Effect of Turbulence Model Uncertainty on Scramjet Strut Injector Flow Field Analysis

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Introduction

- A scramjet has four distinct components: inlet, isolator, combustor, nozzle
- Short residence times of internal flow require fuel-air mixing on the order of milliseconds
- Injector design challenges include balancing total pressure losses with fuel-air mixing
- Solution uncertainties must be understood in order to allow for useful integration of CFD into the design process

Figure 1. Artist's concept of the X-43A in flight.[1]

Objective

- The overall goal is to study the effect of turbulence model uncertainty on the analysis of a scramjet strut fuel injector flow field, specifically that uncertainty arising from the turbulence model closure coefficients
- This study contributes to previous work done on hypervelocity fuel injectors by Drozda et al[3,4]
- This study is unique in that it is the first to focus on the effects of turbulence model closure coefficient uncertainty on a scramjet strut fuel injector flow field
- Selected results presented here illustrate the impact of turbulence model and closure coefficient value selection

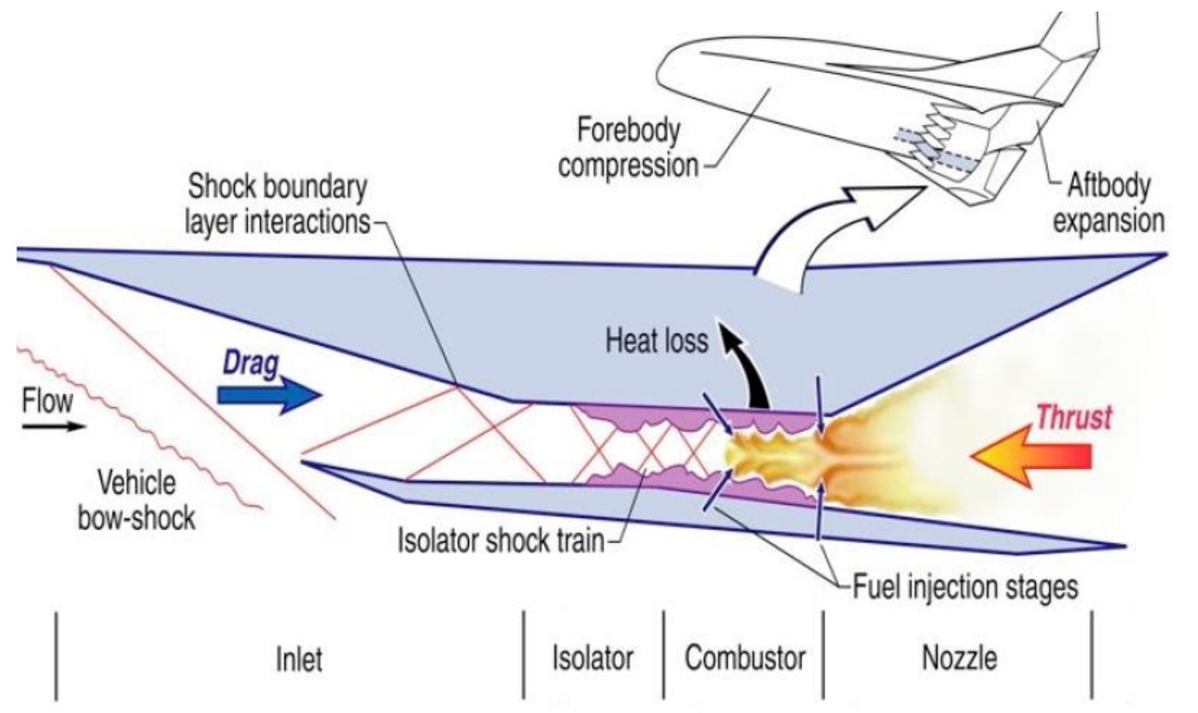

Figure 2. Scramjet engine schematic diagram.[2]

Model Injector

- Created by the Hypersonic Air Breathing Propulsion Branch at NASA Langley Research Center
- The strut injector is 2.23" tall, 5.22" long, 0.32" wide, and has a swept wedge leading edge
- Flow enters at a Mach number of 4.5 and helium is used to simulate non-reacting mixing

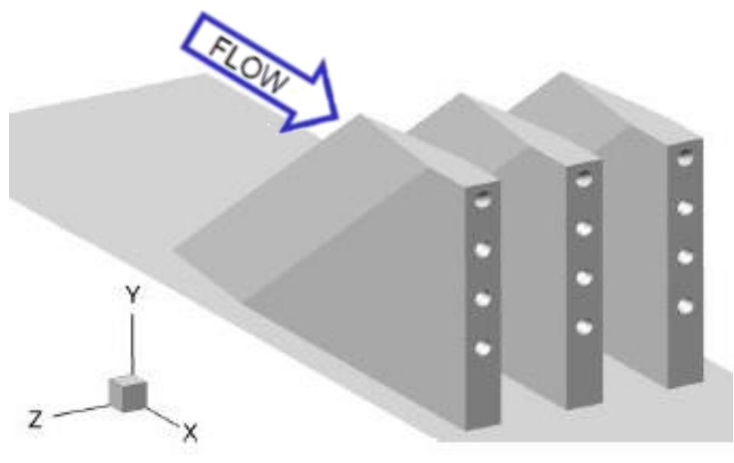

Figure 3. Representation of the strut injector geometry.[3]

Flow Solver and Solutions

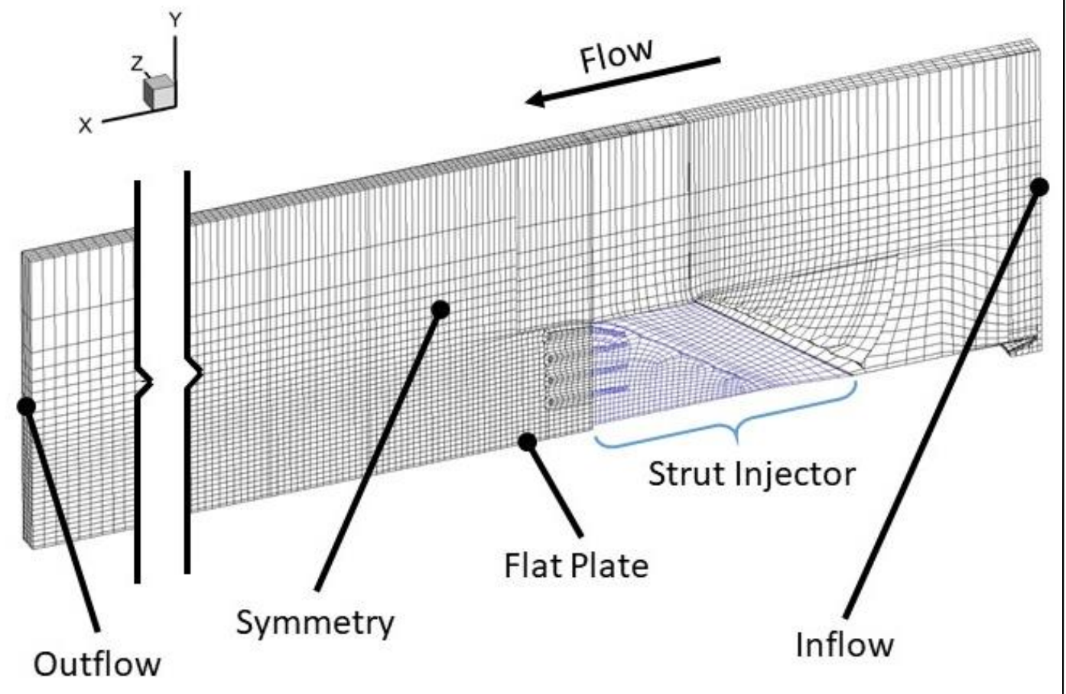

Figure 4. Computational domain. Note that the grid is coarsened for clarity.

- Computational domain is a structured grid with 20,257,280 cells
- Grid resolution selected based on results from previous study[3]
- Advantage is taken of the symmetric nature of the domain to reduce computing time

- The CFD code used is VULCAN, developed and maintained at NASA Langley Research Center
- VULCAN allows the user to modify closure coefficient definitions via input file declarations
- Turbulence models used for this study:
  - Menter Baseline (BSL)
  - 2006 Wilcox k-ω (W06)

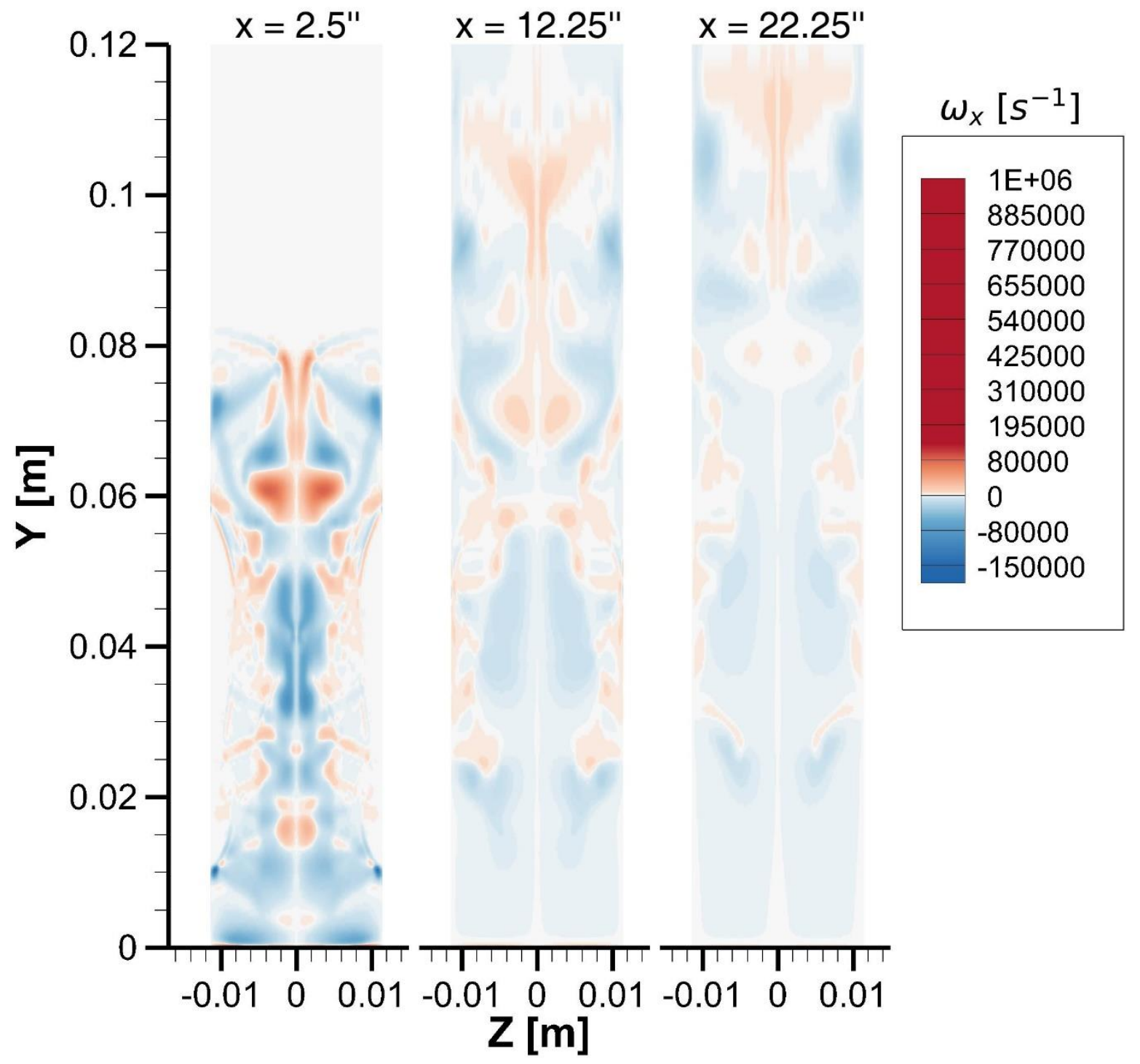

Figure 5. Vorticity distribution at three crossflow planes using the default closure coefficient values.

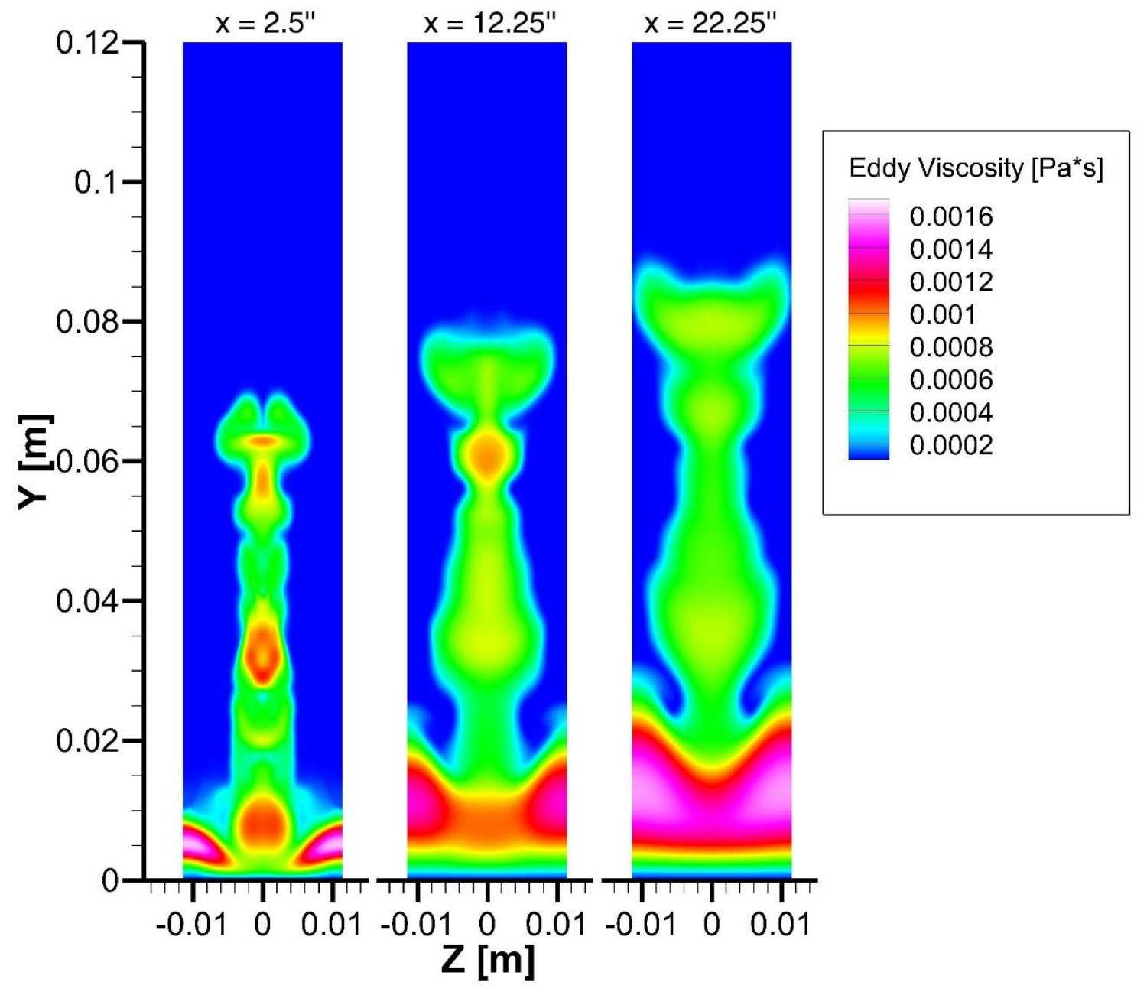

Figure 6. Eddy viscosity distribution at three crossflow planes using the default closure coefficient values.

- Integrated quantities of interest:
  - Mixing efficiency
  - Total pressure recovery factor
  - Mass-flux-weighted Mach number
  - Circulation
- Pointwise quantities of interest:
  - Vorticity
  - Eddy viscosity

Sensitivity Analysis Results

	Distance From Injection Plane		
Coefficient	2.5"	12.25"	22.25"
σ_{k1}	0.00042^7	0.04115^6	0.08609^6
σ_{k2}	0.03540^4	0.11821^4	0.19025^4
$\sigma_{\omega1}$	0.01786^5	0.04114^7	0.05942^7
$\sigma_{\omega2}$	0.40798^2	0.41781^1	0.31404^2
C_μ/β_1	0.00007^8	0.18999^3	0.38948^1
C_μ/β_2	0.08908^3	0.03925^8	0.05025^8
C_μ	0.00148^6	0.06320^5	0.12701^5
κ	0.46293^1	0.35500^2	0.29461^3

Superscript indicates relative ranking for each QoI.

Table 1. Sobol indices for the mixing efficiency analysis using BSL.

	Distance From Injection Plane		
Coefficient	2.5"	12.25"	22.25"
σ_{k1}	0.00230^7	0.10194^6	0.11343^6
σ_{k2}	0.11205^4	0.23546^3	0.26932^3
$\sigma_{\omega1}$	0.02568^5	0.07443^8	0.07799^7
$\sigma_{\omega2}$	0.15008^2	0.17859^4	0.15604^5
C_μ/β_1	0.00094^8	0.46551^1	0.51233^1
C_μ/β_2	0.11912^3	0.07770^7	0.07159^8
C_μ	0.00352^6	0.15814^5	0.17158^4
κ	0.59495^1	0.33026^2	0.30426^2

Superscript indicates relative ranking for each QoI.

Table 2. Sobol indices for the total pressure recovery analysis using BSL.

	Distance From Injection Plane		
Coefficient	2.5"	12.25"	22.25"
σ_{k1}	0.00173^7	0.08384^8	0.10604^6
σ_{k2}	0.02859^5	0.20912^3	0.28093^3
$\sigma_{\omega1}$	0.08029^4	0.10346^6	0.09498^7
$\sigma_{\omega2}$	0.16250^2	0.15754^4	0.13289^5
C_μ/β_1	0.00151^8	0.38111^1	0.47809^1
C_μ/β_2	0.10156^3	0.09544^7	0.08706^8
C_μ	0.00483^6	0.12719^5	0.16029^4
κ	0.62799^1	0.36823^2	0.30755^2

Superscript indicates relative ranking for each QoI.

Table 3. Sobol indices for the one-dimensional Mach number analysis using BSL.

	Distance From Injection Plane		
Coefficient	2.5"	12.25"	22.25"
σ_{k1}	0.00278^7	0.02005^8	0.02831^7
σ_{k2}	0.06821^3	0.06842^5	0.09820^5
$\sigma_{\omega1}$	0.02211^4	0.10087^3	0.15967^3
$\sigma_{\omega2}$	0.54500^1	0.41075^1	0.44475^1
C_μ/β_1	0.00155^8	0.08619^4	0.11310^4
C_μ/β_2	0.01637^5	0.03951^6	0.00788^8
C_μ	0.00311^6	0.03730^7	0.05457^6
κ	0.35097^2	0.35696^2	0.24949^2

Superscript indicates relative ranking for each QoI.

Table 4. Sobol indices for the circulation analysis using BSL.

- Uncertainties fall in to two categories:
  - Epistemic – lack of knowledge
  - Aleatory – random variations
- Closure coefficient uncertainties are treated as epistemic, and analyzed over an interval identified by a previous study[5]
- Uncertainties were propagated using a point-collocation non-intrusive polynomial chaos method[6]
- Solutions were used as inputs to determine the relative coefficient sensitivity, quantified using Sobol indices to rank the relative importance of each closure coefficient
- Results identify coefficients that warrant further investigation

UQ Results

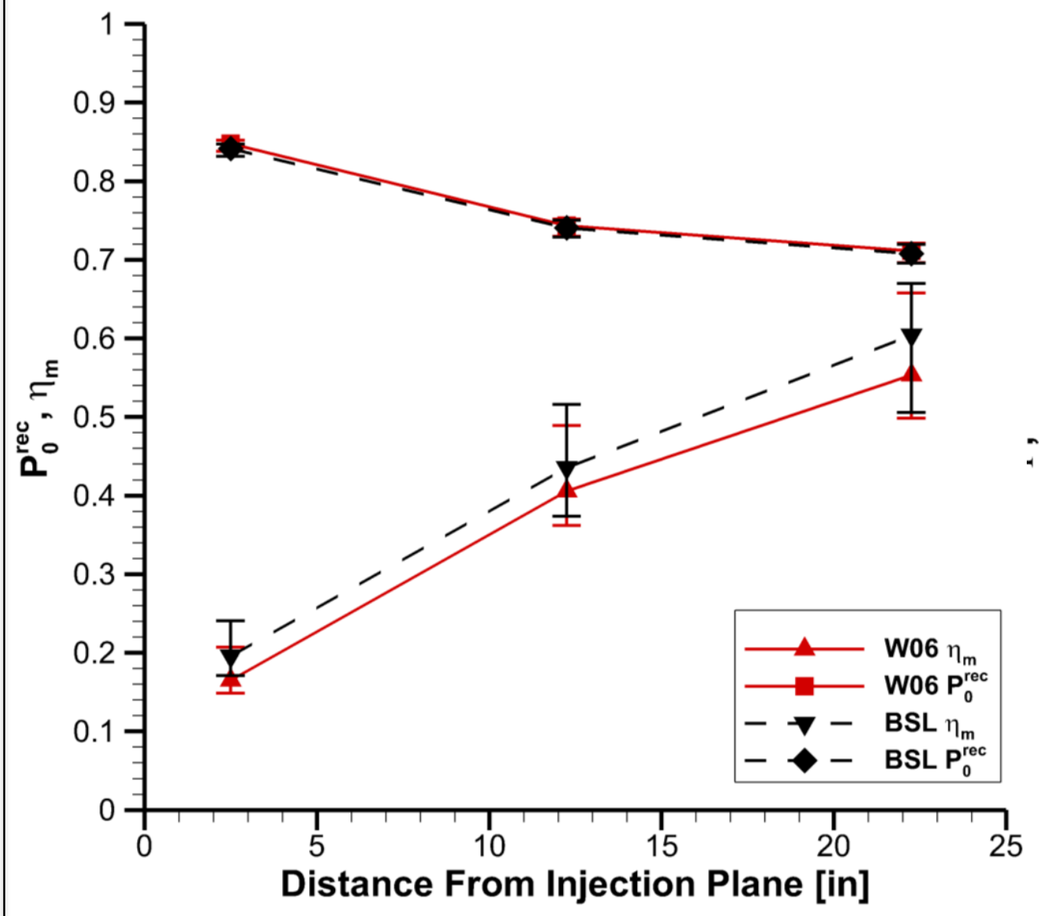

Figure 7. Ranges of mixing efficiency and total pressure recovery factor obtained in this study.

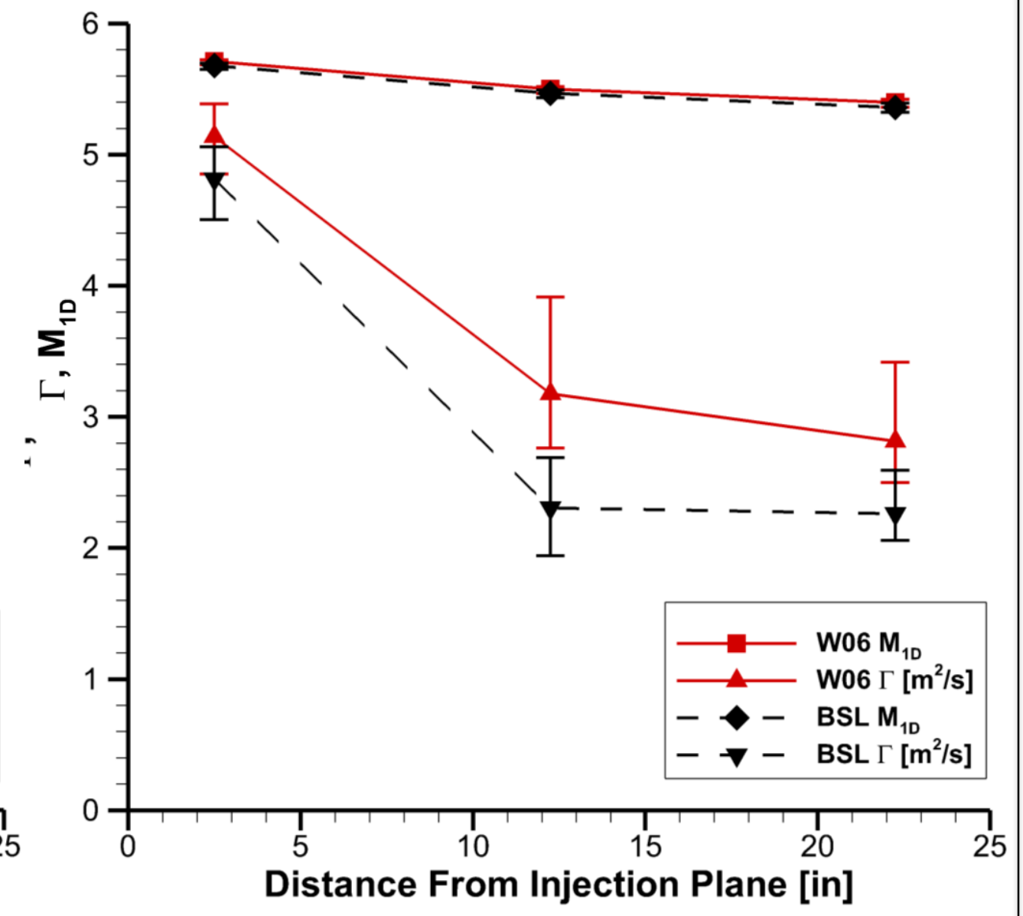

Figure 8. Ranges of mass-flux-weighted Mach number and circulation obtained in this study.

- Pressure recovery factor and mass-flux-weighted Mach number did not show significant variation with closure coefficient uncertainty
- Mixing efficiency and circulation showed significant variation with closure coefficient uncertainty
- Results suggest that vorticity generation is mostly due to the presence of the strut injector and not turbulent effects
- At the 22.25" station, the the present work shows mixing efficiency variation of approximately 27% due to closure coefficient uncertainty while previous work[3,4] showed:
  - Grid discretization error of approximately 5%
  - Mixing efficiency variation of approximately 40% due to variations in the turbulent Schmidt number

Publications

Di Stefano, M. A., Hosder, S., and Baurle, R. A., "Effect of Turbulence Model Uncertainty on Scramjet Strut Injector Flow Field Analysis." *23rd AIAA International Space Planes and Hypersonics Systems and Technologies Conference*, Montreal, Canada, 2020. doi: 10.2514/6.2020-2457

References

[1] "Past Projects: X-43A Hypersonic Flight Program," https://www.nasa.gov/centers/dryden/history/pastprojects/HyperX/index.html [retreived February 2018].

[2] "Hyper-X FactSheet 10/04," FS-2004-10-98-LaRC, https://www.nasa.gov/pdf/67456main_X-43A_Fa.pdf [retreived February 2018].

[3] Drozda, T. G., Lampenfield, J. J., Deshmukh, R. G., Baurle, R. A., and Drummond, J.P., "The Effect of Turbulence Modeling on the Mixing Characteristics of Several Fuel Injectors at Hypervelocity Flow Conditions," *AIAA Scitech 2019 Forum*, San Diego, CA, 2019. doi:10.2514/6.2019-0128

[4] Drozda, T. G., Drummond, J. P., and Baurle, R. A., "CFD Analysis of Mixing Characteristics of Several Fuel Injectors at Hypervelocity Flow Conditions," *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, UT, 2016.

[5] Schaefer, J., West, T., Hosder, S., Rumsey, C., Carlson, J., and Kleb, W., "Uncertainty Quantification of Turbulence Model Closure Coefficients for Transonic Wall-Bounded Flows," AIAA Paper 2015-2461, June 2015.

[6] Hosder, S., Walters, R. W., and Balch, M., "Efficient Sampling for Non-Intrusive Polynomial Chaos Applications with Multiple Input Uncertain Variables," AIAA Paper 2007-1939, April 2007.