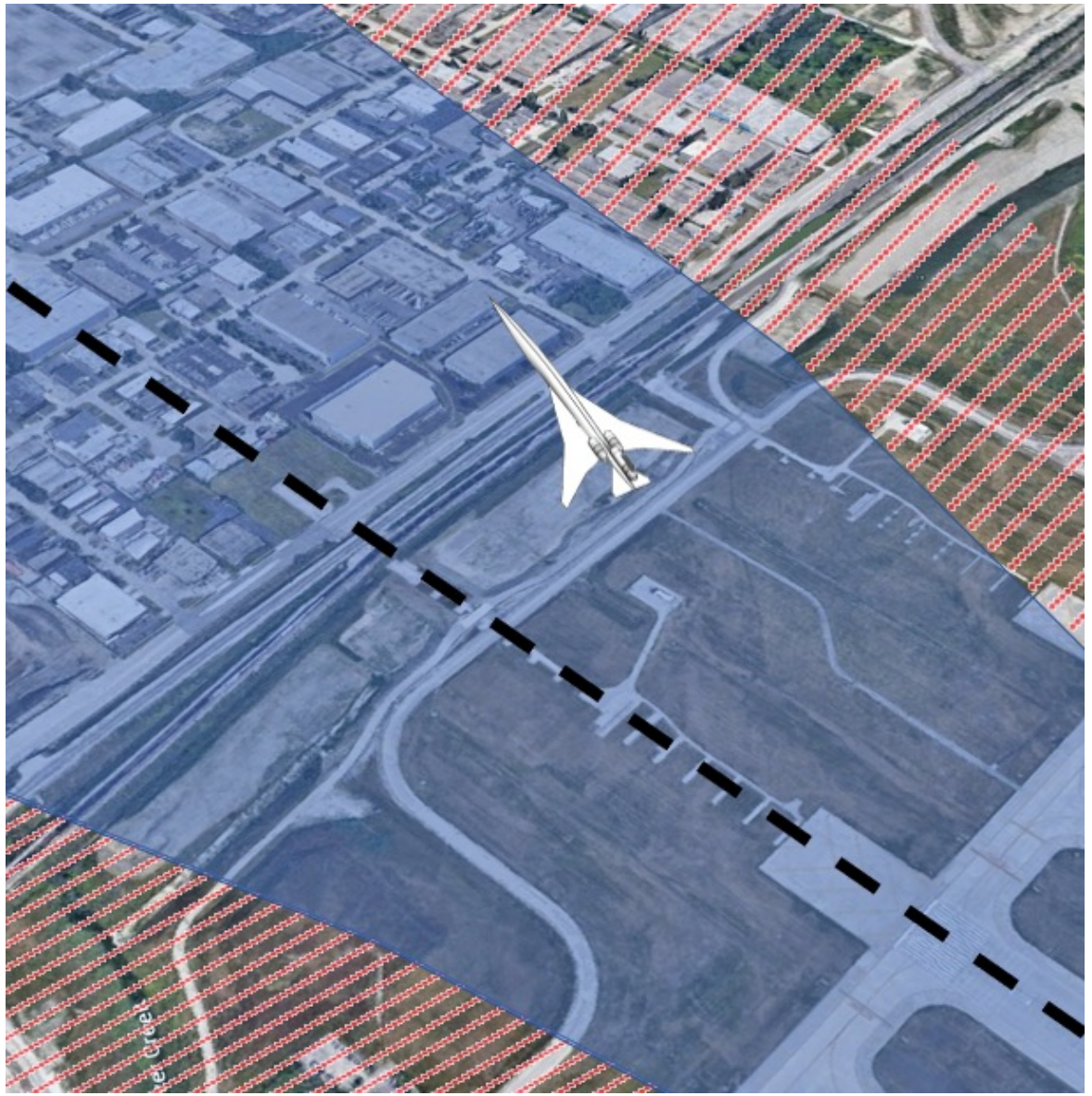
Advanced Parametric Lobe Mixer Concepts for Internally Mixed Nozzles



AIAA Aviation Forum

12 June 2023

Will Banks, HX5, LLC

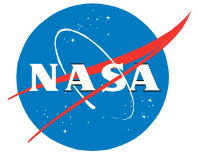
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Supported by Commercial Supersonic Technology (CST) Project

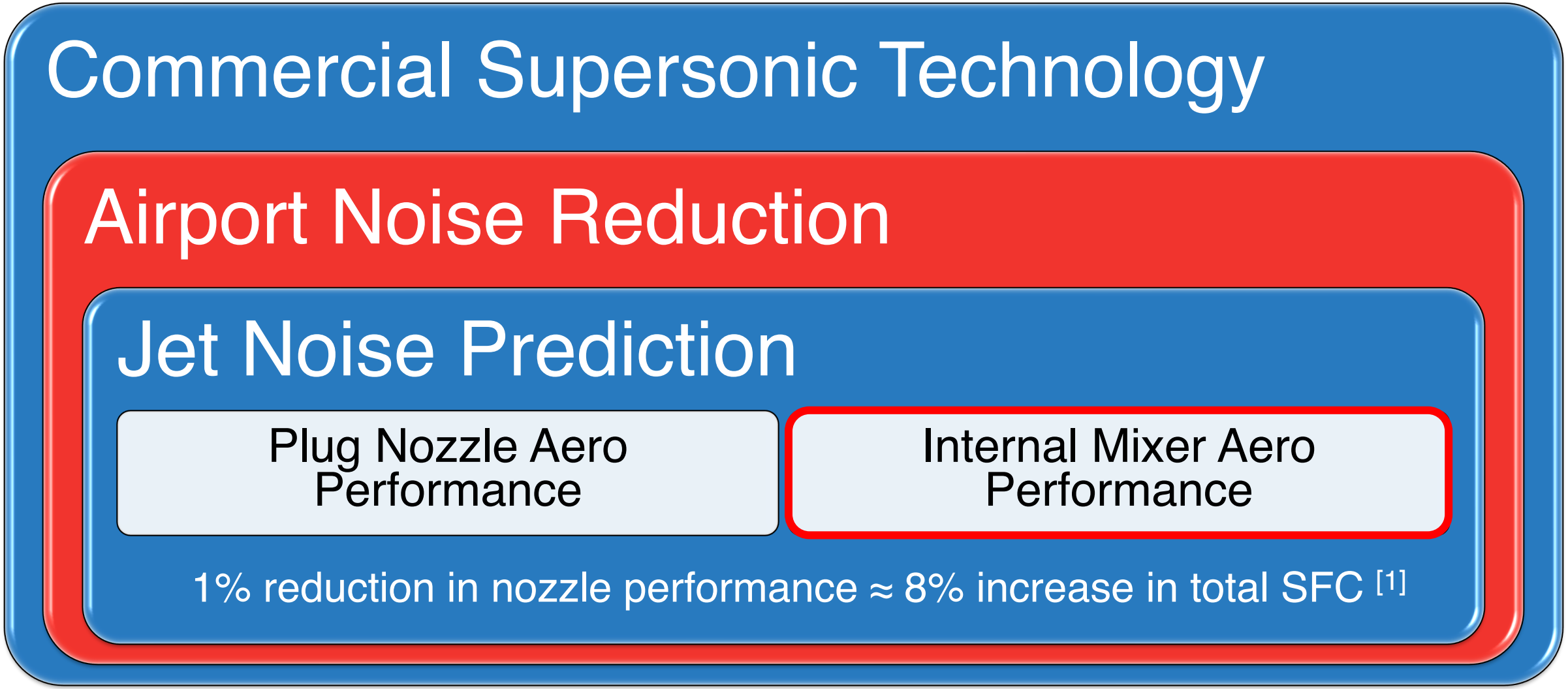
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Table of Contents



- Background
- Study Environment
- Nozzle & Baseline Mixer
- Advanced Features
- Gridding
- Numerical Solution
- Performance Response
- Fluid Mechanics Analysis
- Conclusions

Background – CST Airport Noise



[1] Stitt, L. E., "Exhaust Nozzles for Propulsion Systems With Emphasis on Supersonic Cruise Aircraft," NASA-RP-1235, 1990.

Background – Internally-Mixed Plug Nozzle Toolset

- Plug nozzles offer superior thrust & noise benefits for supersonic turbofan engines
  - Requires internal mixing upstream of plug
- Large database available for subsonic internal lobe mixers, virtually **none for supersonic**
- Objectives of parent project
  - Build **toolchain** to parametrically generate internally-mixed plug nozzles
  - Create **large design pool** and collect RANS simulation data
  - Pass top candidates to **high-fidelity** evaluation methods

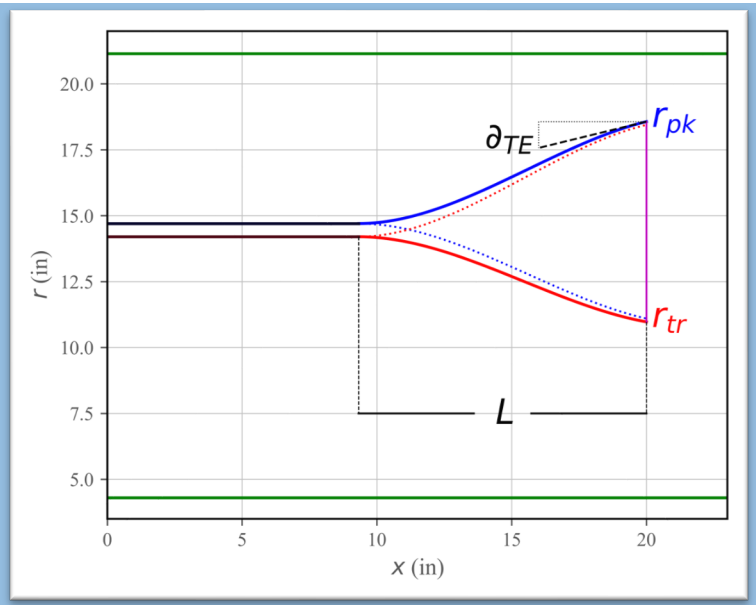


Fig. 1 Mixer spline profile, from Banks. [2]

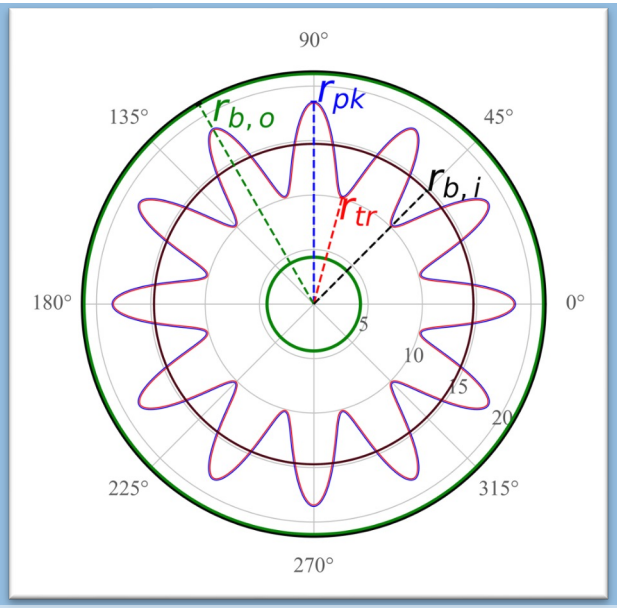


Fig. 2 Mixer TE profile, from Banks. [2]

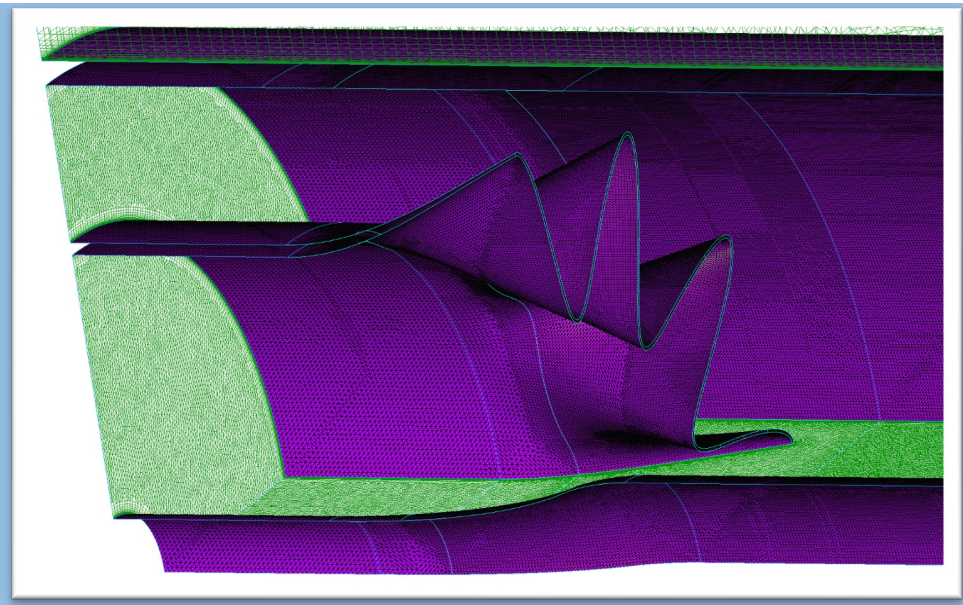


Fig. 3 Grid of mixer in nozzle housing, from Banks. [2]

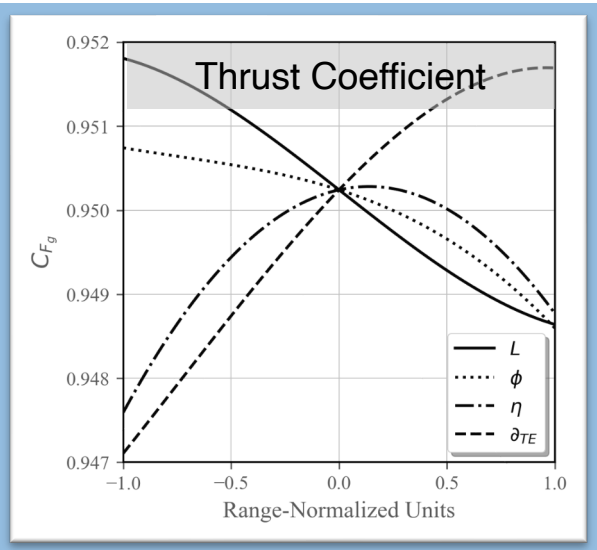
[2] Banks, W. V., "Optimization of a Parametric Lobe Mixer for Internally Mixed Nozzles," AIAA Paper 2022-3261, AIAA Aviation Forum, Chicago, IL, 2022.

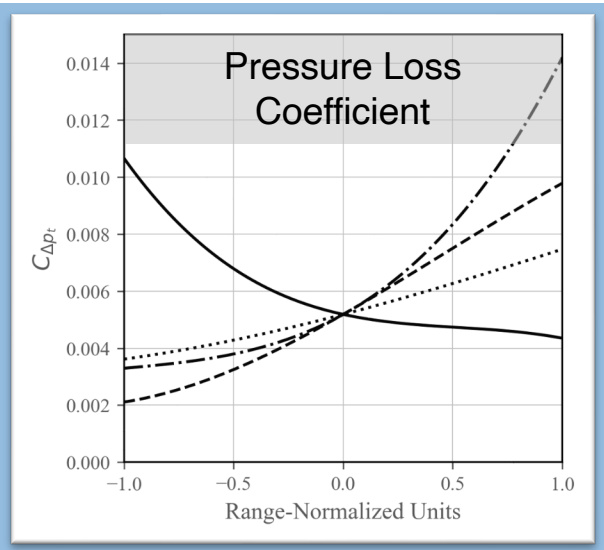
Background – Basic Lobe Mixer Design [2]

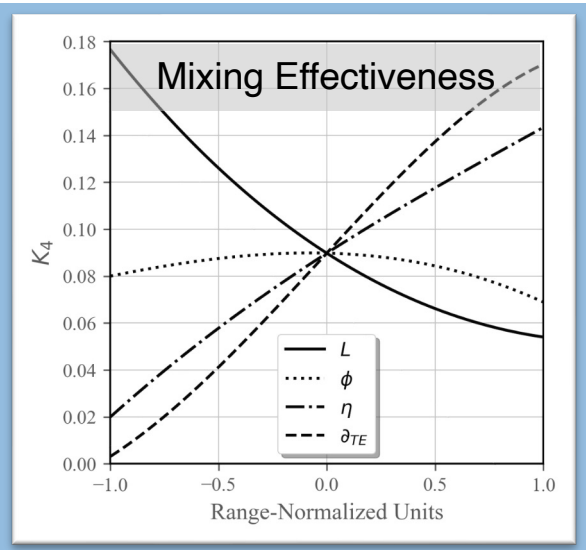
- Python-based tool generates mixer grids from 5 parameters
  - Housed in “academic” plug nozzle with constant-area extended duct
- Response Surface (RS) study on 72 geometries revealed:
  - Mixer penetration - **less performance impact** than expected
  - Trailing edge slope - high performance impact via **axial vorticity**
  - Ineffective mixers **separated streams**
  - Aggressive mixers **separated flow**
- Surrogate model created for performance optimization
  - Optimal designs maximized axial vorticity
- Scarfing and scalloping added as advanced “subtractive” features

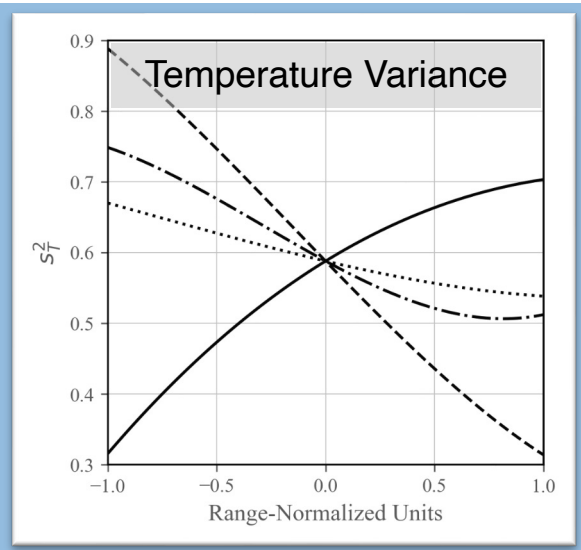
Parameter	RS Min	RS Max
n	12	-
ϕ	50%	70%
L	7.5”	20”
η	-0.25	0.25
∂_{TE}	0	0.5

Table 1 RS study range, from Banks. [2]









Study Environment: STCA

- Supersonic Technology Concept Aeroplane (STCA) is intended to inform ICAO regulations [3]
  - 8-passenger business jet, 55t (121klb) max gross weight
  - Three CFM56s used for analytical donor engine, redesigned for Mach 1.4 cruise @ 50,000ft.
- Ambient conditions and engine specs inform Jet Noise Prediction efforts, including current work

Table 1 Key conditions from 55t STCA supersonic cruise analysis.

Property	Value
p_∞	$1.68\ lb/in^2$
T_∞	$217\ K$
M_∞	1.4
NPR_b	6.158
NPR_c	5.633
NTR_b	1.736
NTR_c	4.654
$\dot{m}$	$146.2\ lbm/s$
BPR	3.33

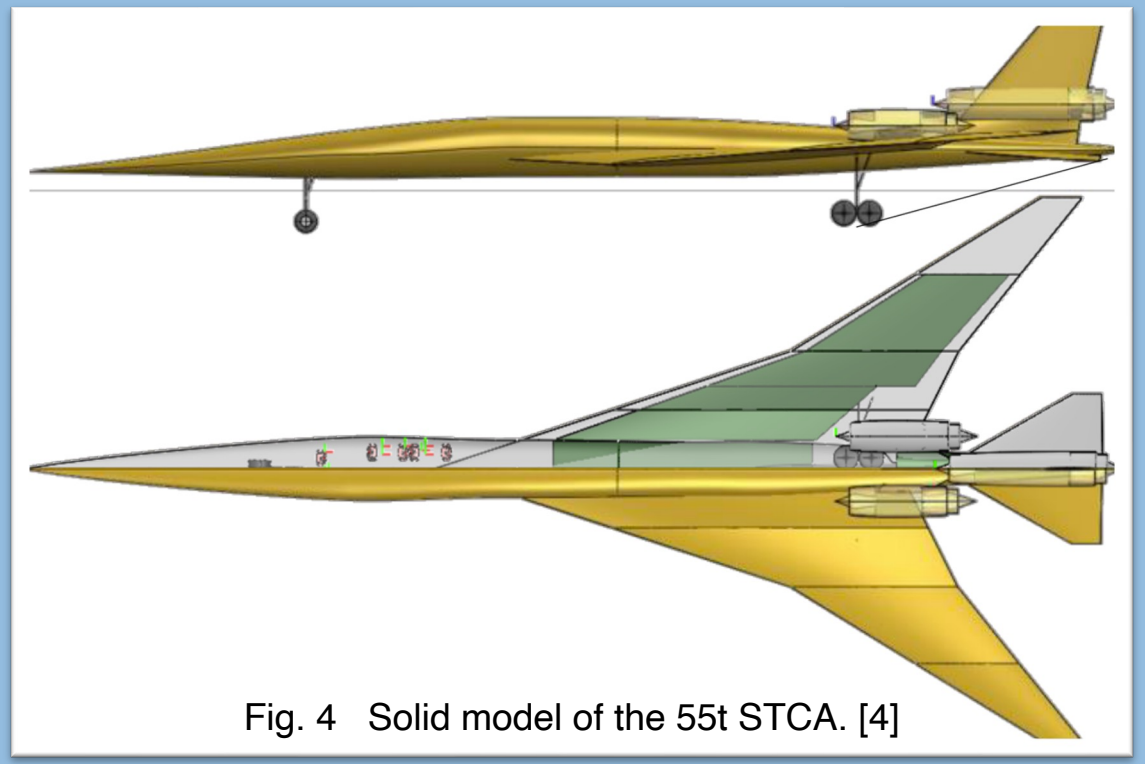


Fig. 4 Solid model of the 55t STCA. [4]

[3] Berton, J., Huff, D., Seidel, J., and Geiselhart, K., "Supersonic Technology Concept Aeroplanes for Environmental Studies," AIAA Paper 2020-0263, AIAA SciTech Forum, Orlando, FL, 2020. https://doi.org/10.2514/6.2020-0263.

Study Environment: SPAND & Nozzle

- **S**upersonic **Pa**rametric **N**ozzle **D**esign (**SPAND**) python tool extended
  - Parameter-to-grid for full plug nozzle geometry & subtractive mixer features
  - Adjusts cowl length for ideal expansion at given NPR
- Plug nozzle contoured to:
  - Reflect geometry for near-term applications
  - Expand flow to SSCR freestream conditions without separation
- Area Ratio (AR) kept constant from inflow to mixer TE

Dimension	Value	Dimension	Value
$r_{ic,6}$	11.5 in	t_6	3.75 in
$r_{ob,6}$	25.75 in	t_9	0.125 in
$r_{ic,7}$	8 in	θ_p	15°
$r_{ob,7}$	25.75 in	L_T	20 in
$r_{ic,7}$	8 in	L_S	20 in
r_8	20.351 in	L_C	30 in
r_n	25.75 in	x^*_{IP}	0.4
r_c	20.351 in	r_{ptr}	0.2 in

Table 2 Plug nozzle dimensions.

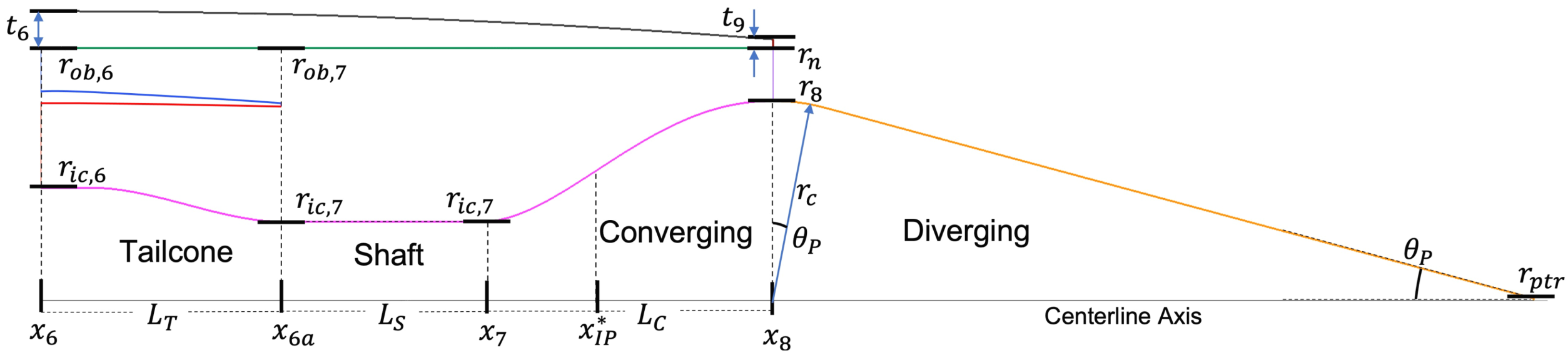


Fig. 5 Plug nozzle cross-section with axisymmetric splitter.

Mixer Construction: Baseline Mixers

- Two top-performing baseline mixers with varying characteristics:
  - **Parallel**
    - Higher penetration, no TE slope
    - High shear layer surface area, minimal flow turning
  - **Vortical**
    - Lower penetration, high TE slope
    - High axial vorticity generation, significant flow turning

Parameter	Confluent	Parallel	Vortical
n	0	12	12
ϕ	0	60%	50%
L_M	0	0.8	0.8
η	0	0	−0.125
∂_{TE}	0	0	0.4

Table 3 Baseline mixer inputs.

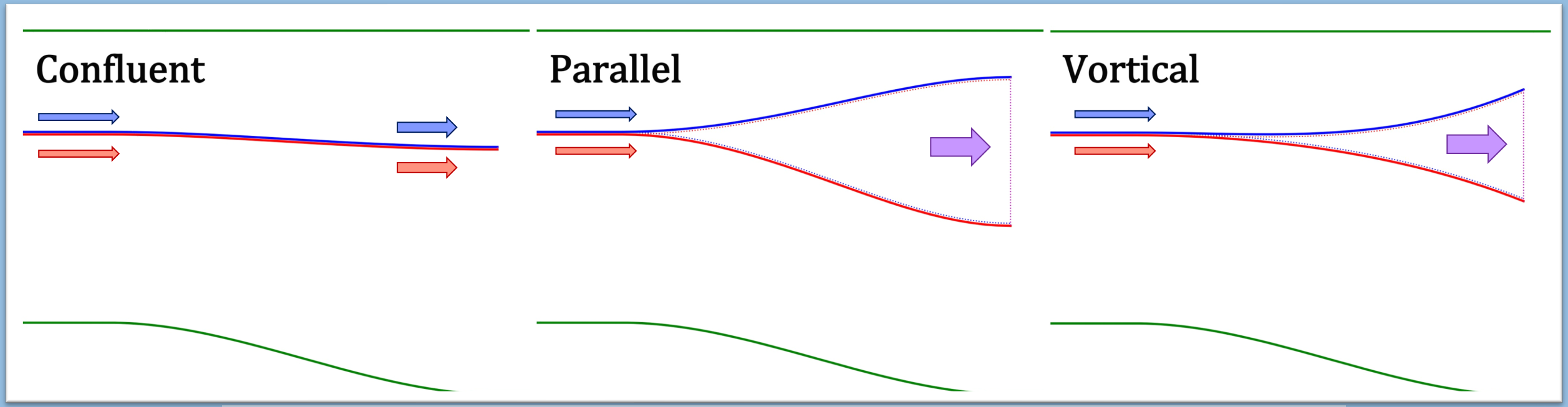


Fig. 6 Baseline mixer x-r spline profiles.

Mixer Construction: Advanced Feature Parameterization

- Subtractive features added as two axisymmetric cuts:
  - **Scarfing**
    - Scarf Angle $\boldsymbol{\zeta}$: Axisymmetric angle at which the lobe mixer trailing edge is scarfed
    - Positive (+) values pivoted from TE trough
    - Negative (-) values pivoted from TE peak
  - **Scalloping**
    - Applied as general conic curve with specified:
      - Endpoints (p_{s1}, p_{s2})
      - Shoulder point (p_{ss})
      - Tangent intersect point (p_{ti})
    - Parameterized by:
      - Scallop Height $\boldsymbol{h_s}$: $\frac{r_{s2}-r_{s1}}{r_{cp}-r_{bt}}$
      - Scallop Depth $\boldsymbol{d_s}$:$\frac{x_{mtm}-x_{ss}}{L_M}$
      - Focal Parameter $\boldsymbol{\rho_s^*}$: $\frac{x_{mtm}-x_{ss}}{x_{mtm}-x_{ti}}$

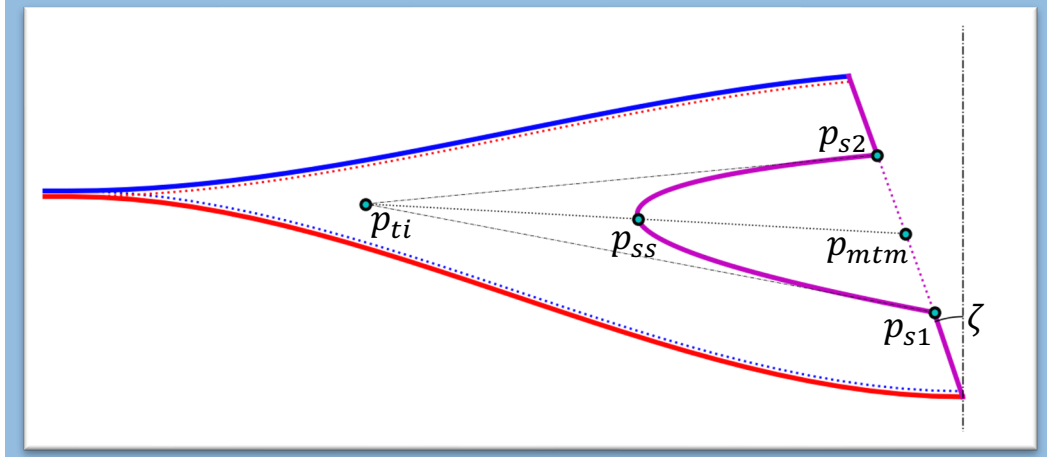


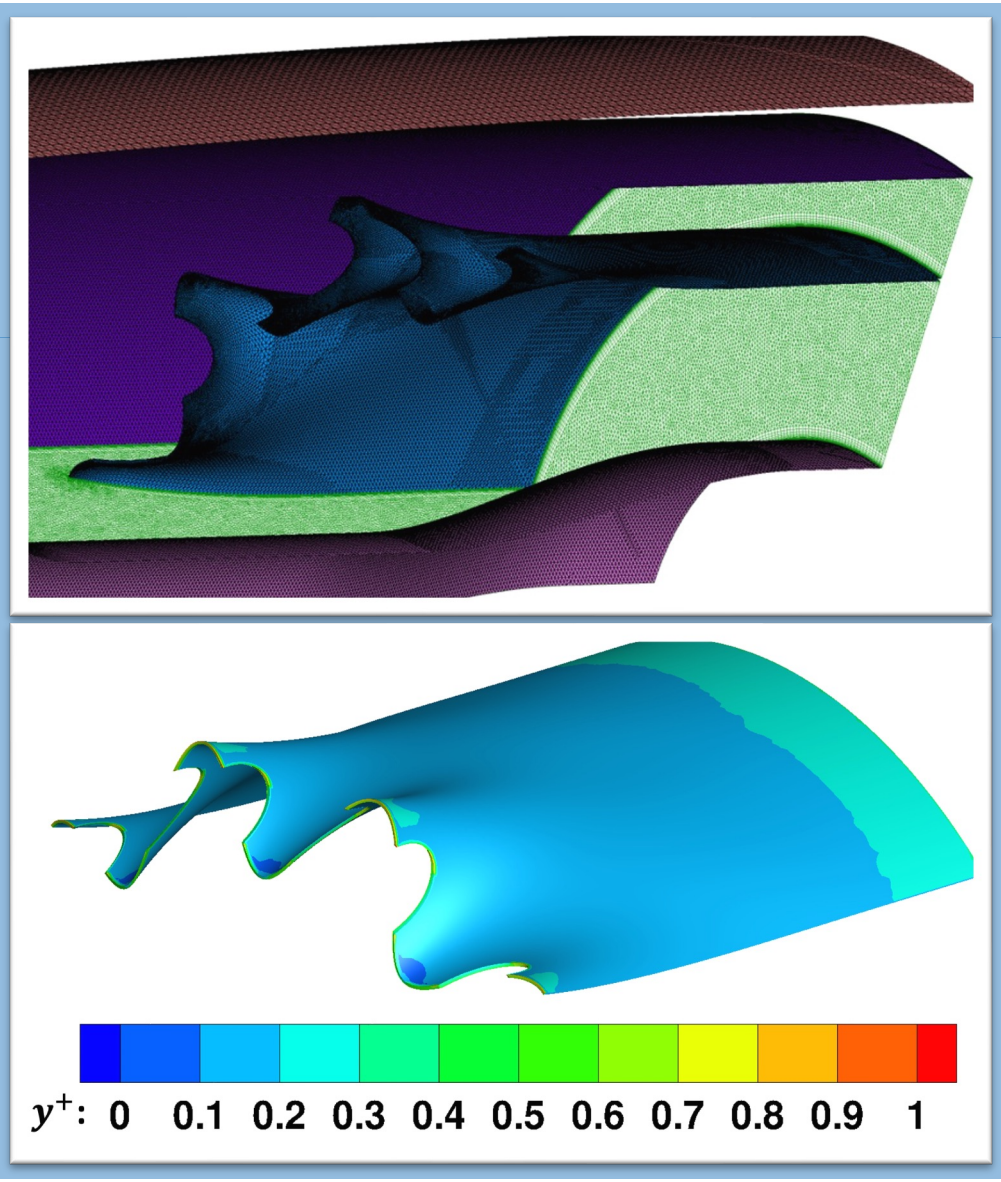
Fig. 7 Subtractive feature x-r profiles.

Gridding

- Grid refinement controlled by connector spacings in Table 4 – results in **12-13M nodes** per case
- Wall y^+ values are universally **near or below 1**
- Previous grid study concluded an error of $C_V \pm 0.001$ should be assumed [2]

Table 4 Connector spacings.

Description	Spacing
Interior Baseline	0.2 *in.*
Exterior Baseline	0.5 *in.*
Mixer Trailing Edge	0.08 *in.*
Mixer Trailing Edge Thickness	0.0625 *in.*
Farfield	10 *in.*
T-Rex 1st Layer	4*e*-5 *in.*
T-Rex Growth Rate	1.3



Numerical Solution

- FUN3D v13.3, perfect-gas version
- Steady RANS equations
  - Fully turbulent, SST-v model
- Boundary conditions per Table 5
  - Walls are adiabatic
  - Symmetric about x-z and x-y planes
- Initialized with M=0.5 flow in nozzle interior
  - Avoids numerical unstart
- Courant # ramping over 1000 iterations
  - Convective: 1 to 100
  - Turbulent: 0.2 to 20
- 1st-order accuracy for 1000 iterations
  - 2nd-order accuracy for remainder
- C_{F_g} & $\dot{m}_{IN}$ monitored for convergence
  - Solutions converge within 3000 iterations
  - Continued to 10000 iterations
- ~1350 CPU hrs per case
  - NASA Advanced Supercomputing Division

Table 5 Simulation boundary conditions.

Boundary	Type	FUN3D Code	NPR	NTR
Core Inflow	Subsonic Inflow	7011	5.534	4.654
Bypass Inflow	Subsonic Inflow	7011	6.268	1.736
X-Z Symmetry	Symmetry_y	6662	–	–
X-Y Symmetry	Symmetry_z	6663	–	–
Farfield Inflow	Freestream	5050	–	–
Farfield	Farfield	5000	–	–
Farfield Outflow	Extrapolate	5026	–	–
Nozzle Surfaces	Viscous Wall	4000	–	–

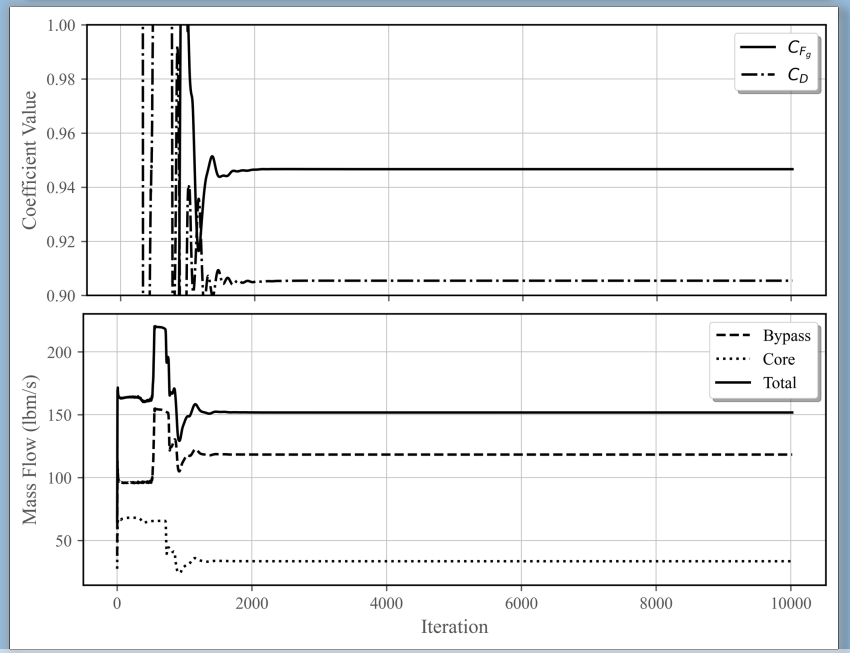


Fig. 8 Sample simulation convergence history.

Case Matrix

- Centerpoint plus two cases per parameter per baseline mixer = 18 cases
- Limitations of each baseline mixer resulted in different ranges for each
- Intents were to
  - Study the impact of **individual** parameters
  - **Verify** SPAND capabilities
  - **NOT** to create a surrogate model

Parallel Baseline Mixer				
Varied Parameter↓	ζ	h_s	d_s	ρ_s^*
ζ	(0° 10°, 20°)	0.7	0.3	0.5
h_s	20°	(0.3, 0.5, 0.7)	0.3	0.5
d_s	20°	0.7	(0.1, 0.3, 0.5)	0.5
ρ_s^*	20°	0.7	0.3	(0.3, 0.5, 0.9)
Vortical Baseline Mixer				
Varied Parameter↓	ζ	h_s	d_s	ρ_s^*
ζ	(0°, 10°, 20°)	0.6	0.1	0.3
h_s	0°	(0.5, 0.6, 0.7)	0.2	0.3
d_s	0°	0.6	(0.1, 0.2, 0.3)	0.3
ρ_s^*	20°	0.5	0.2	(0.3, 0.5, 0.9)

Table 6 Study case matrix.

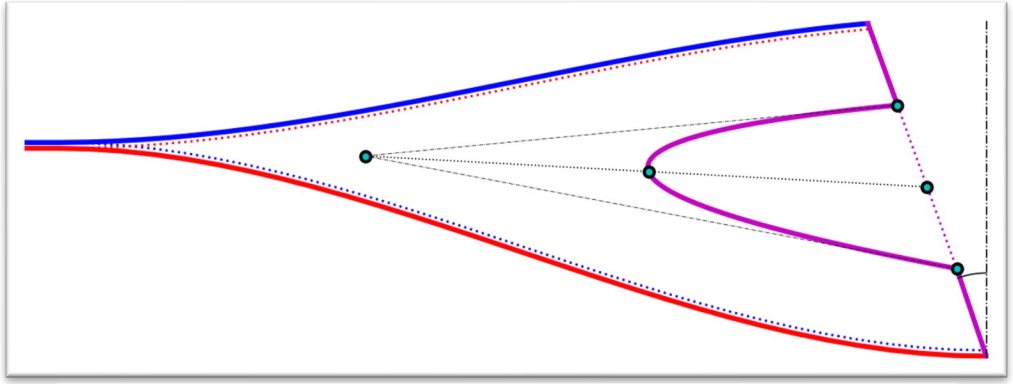


Fig. 9 Centerpoint case, parallel baseline.

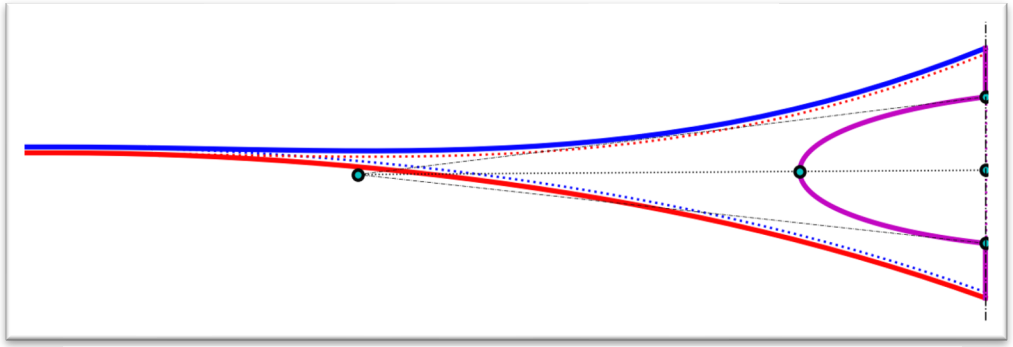


Fig. 10 Centerpoint case, vortical baseline.

Aerodynamic Performance

- C_V was used to ensure thrust performance was not adversely affected
- Baseline comparison
  - Confluent: $C_V = 0.948$
  - Parallel: $C_V = 0.954$
  - Vortical: $C_V = 0.958$
- Cases were compared via ΔC_V to isolate effects of subtractive features
  - $\boldsymbol{h_s}$ and $\boldsymbol{d_s}$ were **beneficial** for **parallel**
    - Increased C_V to the vortical baseline value
  - $\boldsymbol{\zeta}$ was **beneficial** for **vortical**
    - h_s and d_s decreased C_V
- While small, largest $\boldsymbol{\Delta C_V}$ **significant** compared to numerical error
- Larger C_V improvement for parallel with scalloping
  - Merati & Cooper suggest scalloping introduces vorticity [4]
  - **Hypothesis: parallel mixers see greater streamwise vorticity introduction from scalloping**

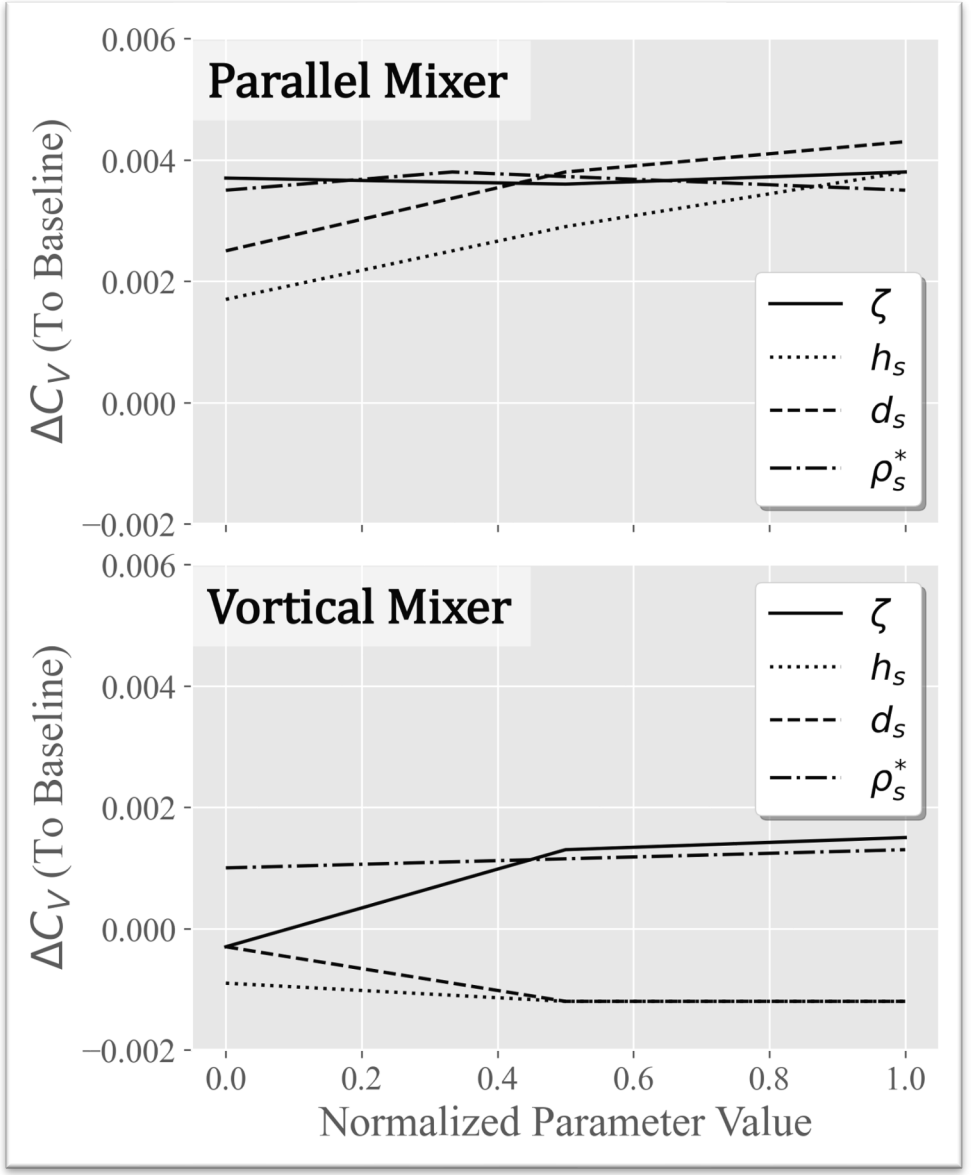


Figure 11 ΔC_V vs. parameter values.

[4] Merati, P., and Cooper, N. J., "Experimental Investigation of Flow Behavior for Scalloped and Lobed Mixers," Advances in Mechanical Engineering, Vol. 8, No. 9, 2016, pp. 1–17.

Mixedness Development: Metrics (Parallel Example)

- Can test hypothesis by measuring flow characteristics through the nozzle body
- Streamwise vorticity approximated by **axial vorticity magnitude**
  - $\|\omega_x \hat{\imath}\|$
- Cross-stream vorticity approximated by **transverse vorticity magnitude**
  - $\omega_{yz} = \|\omega_y \hat{\jmath} + \omega_z \hat{k}\|$
- Mixedness inversely approximated by **density variance**
  - $(\bar{\rho} - \rho)^2$
  - $\bar{\rho} = \frac{\oiint \rho dA}{A}$
- Snapshot contours show relation between local $\|\omega_x \hat{\imath}\|$ and $(\bar{\rho} - \rho)^2$
  - Vortical baseline shows:
    - **Greater** $\|\boldsymbol{\omega_x \hat{\imath}}\|$ overall
    - **Larger low-variance** region at converging plane

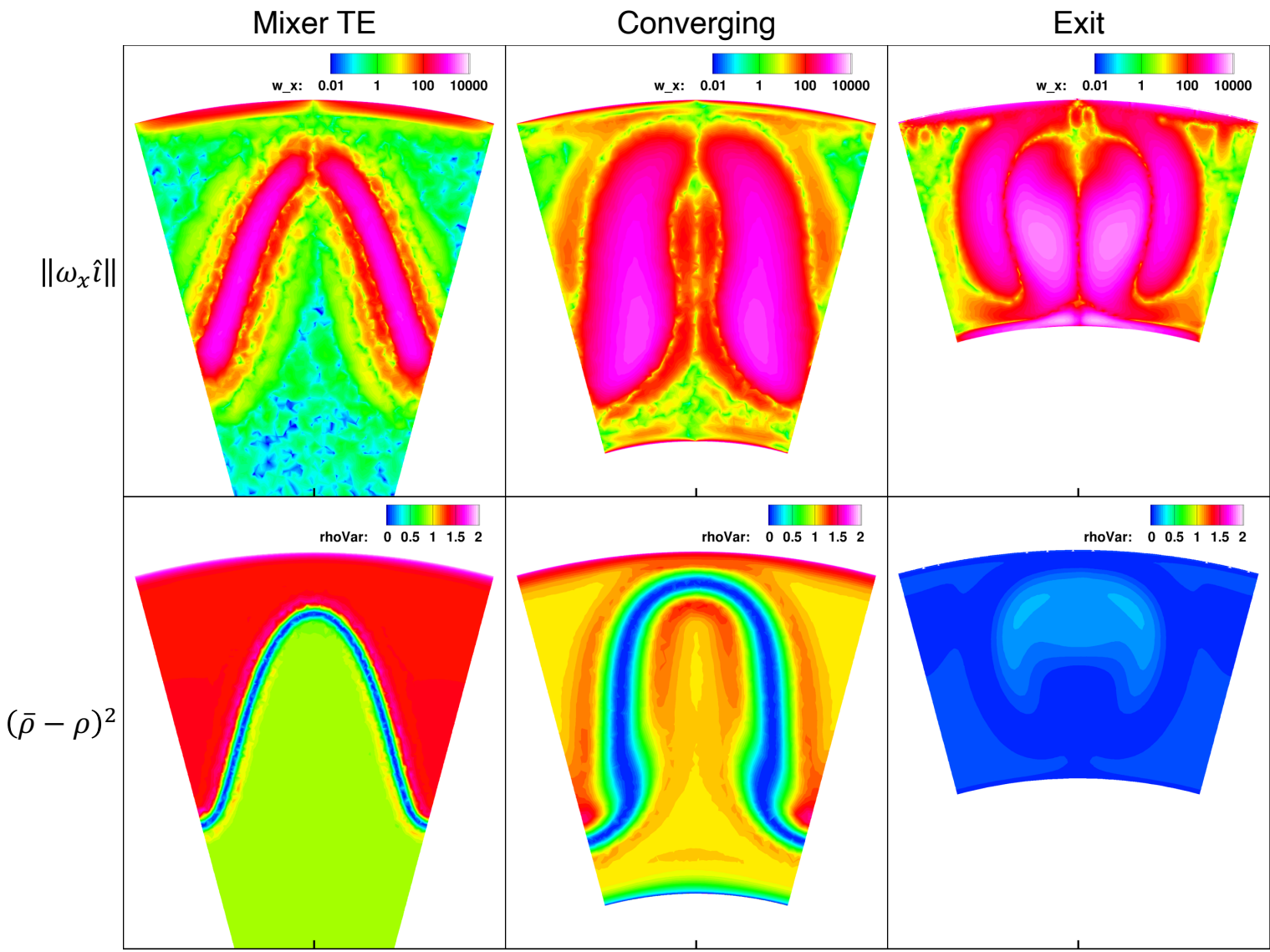


Figure 12 Mixing development, parallel baseline.

Mixedness Development: Metrics (Vortical Example)

- Can test hypothesis by measuring flow characteristics through the nozzle body
- Streamwise vorticity approximated by **axial vorticity magnitude**
  - $\|\omega_x \hat{\imath}\|$
- Cross-stream vorticity approximated by **transverse vorticity magnitude**
  - $\omega_{yz} = \|\omega_y \hat{\jmath} + \omega_z \hat{k}\|$
- Mixedness inversely approximated by **density variance**
  - $(\bar{\rho} - \rho)^2$
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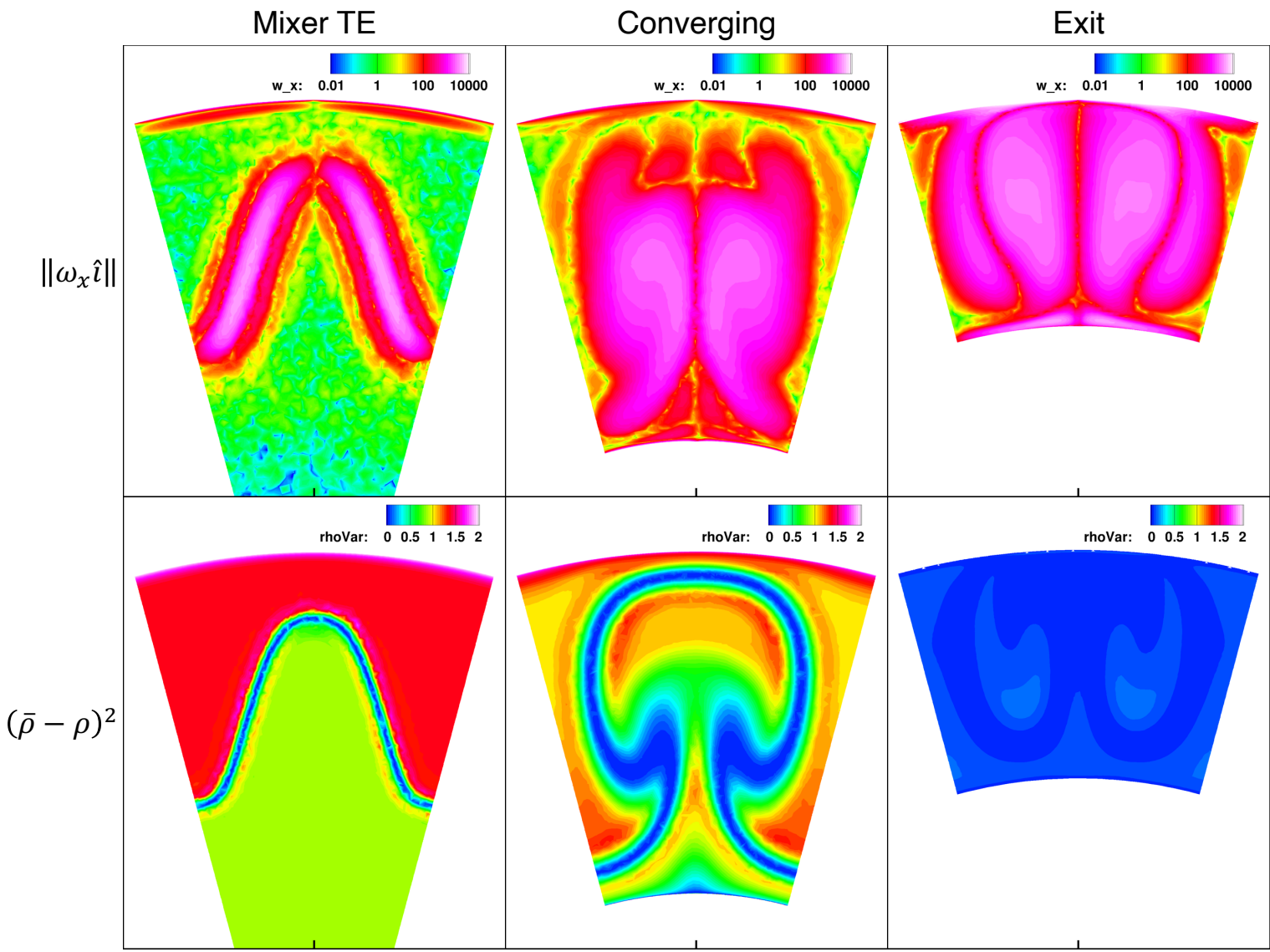
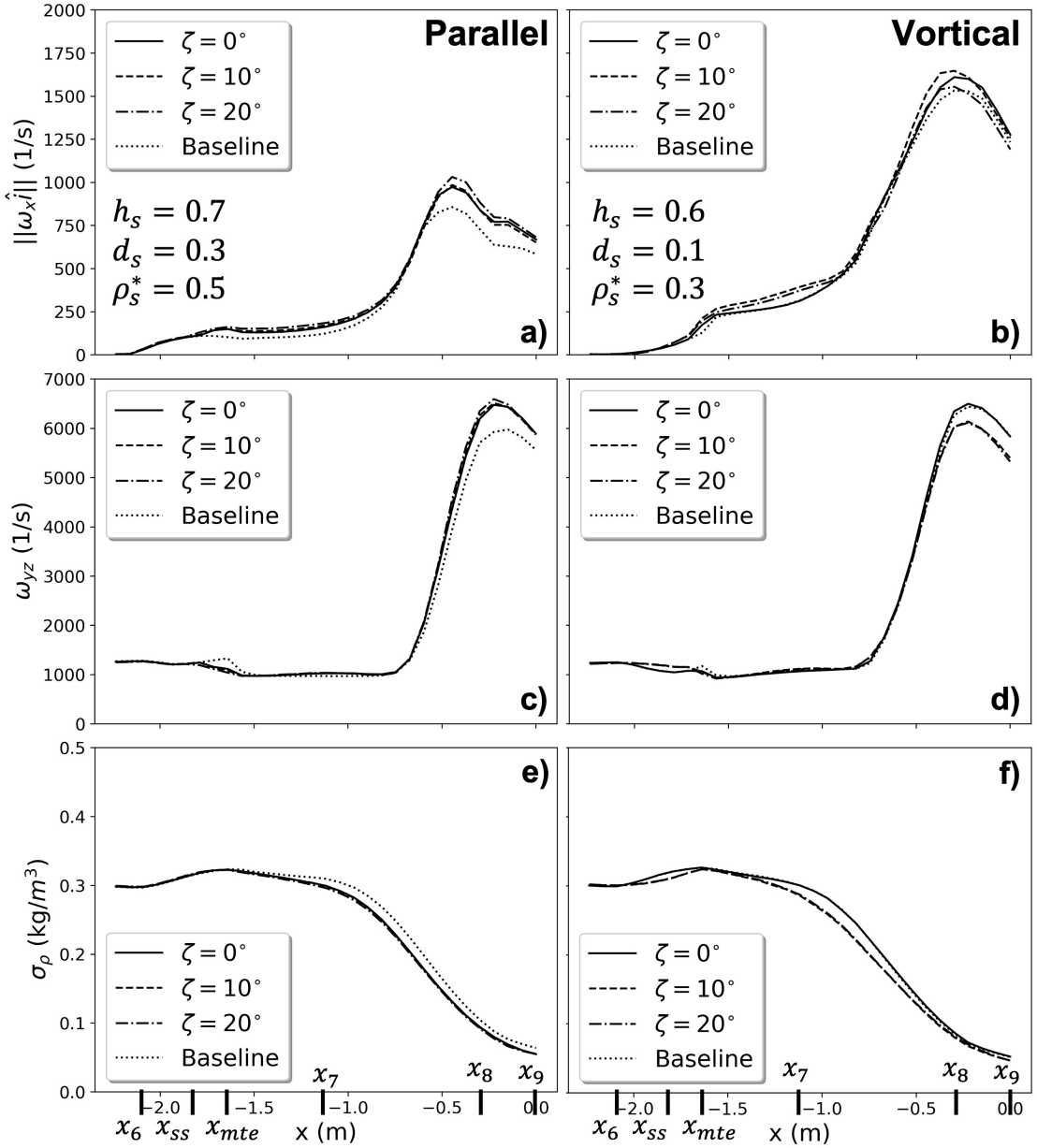


Figure 13 Mixing development, vortical baseline.

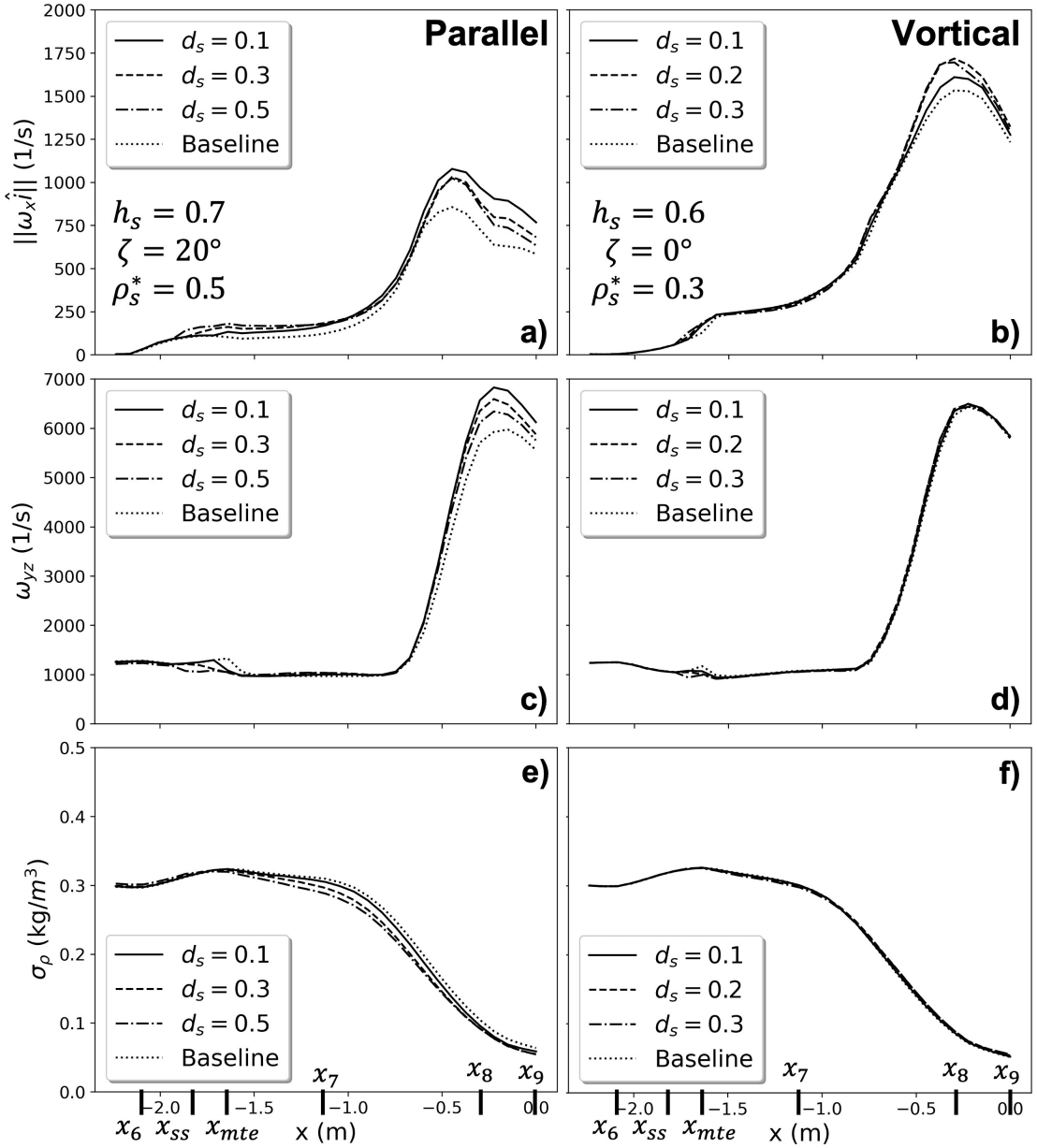
Mixedness Development: Planar Integrals, Scarf Angle

- Integrating quantities over r-θ planes gives a summary of mixing development
  - Mass flow-averaged $\|\omega_x \hat{\imath}\|$ and ω_{yz}
  - Area-integrated $\sigma_\rho = \oiint(\bar{\rho} - \rho)^2 dA$
- Increasing scarf angle amplifies $\|\omega_x \hat{\imath}\|$ generation for vortical cases
  - Plot **b)** – higher $\|\omega_x \hat{\imath}\|$ vs. x slope from x_{ss}
  - Plot **f)** – leads to faster σ_ρ decay
- Converging section catch-up
  - Higher cross-stream density variance & streamwise pressure gradient increases vorticity via **baroclinic torque**
  - Faster σ_ρ decay for low-angle cases
- Parallel cases appear largely unaffected by scarfing
  - Changes in plots **a), c),** & **e)** to baseline due to scalloping



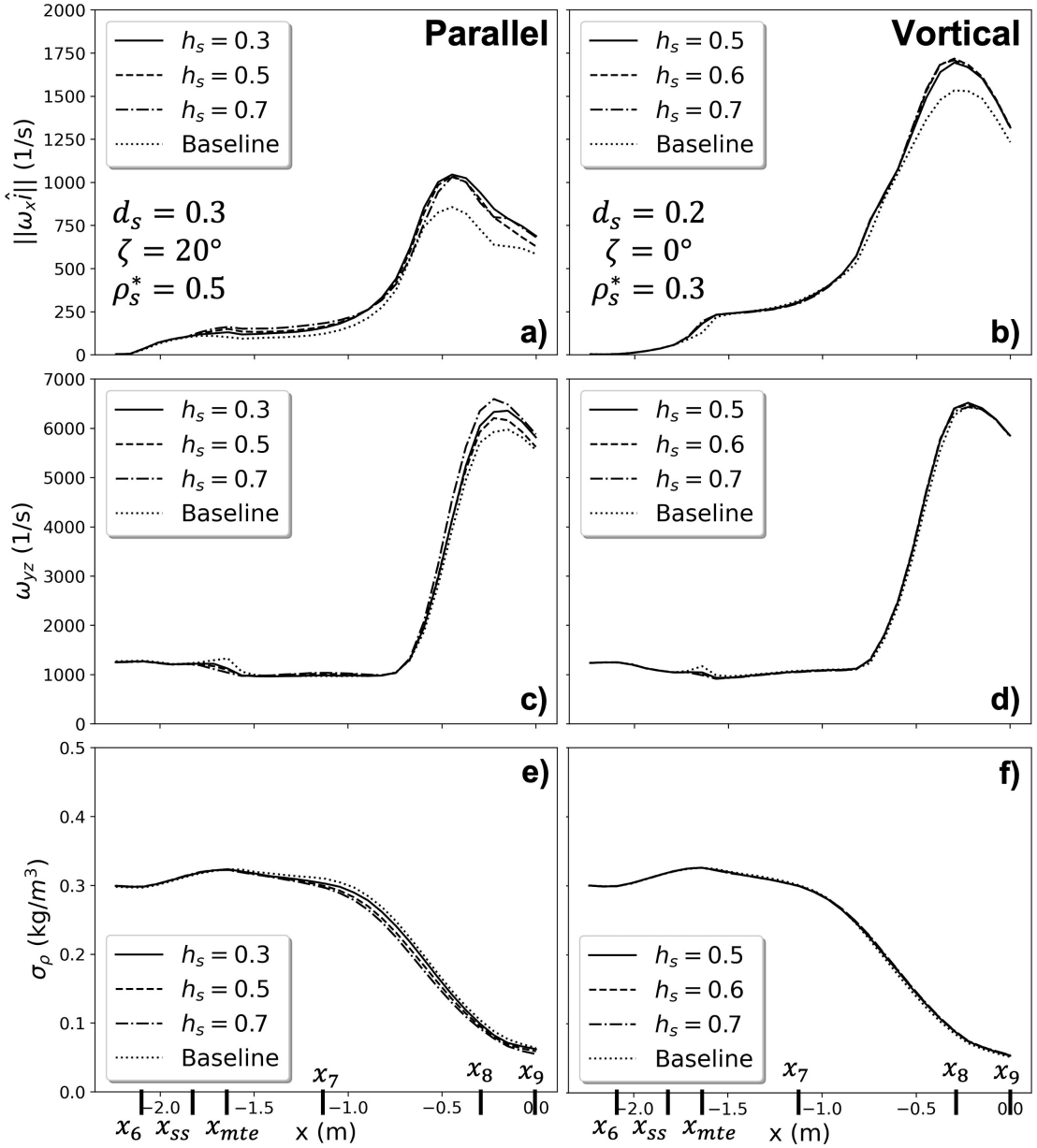
Mixedness Development: Planar Integrals, Scallop Depth

- Integrating quantities over r-θ planes gives a summary of mixing development
  - Mass flow-averaged $\|\omega_x \hat{\imath}\|$ and ω_{yz}
  - Area-integrated $\sigma_\rho = \oiint (\bar{\rho} - \rho)^2 dA$
- Increasing scallop depth triggers earlier $\|\omega_x \hat{\imath}\|$ generation for parallel cases
  - Plot **a)** – jump at the case-specific x_{ss} location
  - Plot **e)** – leads to faster σ_ρ decay
- Converging section catch-up
  - Higher cross-stream density variance & streamwise pressure gradient increases vorticity via **baroclinic torque**
  - Faster σ_ρ decay for low-depth cases
- Vortical cases appear largely unaffected upstream of supersonic transition



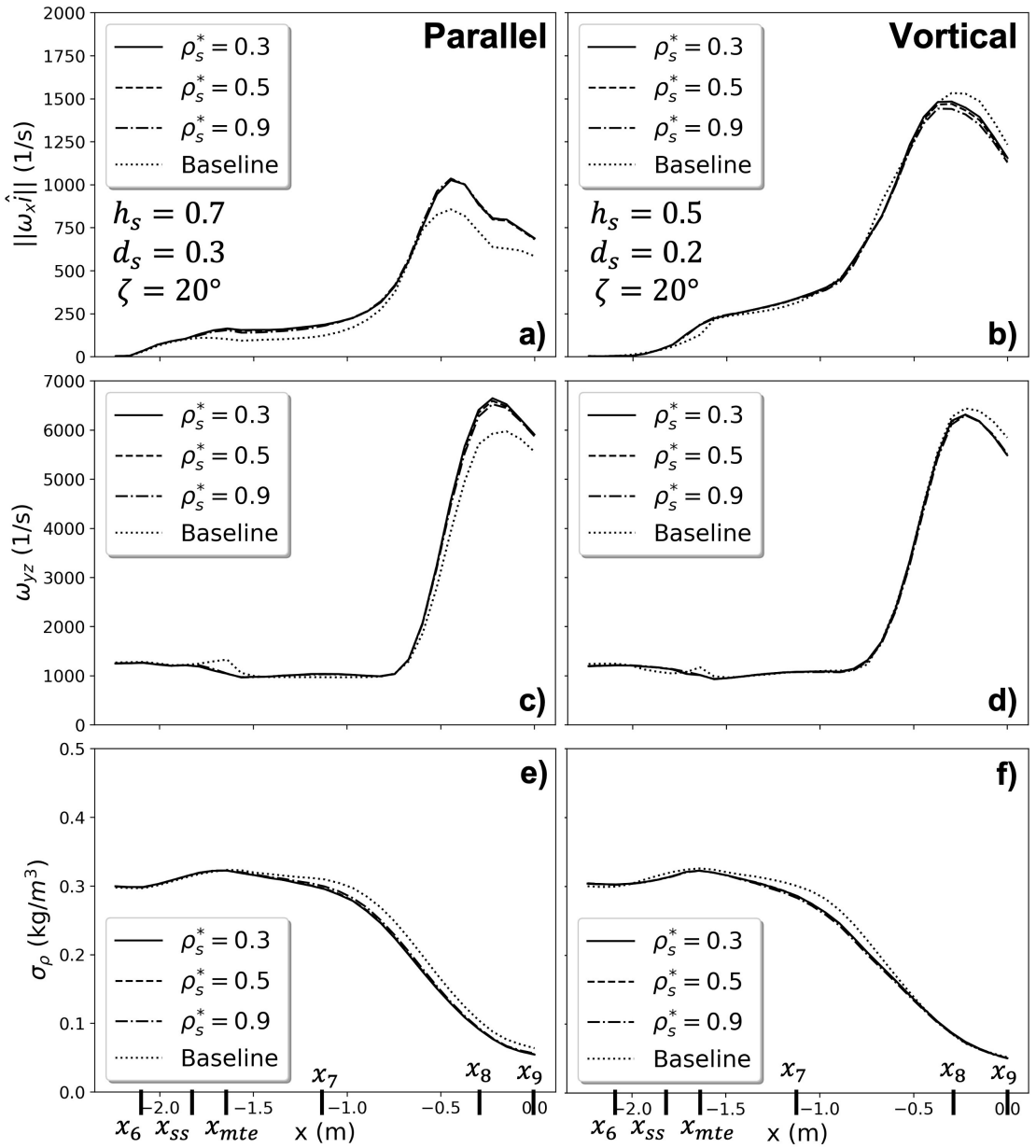
Mixedness Development: Planar Integrals, Scallop Height

- Integrating quantities over r-θ planes gives a summary of mixing development
  - Mass flow-averaged $\|\omega_x \hat{\imath}\|$ and ω_{yz}
  - Area-integrated $\sigma_\rho = \oiint(\bar{\rho} - \rho)^2 dA$
- Increasing scallop height slightly amplifies $\|\omega_x \hat{\imath}\|$ generation for parallel cases
  - Plot **a)** – jump at the case-specific x_{ss} location
  - Plot **e)** – leads to faster σ_ρ decay
- Converging section catch-up
  - Higher cross-stream density variance & streamwise pressure gradient increases vorticity via **baroclinic torque**
  - Faster σ_ρ decay for low-height cases
- Vortical cases appear largely unaffected upstream of supersonic transition



Mixedness Development: Planar Integrals, Focal Parameter

- Integrating quantities over r-θ planes gives a summary of mixing development
  - Mass flow-averaged $\|\omega_x \hat{\imath}\|$ and ω_{yz}
  - Area-integrated $\sigma_\rho = \iint (\bar{\rho} - \rho)^2 dA$
- Little to no change in flow characteristics with increasing $\boldsymbol{\rho_s^*}$ on either baseline mixer
- Reflects consistent C_V values calculated



Conclusions

- Python-based SPAND tool capable of parameter-to-grid plug nozzle generation with advanced mixer features
- Four scarfing & scalloping parameters studied for flow-mixing characteristics on two baseline mixers
- Increasing scallop height and depth (h_s and d_s) improved C_V for a parallel mixer
- Increasing scarf angle (ζ) improved C_V for a vortical mixer
- Correlation was established between $\|\omega_x \hat{\imath}\|$ and decay of σ_ρ
  - Increased $\boldsymbol{d_s}$ **= earlier** $\|\boldsymbol{\omega_x \hat{\imath}}\|$ generation (parallel)
  - Increased $\boldsymbol{h_s}$ **= amplified** $\|\boldsymbol{\omega_x \hat{\imath}}\|$ generation (parallel)
  - Increased $\boldsymbol{\zeta}$ **= faster** $\|\boldsymbol{\omega_x \hat{\imath}}\|$ generation (vortical)
- Increased $\|\boldsymbol{\omega_x \hat{\imath}}\|$ generation also correlated to improved C_V

Future Work

- Continue to add capabilities to SPAND
  - Chevrons/Vortex generators
  - External plug contouring
  - Plug porosity
  - Analytical/Model-based solutions

- Expand the dataset for subtractive features
  - More baseline cases
  - Surrogate model development
  - Increased input parameter robustness

- Develop RANS-based acoustic analysis capability
  - Leverage existing acoustic analogy codes
  - Find analogous flow characteristics for low-fidelity prediction

Thank You

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