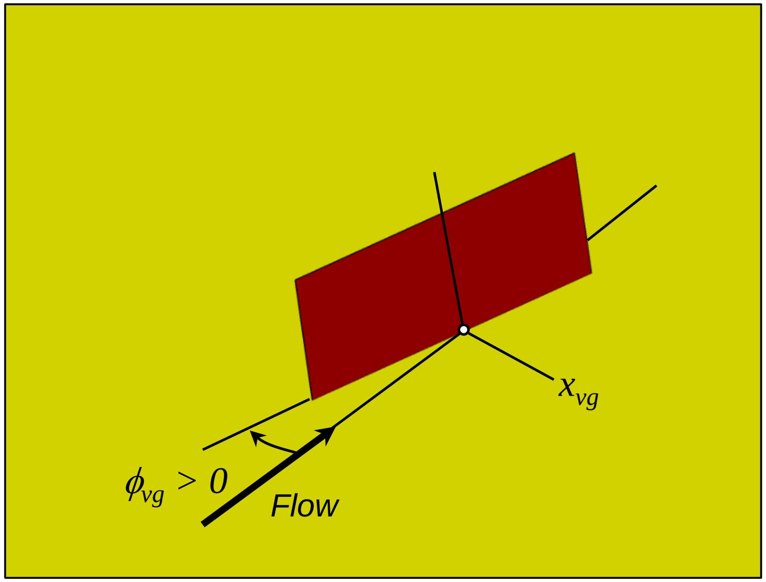


Vortex Generators: Vane-Type

- Explore vane-type VGs.
- Design parameters:
  - L_{vg}, Length (ft)
  - h_{vg}, Height (ft)
    - Traditional VGs
    - Micro-VGs
  - AR_{vg}, Aspect ratio (h/L)
  - ϕ_{vg}, Angle of incidence (deg)
  - s_{vg}, Spacing (ft)
  - x_{vg}, Axial placement of vane center (ft)

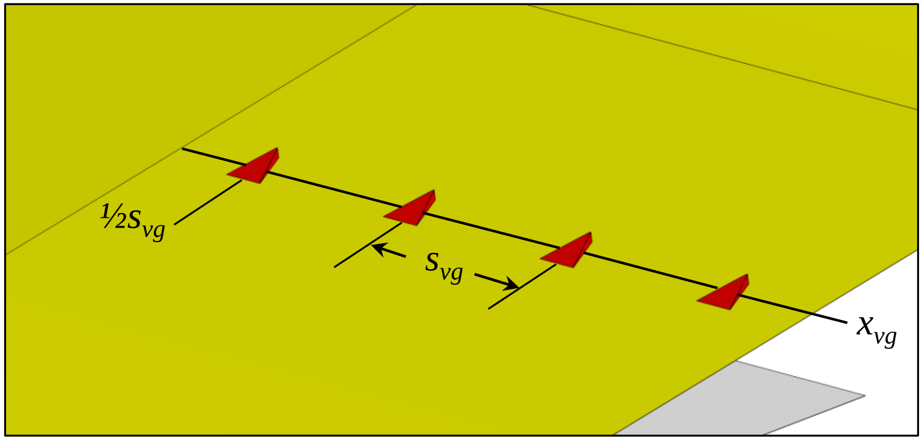


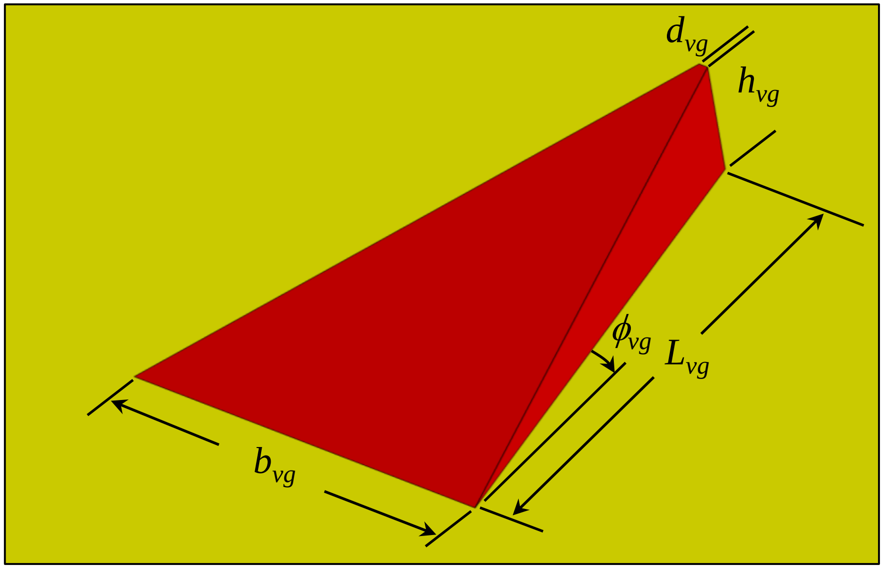




Vortex Generators: Ramp-Type

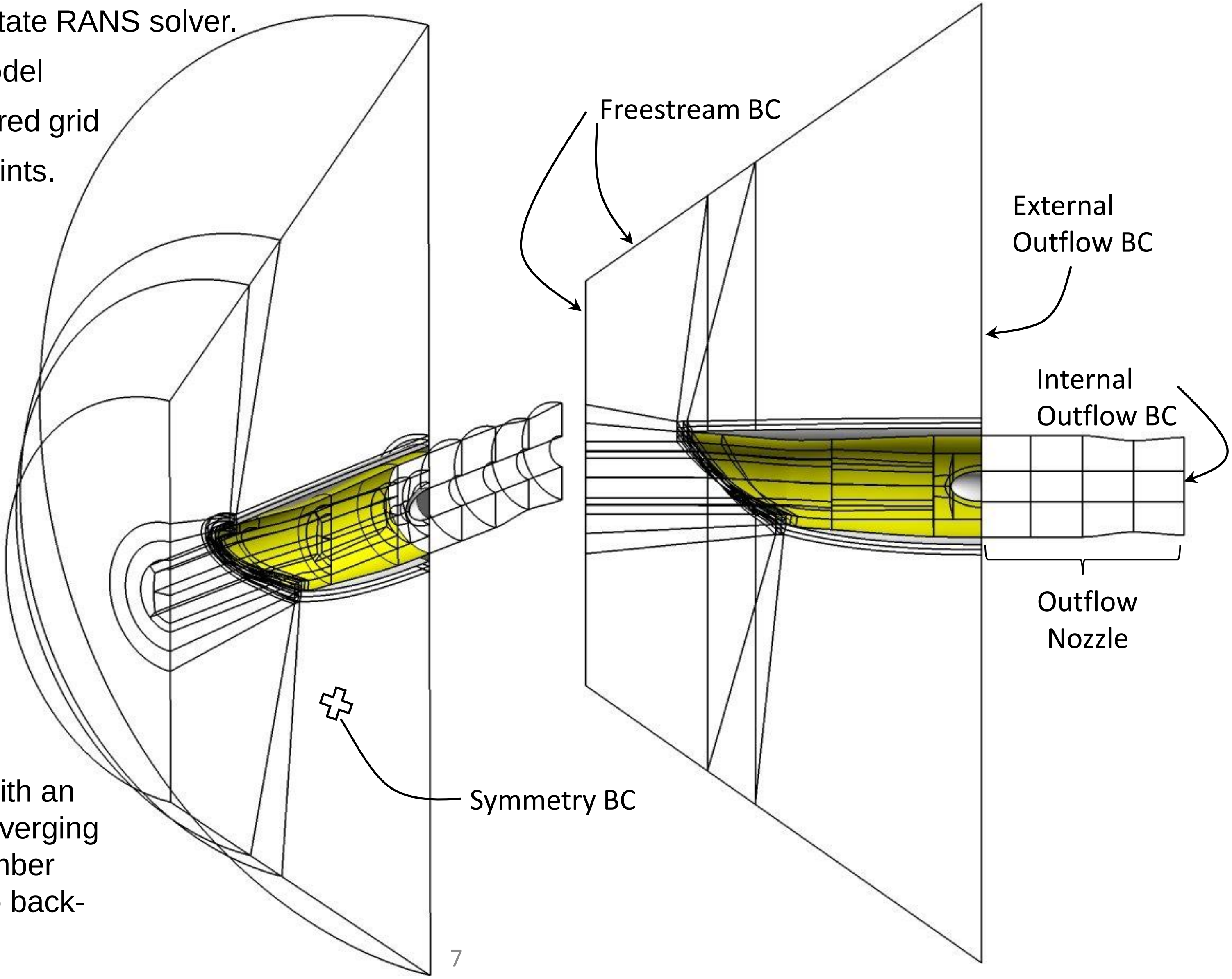
- Explore ramp-type VGs.
- Design parameters:
  - b_{vg}, Width of the base (ft)
  - L_{vg}, Length (ft)
  - h_{vg}, Height (ft)
  - d_{vg}, Width of trailing edge (ft)
  - AR_{vg}, Aspect ratio (h/L)
  - ϕ_{vg}, Angle of incidence (deg)
  - s_{vg}, Spacing (ft)
  - x_{vg}, Axial placement of ramp center (ft)





CFD Analysis

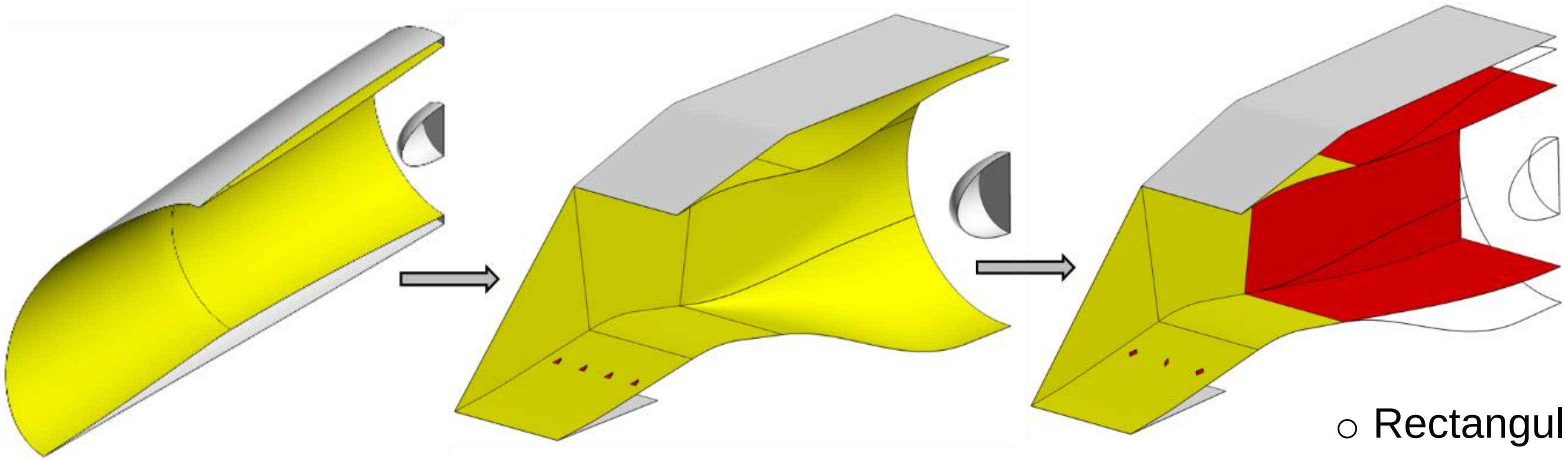
- ○ Wind-US, steady-state RANS solver.
- ○ SST turbulence model
- ○ Multi-block, structured grid
- ○ 2-15 million grid points.
- ○ $\Delta y^{+} \approx 1$.



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

Preliminary VG Study: 2D Inlet

Simplification of STEX inlet to 2D inlet for a preliminary study:

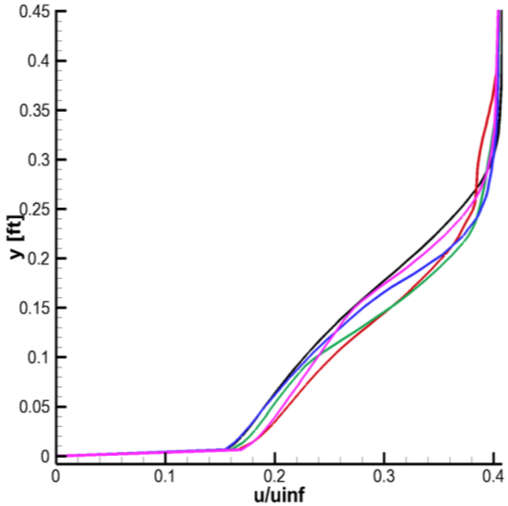


- Rectangular Duct
- Inviscid Sidewalls
- No corner flows

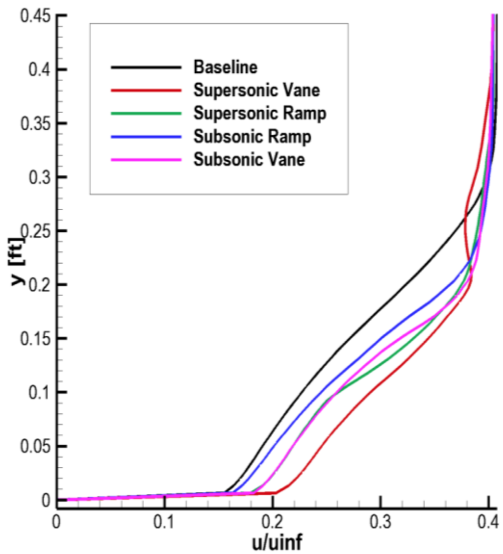
- **Objective:**
  - Study vane-type and ramp-type flow controls within the 2D inlet for the improvement of the total pressure recovery and reduction of total pressure distortion.
- **Observation**:
  - Implementation of **vanes** on the 2D inlet show overall more improvement in the AIP boundary layer compared to **ramps.**
- **Comparison study:**
  - Best performing **vane** of the inlet was compared to a BAY model.

Flow control study on 2D inlet

Upwash:



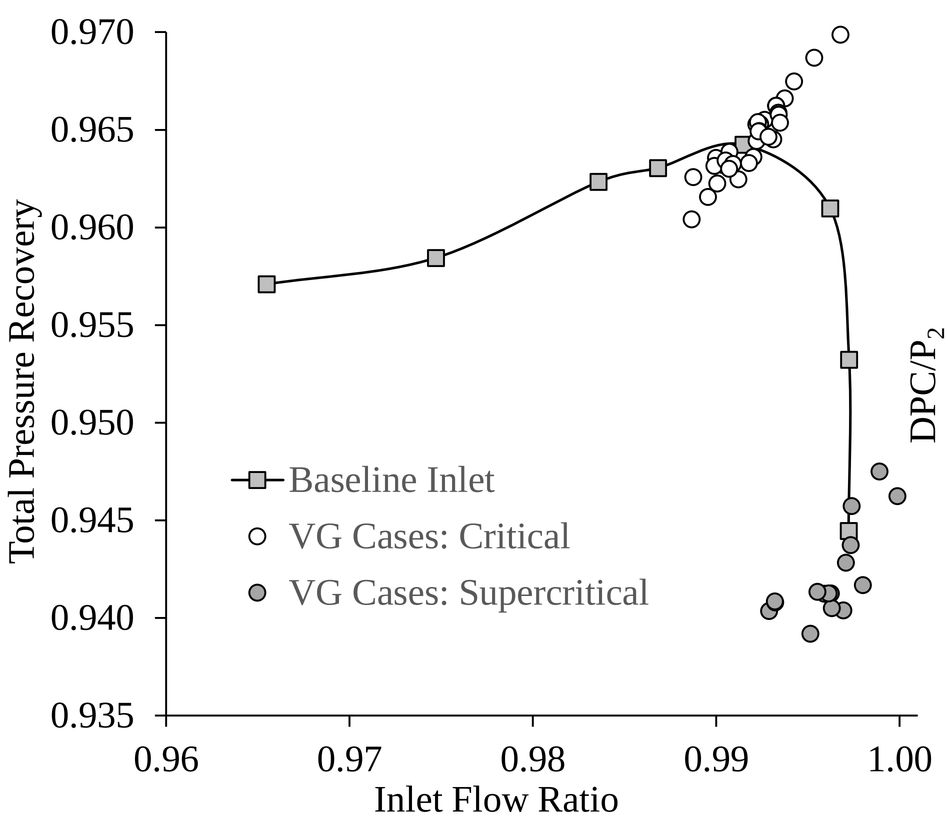
Downwash:

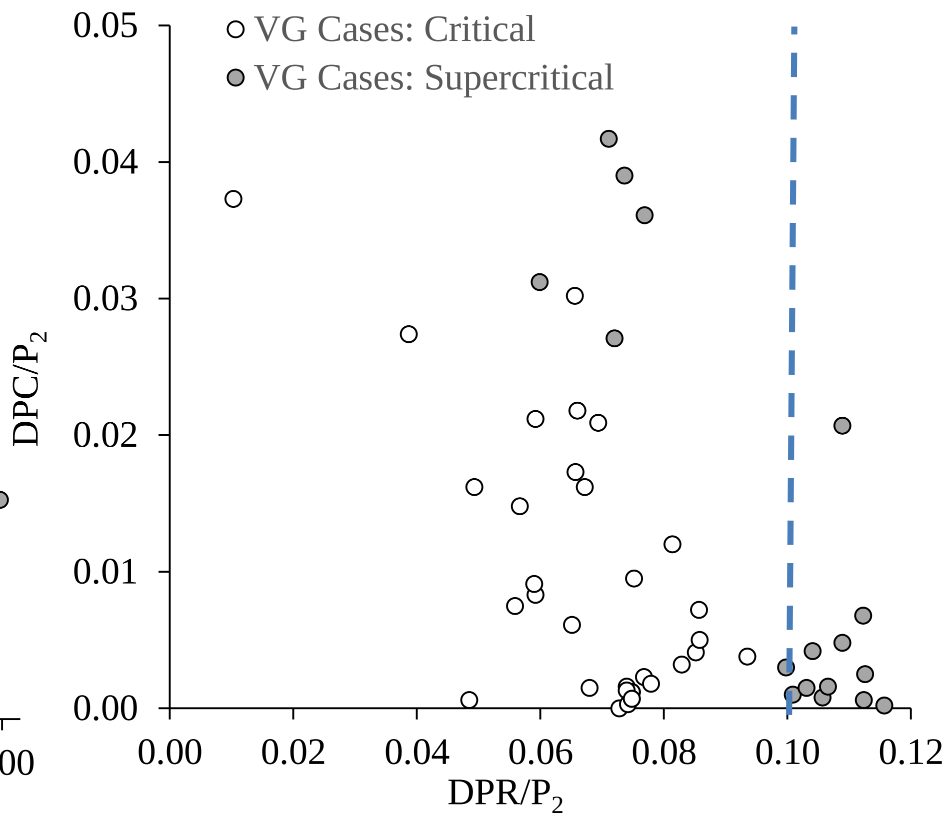


b)

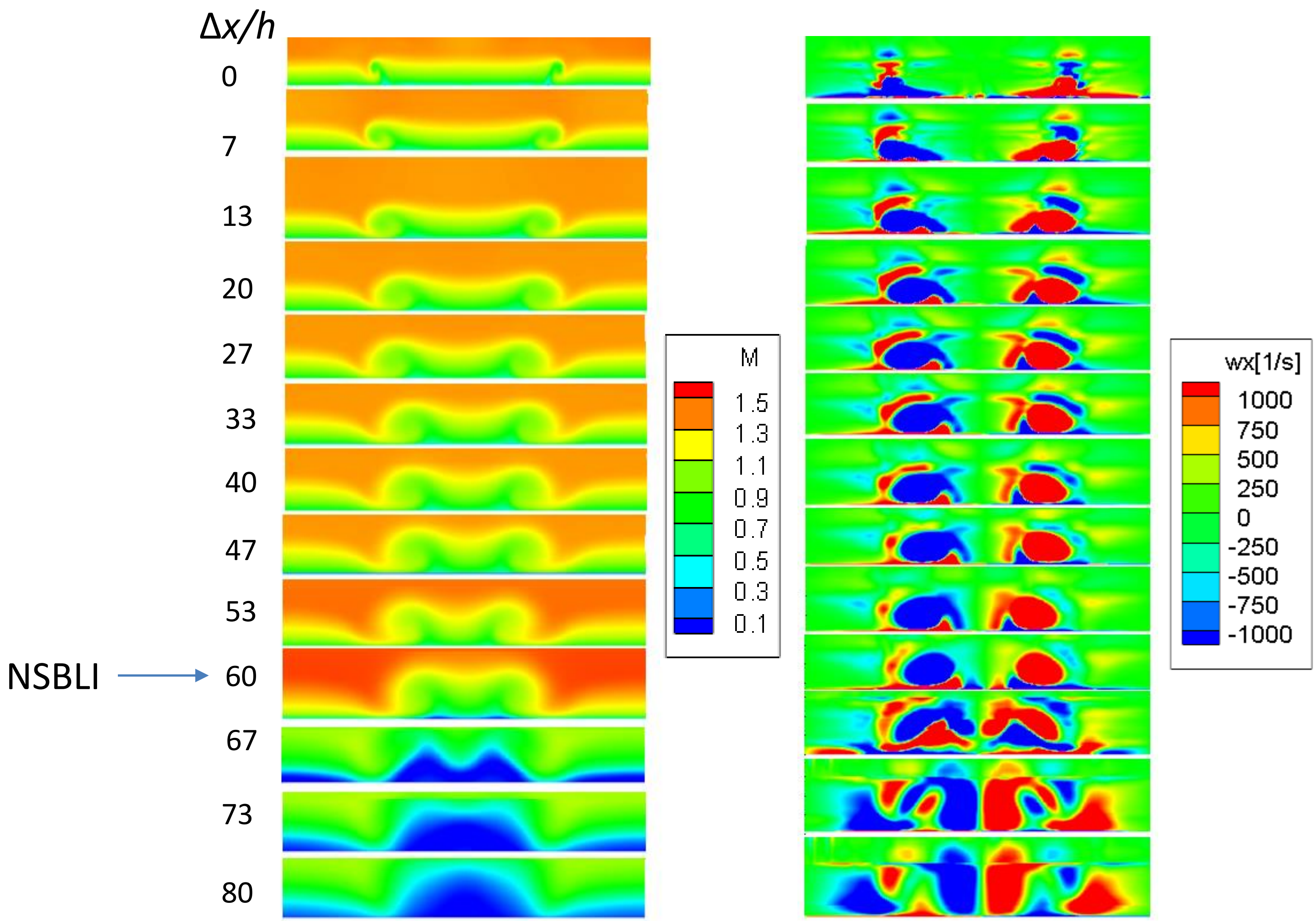
Case	c/h	s/h	DIST
Baseline	-	-	0.1916
Anderson	7.2	7.5	-
DV1	4.2	6.0	0.1834
DV2	3.7	8.3	0.1885
DR1	5.5	13.4	0.1863
DR2	6.6	10.8	0.1910
UV1	2.1	12.5	0.1862
UV2	2.0	12.5	0.1866
UR1	5.5	31.3	0.1870
UR2	4.3	25.3	0.1905

Flow control study on 2D inlet





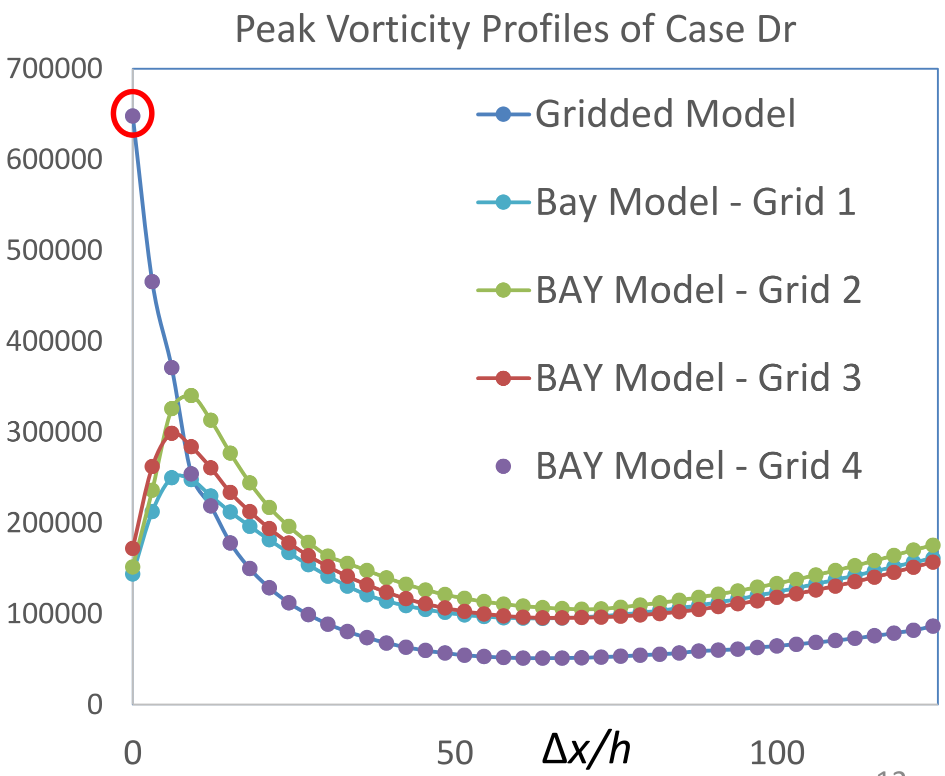
US Vane Study on 2D inlet

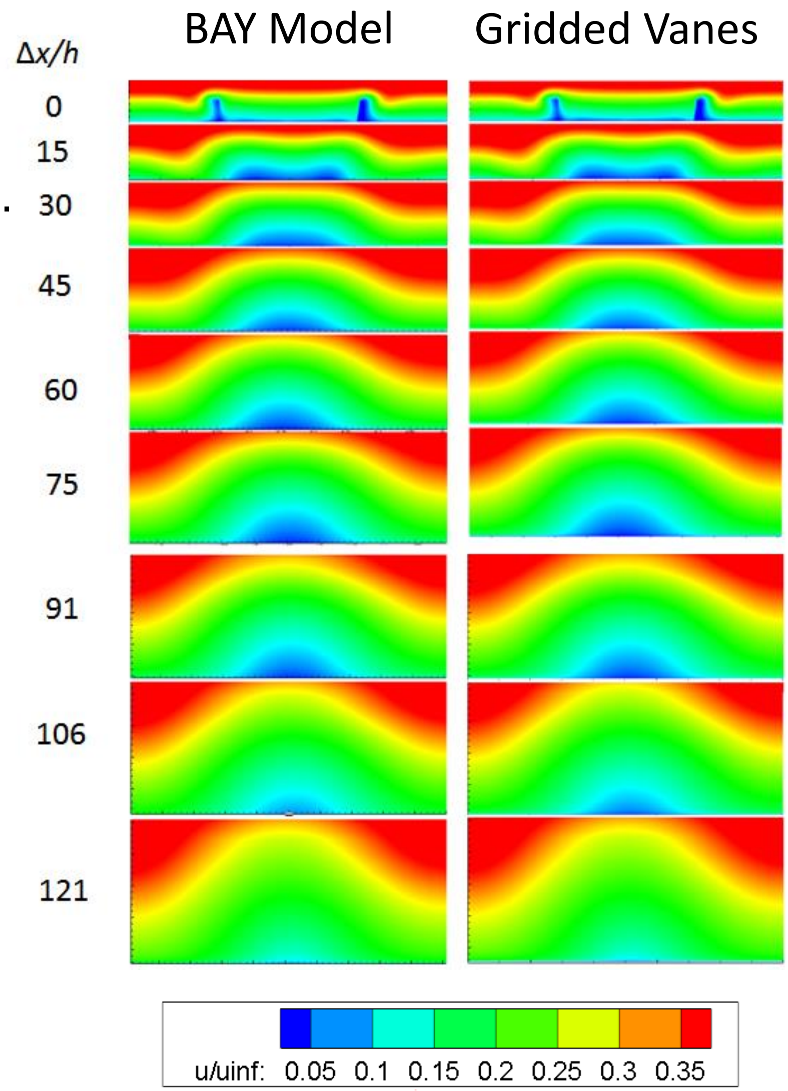


DS Vane Study on 2D inlet

Grid Resolution Study

- Grid I: Coarsest spacing. Equivalent to Baseline.
- Grid II: One-half spacing of Grid I.
- Grid III: One-third spacing of Grid II.
- Grid IV: Finest spacing. Equivalent to Gridded Vanes.

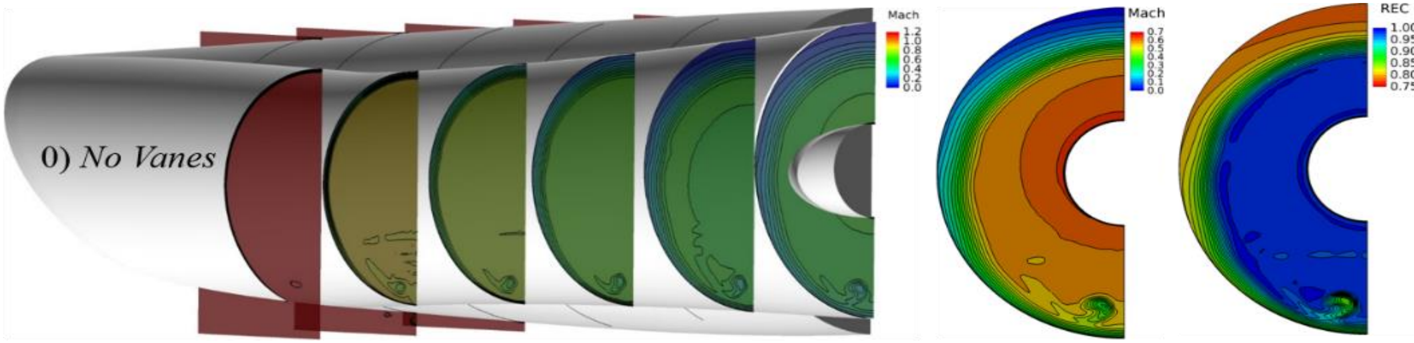




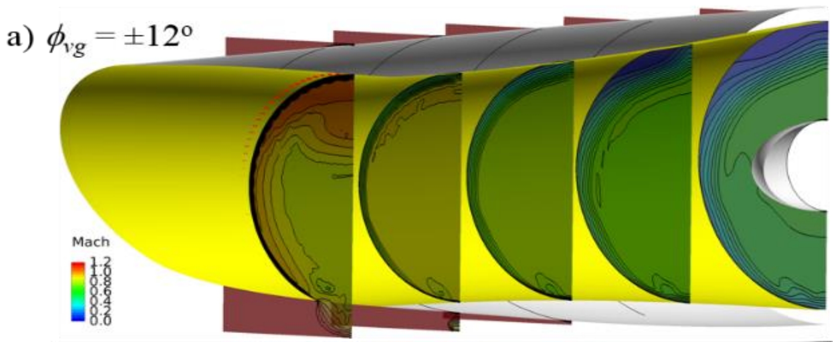
Study of VGs in the STEX Inlet

- Study vane-type flow control within the STEX inlet for the improvement of the total pressure recovery and reduction of total pressure distortion.
- Objectives include:
  - Discern significant differences between upstream and downstream vanes (ahead or downstream of the terminal shock).
  - Discern significant differences between counter-rotating vanes and co-rotating vanes.
  - Quantify significant relationships between vane geometry factors (height, length, spacing, angle, position).
- Responses: 1) Total pressure recovery at AIP (cane curve), 2) IDC and IDR.

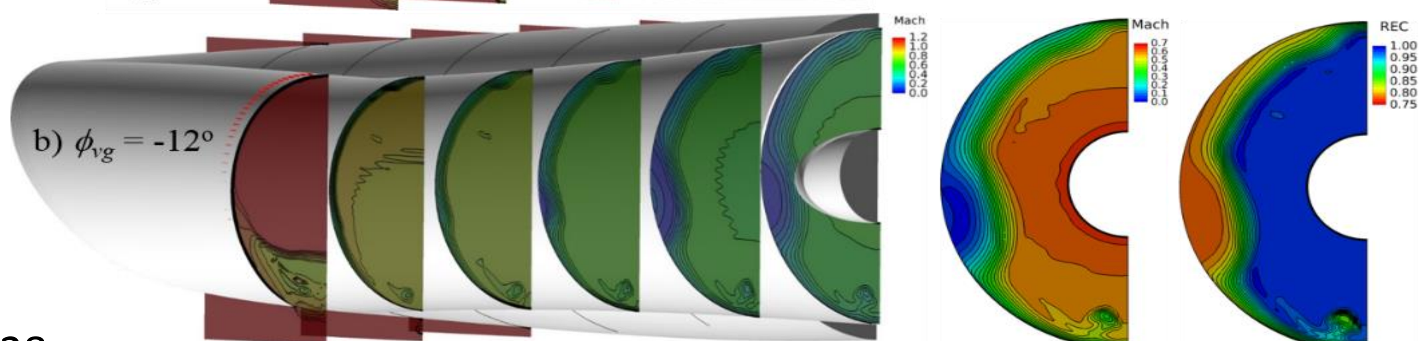
Preliminary Study of VGs on the External Supersonic Diffuser



w2/w0 = 0.9710
pt2/pt0 = 0.9343
IDC = 0.0857
IDR = 0.0976



w2/w0 = 0.9615
pt2/pt0 = 0.9235
IDC = 0.0891
IDR = 0.1054

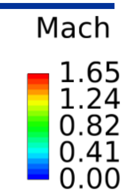


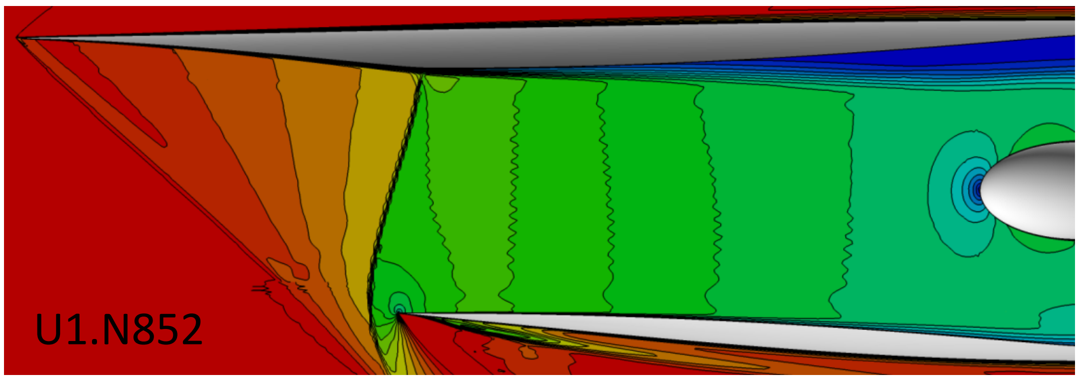
w2/w0 = 0.9648
pt2/pt0 = 0.9280
IDC = 0.1166
IDR = 0.0800

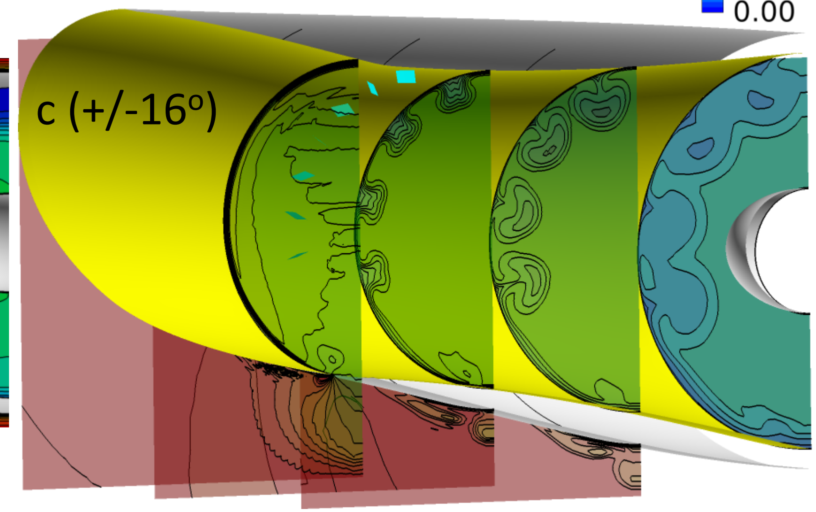
28 vanes
Height comparable to the sonic height
$h/L \approx 0.275$
$h/\delta \approx 0.359$

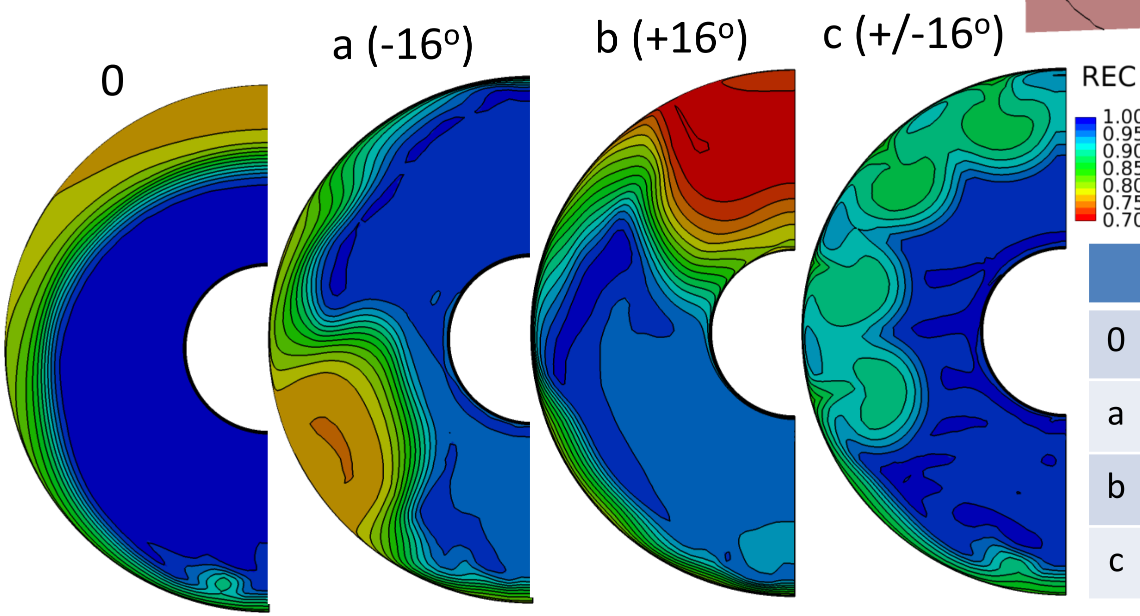
Preliminary Study of VGs in the Subsonic Diffuser

- Started exploring vanes in subsonic diffuser using BAY model of Wind-US.
- Vanes of local boundary layer height (0.381 inches). Aspect ratio is 2.0.
- Solution U1.N852.





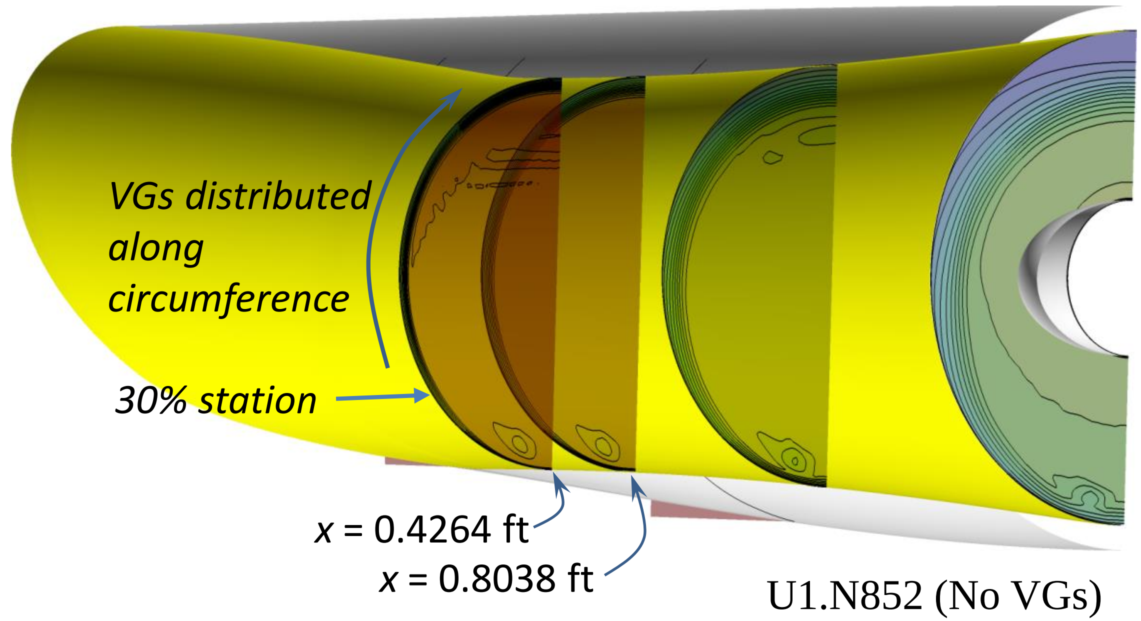




	W_2/W_{cap}	p_{t2}/p_{t0}	IDC	IDR
0	0.9726	0.9302	0.0936	0.1046
a	0.9464	0.9103	0.1205	0.0527
b	0.9299	0.8863	0.1733	0.0282
c	0.9676	0.9415	0.0374	0.0445

Two-Level Fractional Factorial Design

- Vane-type VGs
- Distribute VGs about upper 70% of the inner circumference of inlet.
- Height of the vanes will vary along the circumference of the diffuser to keep proportional to local boundary layer.
- Use outflow nozzle setting of Baseline U1 inlet at the critical point (U1N851).
- Use BAY model of Wind-US.
- Four groupings:
  - i. Downstream. Con-Div Pairs.
  - ii. Downstream. Co-Rot Array.
  - iii. Upstream. Con-Div Pairs.
  - iv. Upstream. Co-Rot Array.



Factors (i. Downstream. Con-Div Pairs.)

1) x_{VG} (ft): 0.4264, 0.8038
2) $(h/\delta)_{VG}$: 0.5, 1.0
3) α_{VG} (deg): 8 deg, 16 deg
4) $(L/h)_{VG}$: 2, 3
5) $(s/h)_{VG}$: 3, 5

Responses

1) *Flow Ratio*
2) *Total Pressure Recovery*
3) *Distortion (IDC, IDR)*

2_{III}^{5-2} Design uses 8 runs to establish main effects

Quarter-Fractional Factorial Design $2_{III}^{k-2}, k = 5$

- **Fractional Factorial Design consists of 8 Runs & 5 Factors to establish main effects**:

Runs	Zone	h/δ	L/h	s/h
#1	US	1	2	3
#2	DS	0.5	2	3
#3	DS	1	3	3
#4	US	1	2	5
#5	US	0.5	3	5
#6	US	0.5	3	3
#7	DS	1	3	5
#8	DS	0.5	2	5

Counter-Rotating α (°)
-/+ 16
-/+ 8
-/+ 8
-/+ 8
-/+ 8
-/+ 16
-/+ 16
-/+ 16

Co-Rotating α (°)
- 16
- 8
- 8
- 8
- 8
- 16
- 16
- 16

- **Two-Level Operators**:

	Zone	h/δ	α (°)	L/h	s/h
"Low" operator:	US	0.5	8	2	3
"High" operator:	DS	1	16	3	5

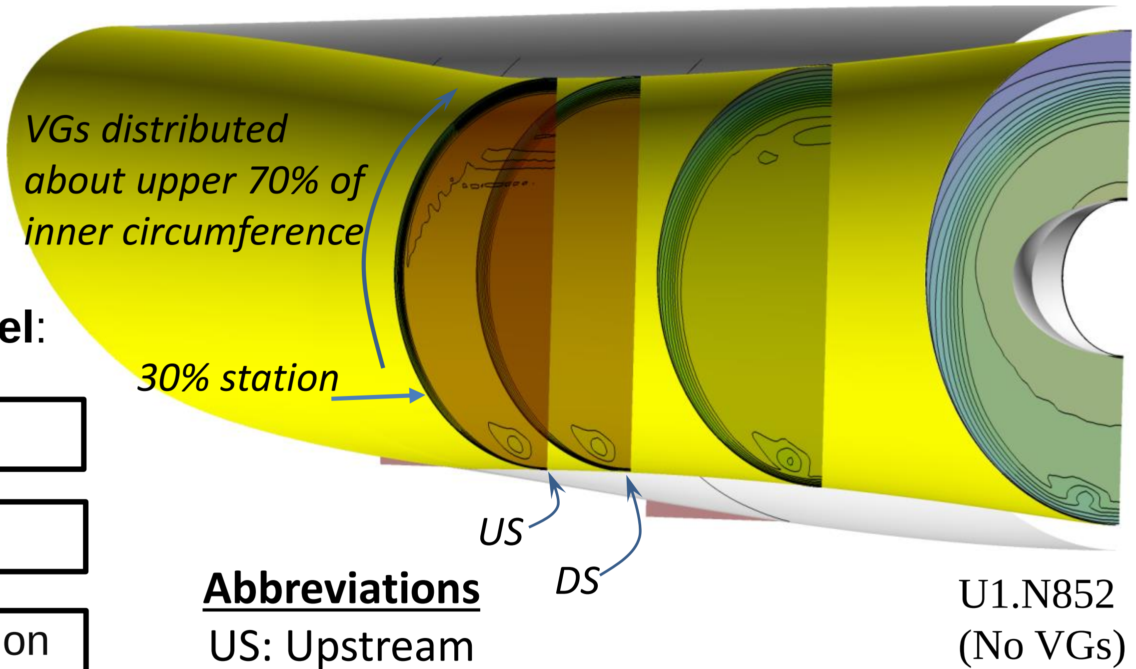
- **Responses**:
  - Response I: Total Pressure Recovery
  - Response II: Circumferential distortion descriptor
  - Response III: Radial tip distortion descriptor

Abbreviations

US: Upstream

DS: Downstream

Fractional Factorial Design for Vane-Type VGs



Grid Interpolation to Bay Model:

Reference Data

↓

Interpolation onto Grid

↓

Interpolation in Streamwise Direction
Interpolation in Angular Direction
Interpolation in Radial Direction

↓

Numerical Estimation

↓

Polar/Cartesian to Vector Conversion

↓

Interpolation (with Reference Data)

Abbreviations

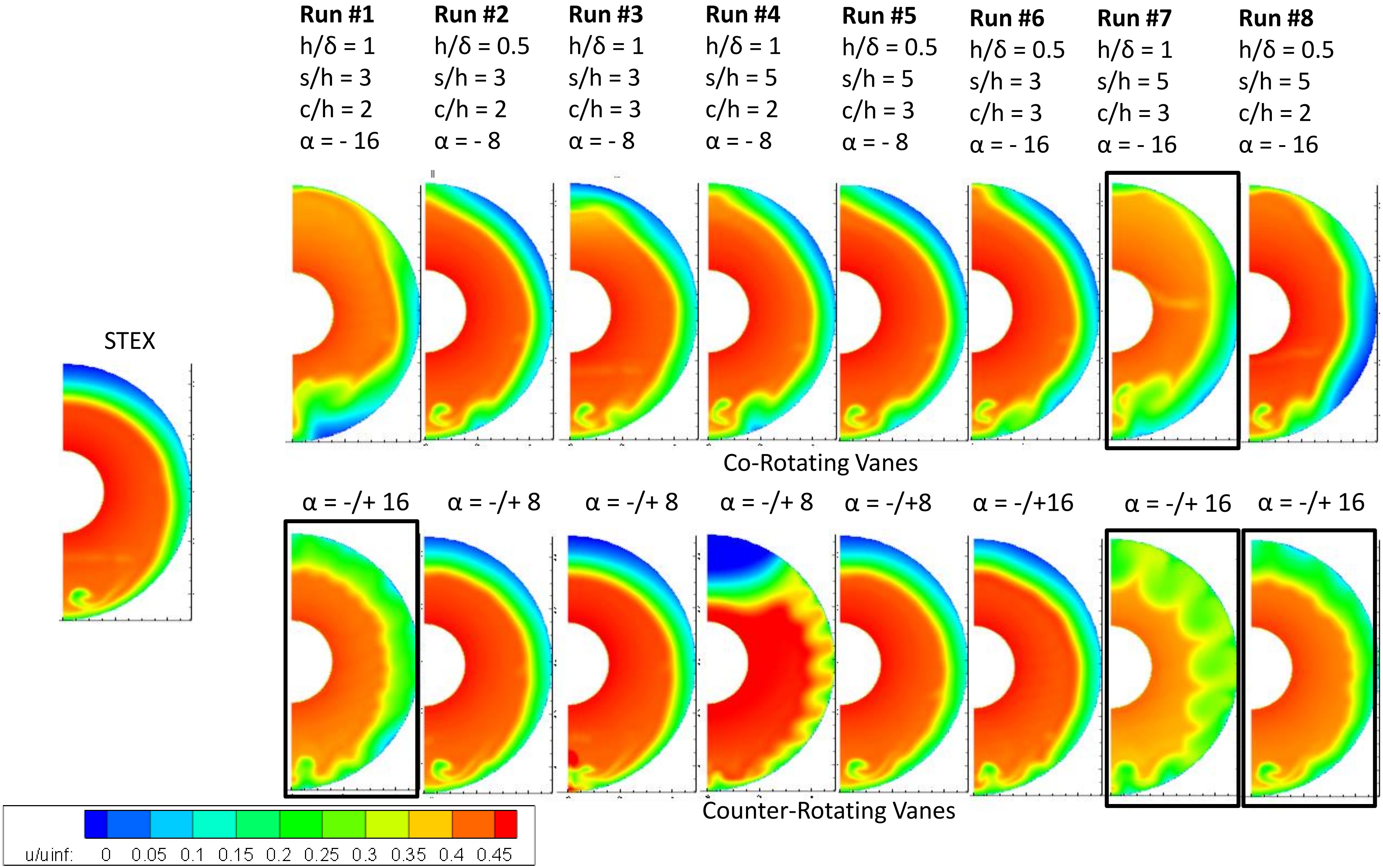
US: Upstream

DS: Downstream

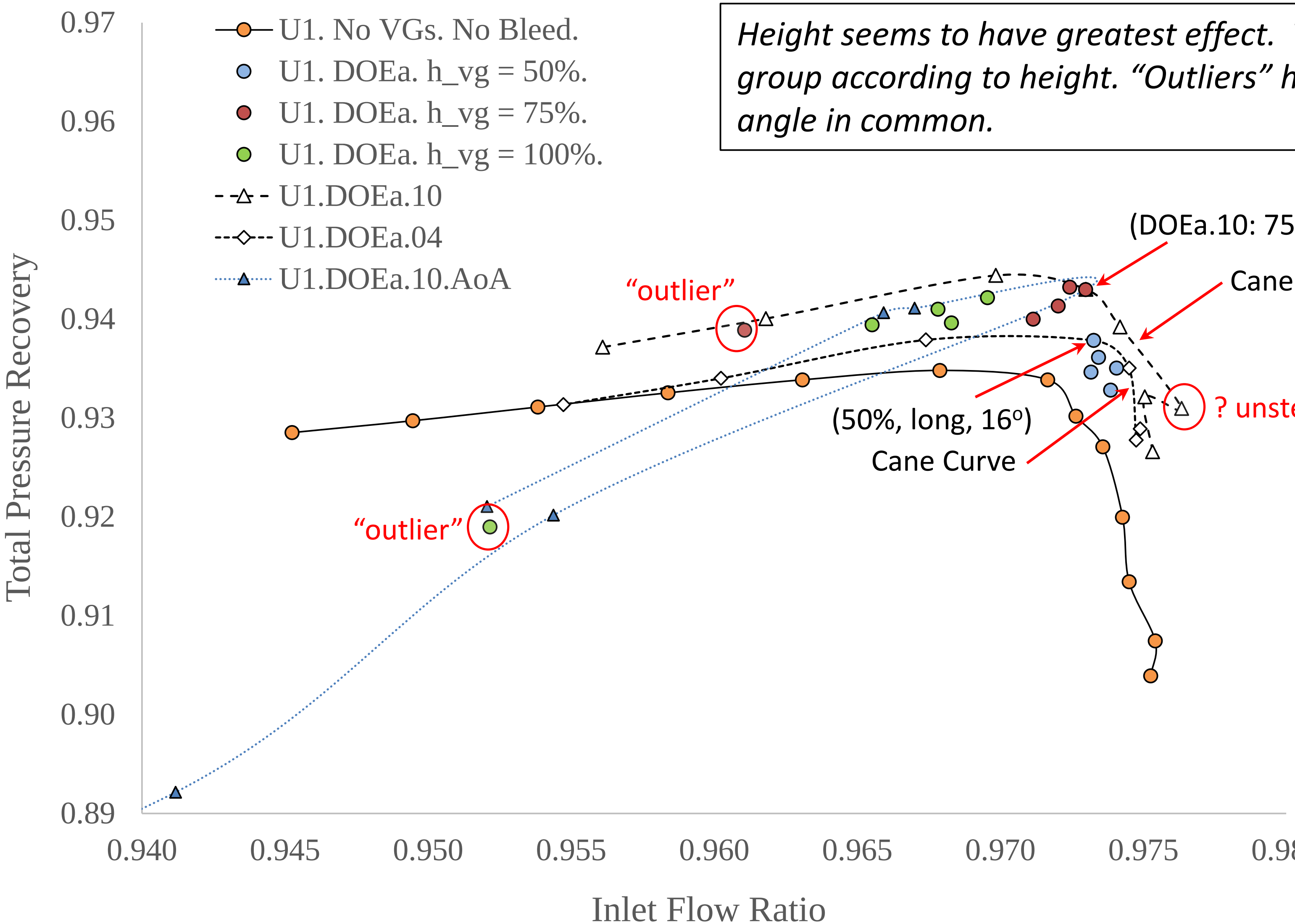
Notes:

- VG heights vary along the circumference of the diffuser to keep proportional to local boundary layer.

Fractional Factorial Design Study @ AIP

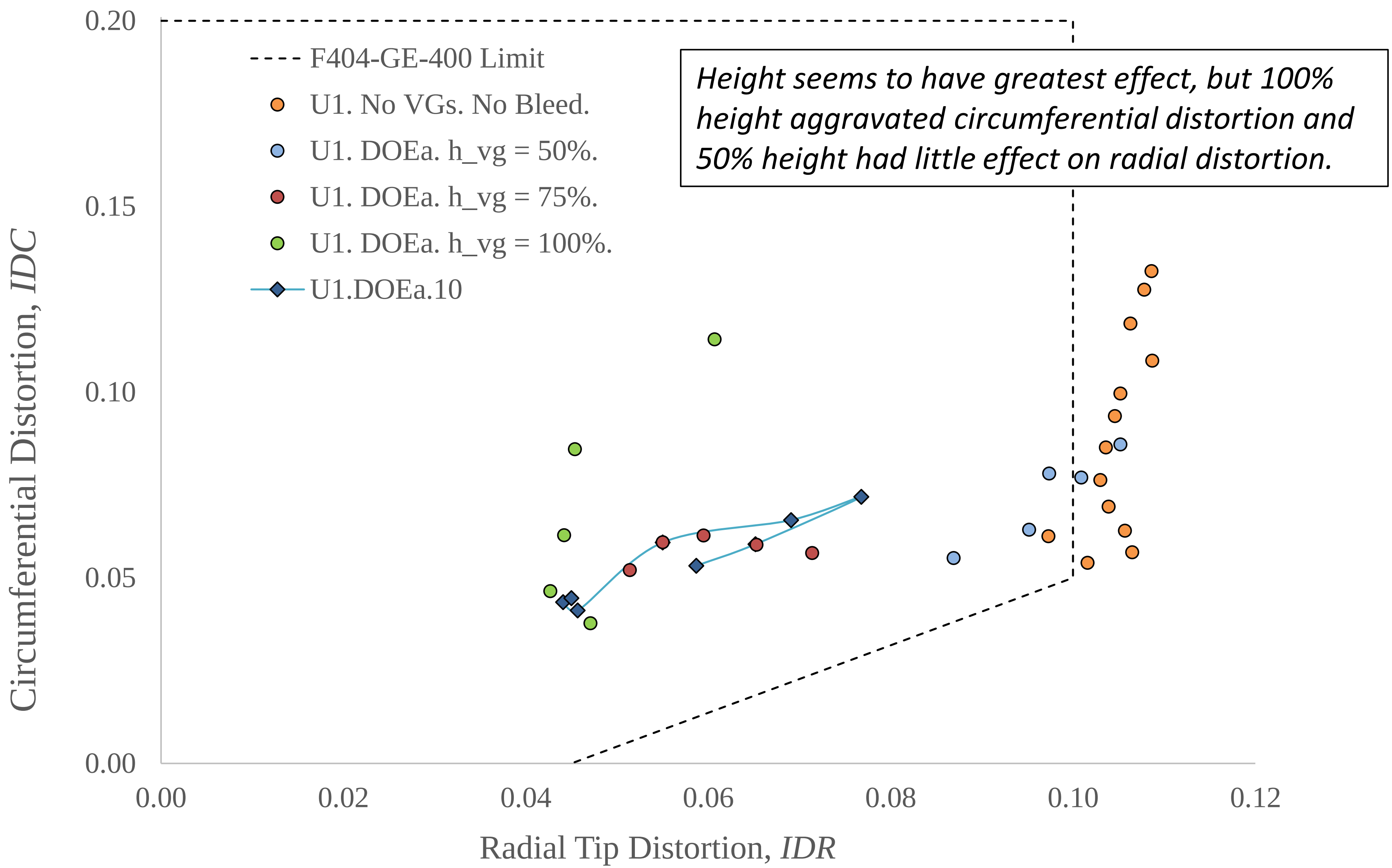


Characteristic Cane Curves



Height seems to have greatest effect. The points group according to height. "Outliers" have 8º angle in common.

Distortion



0.20
0.15
0.10
0.05
0.00
0.00
0.02
0.04
0.06
0.08
0.10
0.12
Circumferential Distortion, *IDC*
Radial Tip Distortion, *IDR*
F404-GE-400 Limit
U1. No VGs. No Bleed.
U1. DOEa. h_vg = 50%.
U1. DOEa. h_vg = 75%.
U1. DOEa. h_vg = 100%.
U1.DOEa.10
Height seems to have greatest effect, but 100% height aggravated circumferential distortion and 50% height had little effect on radial distortion.

Conclusions and Future Plans

- Explore the use of flow control devices within the inlet.
- Continue to work on the DOE of vane-type VGs in a converging-diverging pattern that will explore height, aspect ratio, and spacing for one nozzle setting. Response variables will be flow ratio, total pressure recovery, IDC and IDR.
- Explore interactions between different factors.
- Explore unsteady (DES) simulation of inlet flow with and without VGs.