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LES of a Compressible Mixing Layer and the Significance of Inflow Turbulence

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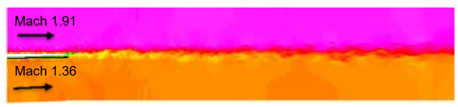

AIAA SciTech 2017

Objectives

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- Develop an improved prediction capability for turbulent shear flows
- Analyze the effects of inflow turbulence on the shear layer
- Apply the Synthetic Eddy Method (SEM) to model inflow turbulence
- Compare SEM-LES to a Fixed-LES with no inflow turbulence
- Access sensitivity to spanwise width
- Compare turbulence intensity profiles with experiments
- Apply best practices developed for $M_c = 0.46$ to a high convective Mach number case, $M_c = 0.87$.

Motivation

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Pervious Work(s)
LES was used by Georgiadis et al.[1] and Mankbadi et al.[2] that pointed to the need to account for inflow turbulence.

New Work
SEM is utilized as a means to simulate the effects of inflow turbulence on compressible mixing layers.

[1]Mankbadi M. R., Georgiadis N. J., DeBonis J. R., "Comparison of High-Order and Low-Order Methods for Large-Eddy Simulation of a Compressible Shear Layer", 45th AIAA Fluid Dynamics Conference, AIAA Aviation, 2015-2939.

[2]Georgiadis N. J., Alexander J. I. D., Reshotko E., "Hybrid Reynolds-Averaged Navier–Stokes/Large-Eddy Simulations of Supersonic Turbulent Mixing," AIAA Journal, Vol. 41, pp. 218–229, 2003.

Introduction

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Compressible mixing layers

- Examples: supersonic combustion, exhaust nozzles, and internal flows present in jet engines and scramjets
- Experimental studies investigating compressibility effects: *Chinzei et al., Papamoschou & Roshko, Goebel and Dutton, Samimy & Elliot, Hall et al., and Clemens & Mungal.*

Turbulent Inflow Conditions

(1) full LES of upstream boundary layers
(2) Recycling/Rescaling
(3) Hybrid RANS/LES
(4) synthetic turbulence inflow boundaries

Description of the Flow

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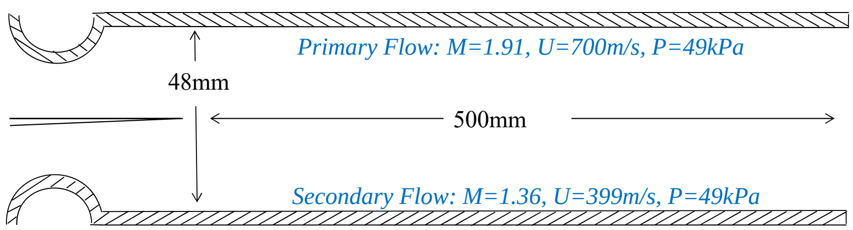

Parameter	Case 2 M_c=0.46		Case 4 M_c=0.87	
	Primary Flow	Secondary Flow	Primary Flow	Secondary Flow
M	1.91	1.36	2.35	0.30
U (m/s)	700	399	616	100
T_t (K)	578	295	360	290
P (kPa)	49	49	36	36
δ^* (mm)	0.90	0.44	0.70	0.24

The Synthetic Eddy Method

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Jarrin et al. is applied to the mixing layer under consideration to simulate the effects of inflow turbulence.

Inputs:

(1) A Reynolds stress tensor and mean flow

(2) A length scale

(3) A convective velocity

SEM succeeded in replicating the Reynolds stress tensor when the length scale was approximately 1/10 of the boundary layer thickness.

Digital Filtering requires three input length scales.

Computational Approach

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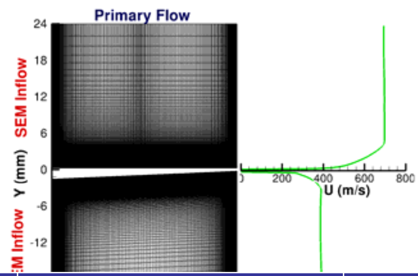
- Tenth-Order NASA GRC Wave-Resolving LES (WRLES) code solves the discretized Favre-Filtered Navier-Stokes.



Parameter	Baseline Grid			Axially Refined Grid		
	x	y	z	x	y	z
Number of points	1025	425	138	2049	425	138
Length of domain (mm)	500	48	24	250	48	24
Minimum spacing (mm)	0.0125	0.0125	0.1875	0.00625	0.0125	0.1875
Maximum spacing (mm)	5	0.2	0.1875	5	0.2	0.1875

Results

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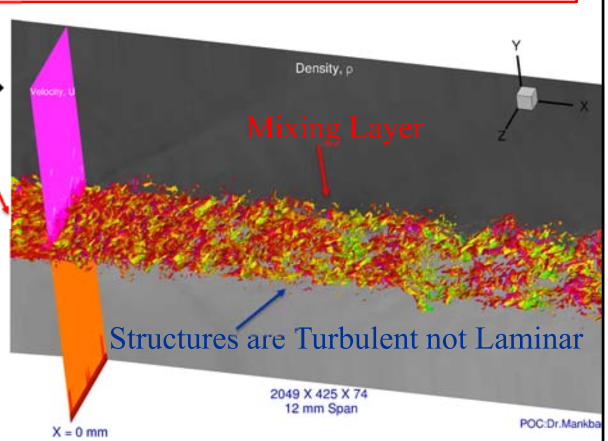
SEM delivers turbulent boundary layer to splitter-tip which enhances downstream mixing.

Primary Flow→

SEM of Primary/Secondary Flow

Secondary Flow→



Fixed-LES: Spanwise width Grid Study

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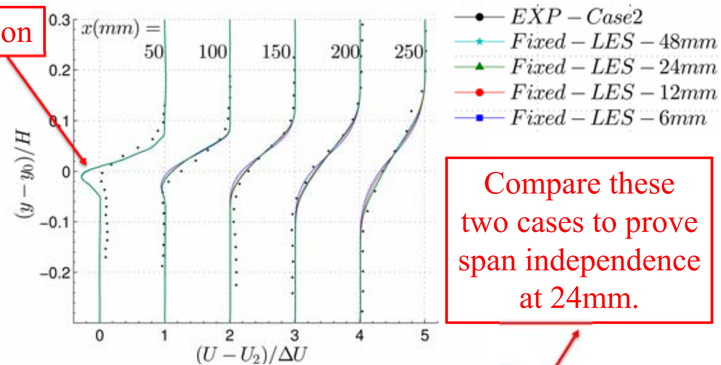
A wake-like region



Compare these two cases to prove span independence at 24mm.

Case	Methodology	Grid Size	Width	Grid Pts
A	Fixed-LES	1025 x 425 x 33	6mm	14.4 M
B	Fixed-LES	1025 x 425 x 65	12mm	28.3 M
C	Fixed-LES	1025 x 425 x 129	24mm	56.2 M
D	Fixed-LES	1025 x 425 x 257	48mm	112 M
E	SEM-LES	2049 x 425 x 42	6mm	36.6 M
F	SEM-LES	2049 x 425 x 74	12mm	64.4 M
G	SEM-LES	2049 x 425 x 138	24mm	120.2 M
H	SEM-LES[QUAD]	2049 x 425 x 138	24mm	120.2 M

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Fixed-LES: Spanwise width Grid Study

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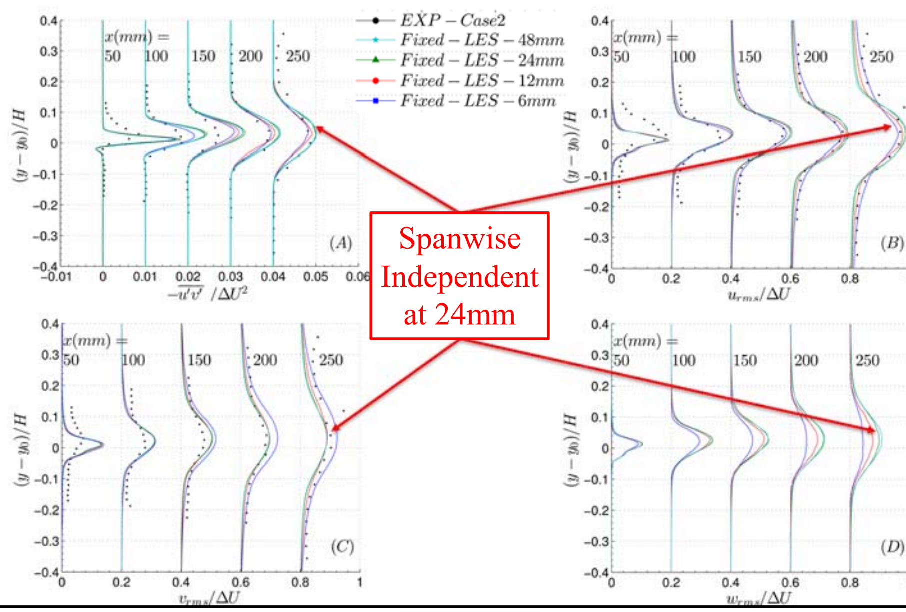

Fixed-LES: Spanwise width Grid Study

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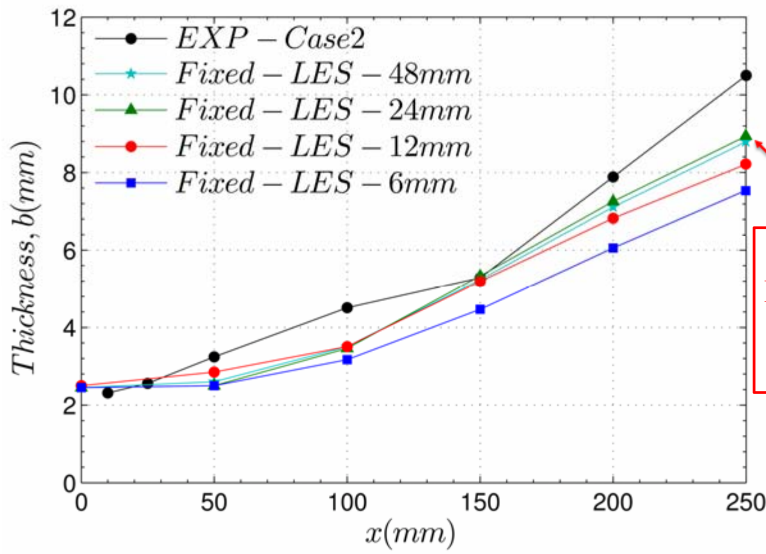

Spanwise Independent thickness at 24mm.

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SEM-LES: Grid Study

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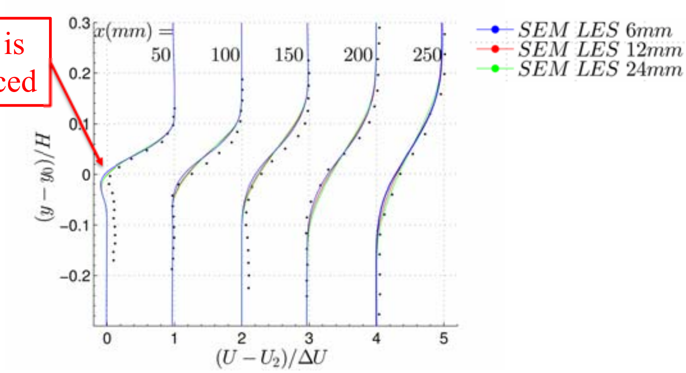
wake-like region is significantly reduced



SEM-LES is in better agreement with exp.

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SEM-LES: Grid Study

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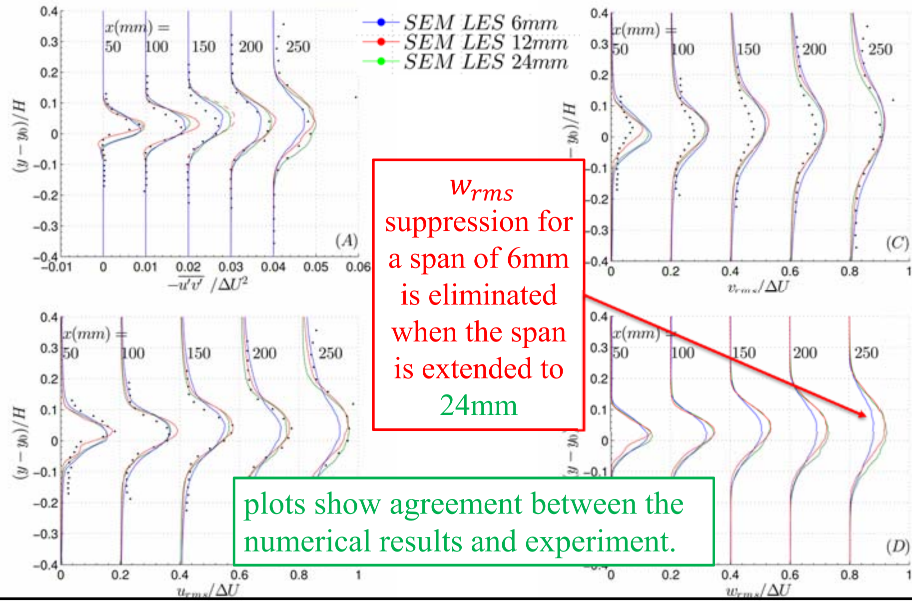

Effect of Inflow Turbulence

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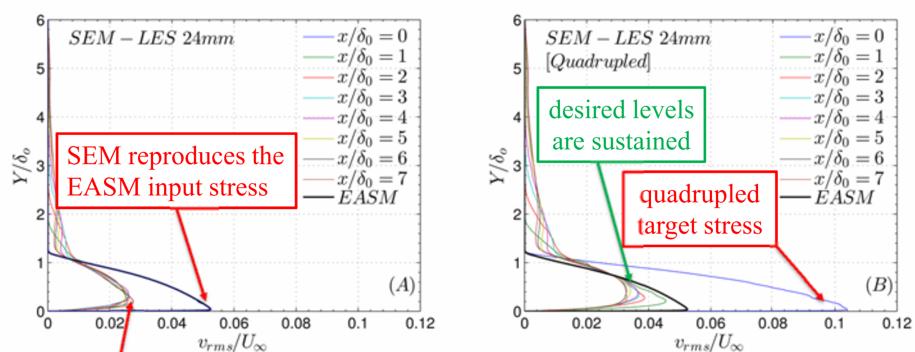

projection error:

(1) the Reynolds tensor specified at the inflow satisfies the RANS equations instead of the Favre-filtered Navier Stokes

(2) the inability of the numerical scheme to represent the prescribed flow field on the grid

(3) the synthetic eddies are not real turbulence and therefore undergo a process whereby they adjust to the Navier-Stokes equations.

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Effect of Inflow Turbulence

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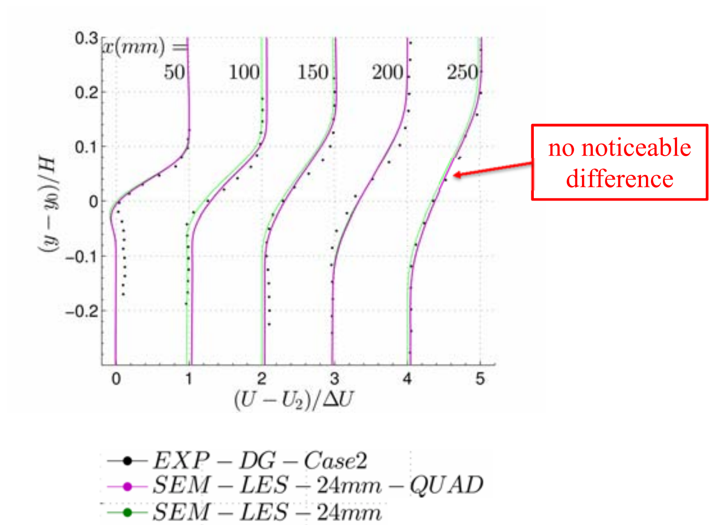

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Effect of Inflow Turbulence

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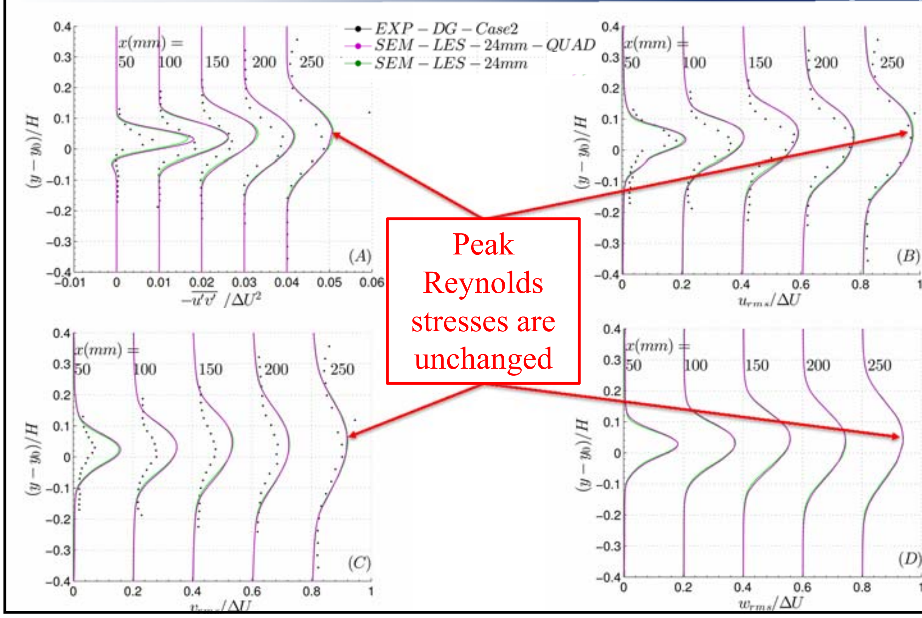

Effect of Inflow Turbulence

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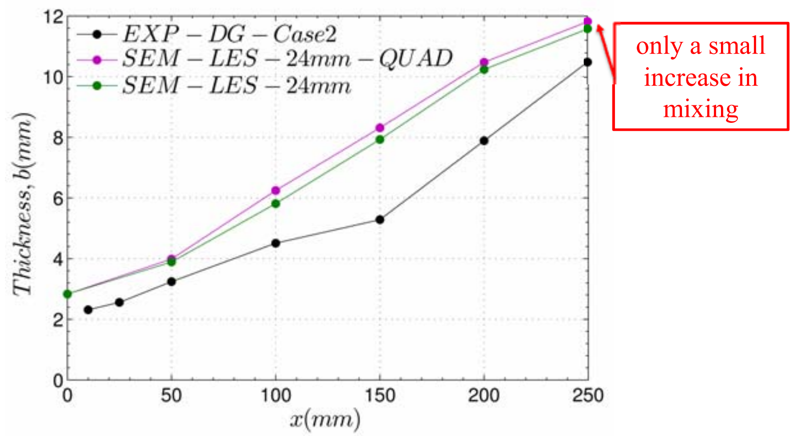

Key Finding: Variations in Reynolds tensor supplied to SEM do not affect the solution.

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Transition to Turbulent Mixing

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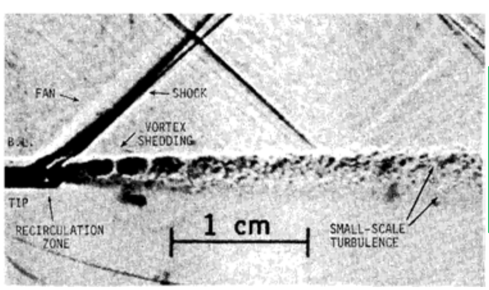
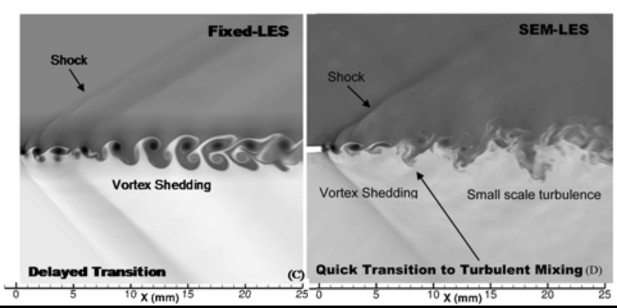


Clemens and Mungal's schlieren concurs with the quick transition to turbulent mixing of SEM-LES.



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Transition to Turbulent Mixing

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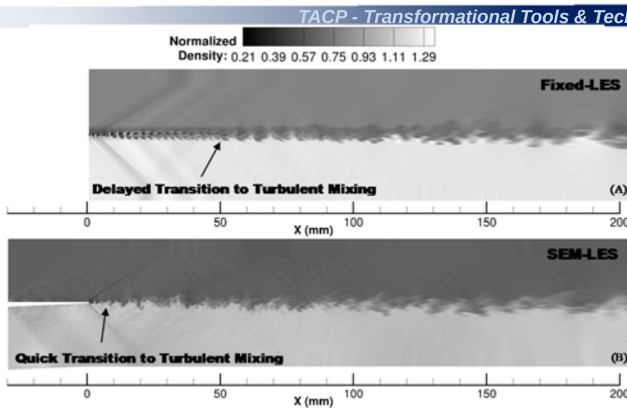

- SEM-LES's inclusion of inflow turbulence makes a dramatic difference in the transition process.
- The specified turbulence quickly destroys the organized structures and transition occurs immediately downstream of the splitter tip.
- The entire shear layer exhibits a broader range of structures which closely resemble the schlieren images of the experiment.

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Mixing Layer's Thickness

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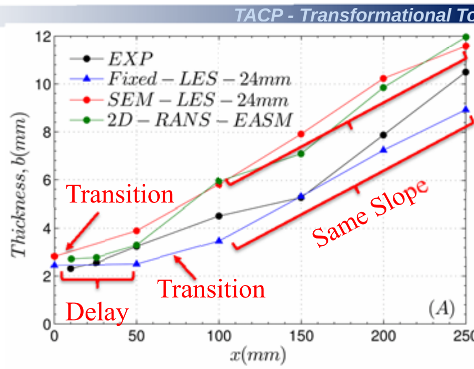

- Fixed-LES transitions to turbulent mixing at $\sim x = 50\text{mm}$ upward change in slope.
- SEM-LES transitions earlier than Fixed-LES.
- Both SEM-LES and Fixed-LES eventually have the same slope downstream, after the Fixed-LES fully transitions to turbulent mixing.

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Compressibility Effects at High Convective Mach Number

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Leveraging the practices developed for the low convective Mach number, we subsequently investigated the high convective Mach number case.

Case	Methodology	Grid Size	Width
J	SEM-LES	2049 x 425 x 42	6mm
K	SEM-LES	2049 x 425 x 74	12mm
L	SEM-LES	2049 x 425 x 138	24mm

	Case 2 M_c=0.46		Case 4 M_c=0.87	
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Compressibility Effects at High Convective Mach Number

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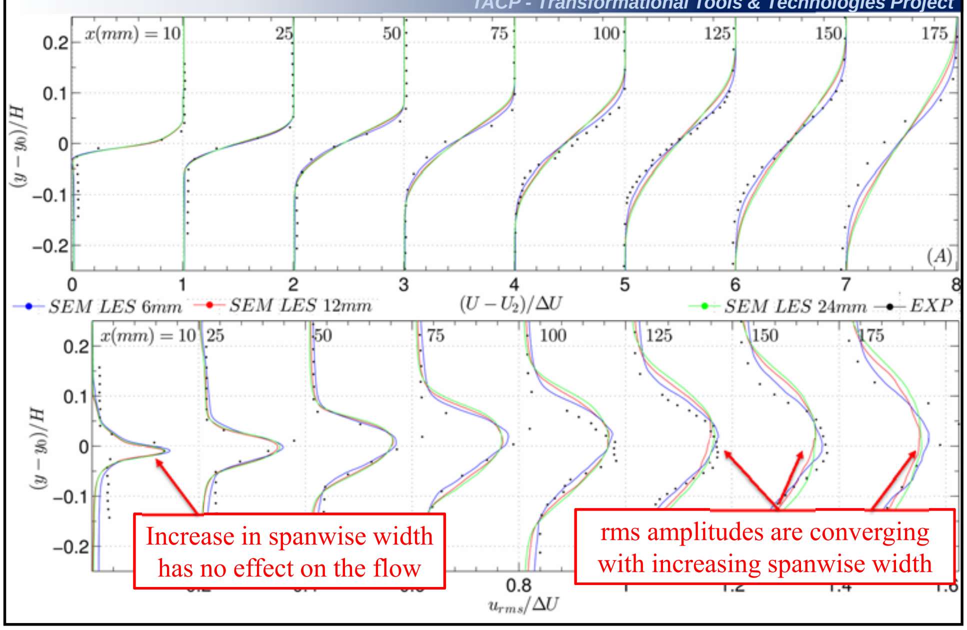

Compressibility Effects at High Convective Mach Number

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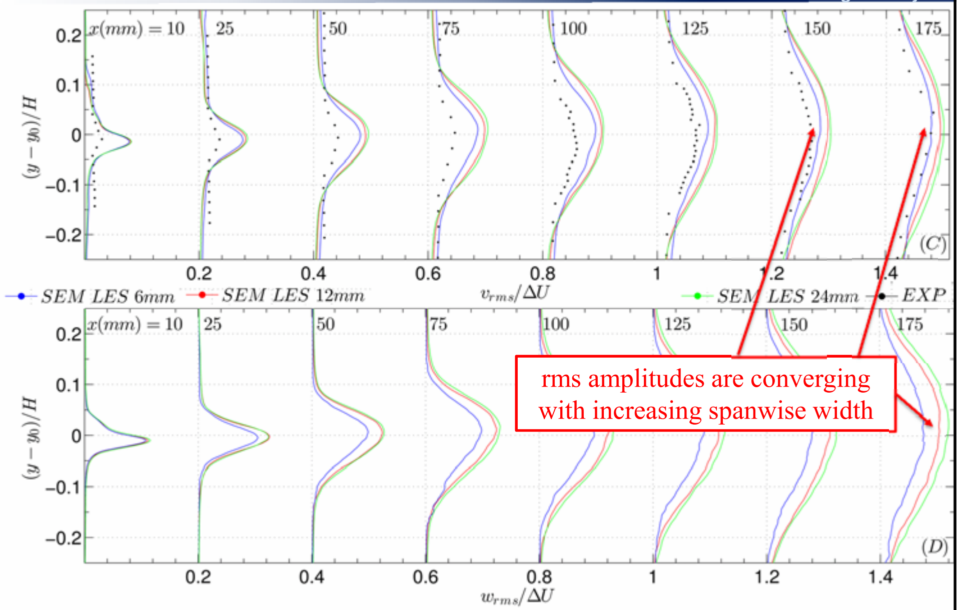

Compressibility Effects at High Convective Mach Number

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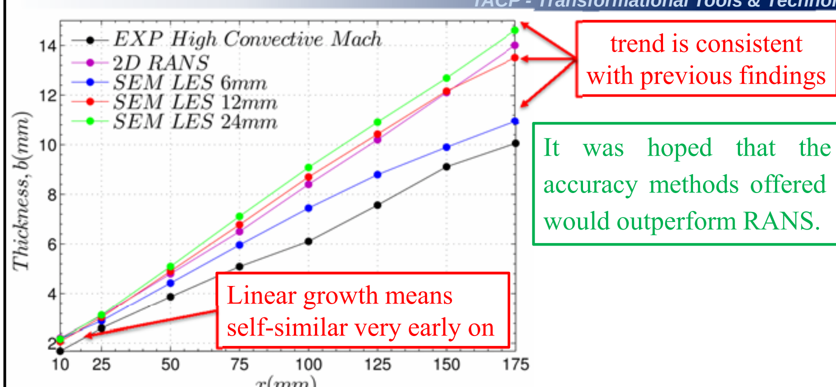

It was hoped that the higher accuracy methods offered by LES would outperform RANS.

SEM-LES assuming (1) periodic flow in z-direction; (2) neglected upper and lower viscous walls; (3) inexact approximation of the inflows and outflow (due to limited experimental measurements).

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Conclusions

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- LES of a compressible shear layer for: M_c = 0.46 (case 2), and M_c = 0.87 (case 4).
- Spanwise turbulent stresses and mixing layer thickness were suppressed if the domain is too narrow (6mm).
  1. Fixed inflow neglects inflow turbulence
  2. SEM inflow accounts for inflow turbulence.
- For M_c = 0.46, Fixed-LES showed large laminar structures in the initial portion of the shear layer and a delayed transition to turbulent mixing.
- SEM-LES eliminated the organized vortical structures and transition to turbulent mixing occurred immediately following the splitter tip.
- SEM-LES better replicated the experimental trends in turbulent stresses.
- For M_c = 0.87, similar trends were found when investigating spanwise width.
- The experimentally observed mixing rate was overpredicted by LES which agreed with RANS-EASM. Neither RANS nor LES have yet to capture the reduced growth rate trend with increasing convective Mach number.
- The key finding was that accounting for inflow turbulence through SEM-LES is a viable option alongside recycling/rescaling LES

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Future Work: Flow Separation
WR-LES and WM-LES

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