High-Fidelity Modeling and Simulation of the NexGen Burner

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Computations: Overall Goals

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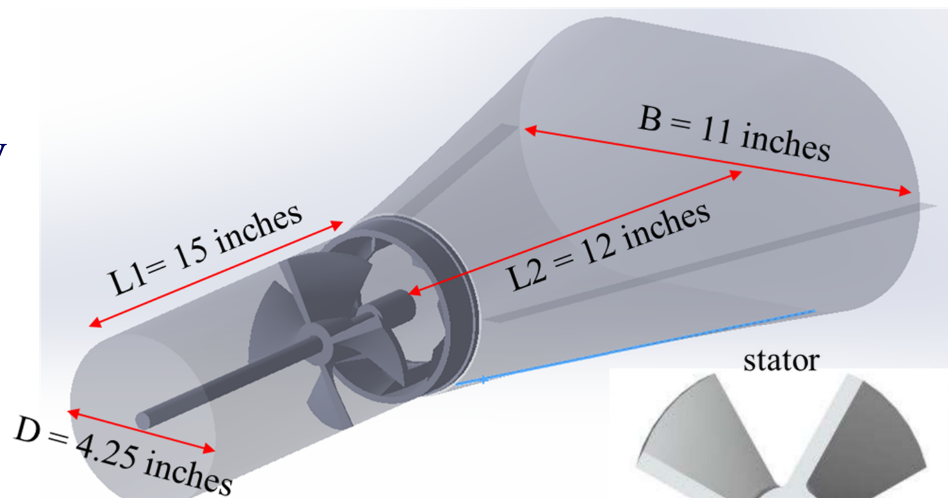
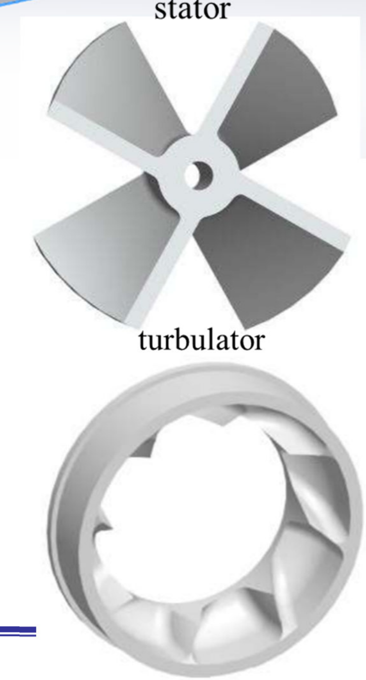
- **Identify the detailed flow physics in the current and modified FAA NexGen burner systematically using high-fidelity LES computations**
  - cold flow without fuel spray
  - cold flow with fuel spray
  - “hot flow” with vaporizing fuel spray
  - reacting flow
- **Establish a reference database developed using high-fidelity LES simulations for the above conditions**

current FAA burner assembly





Objectives of this presentation

- Cold flow computations without fuel spray in current geometry
  - identify the detailed flow physics
  - compare results with experimental measurements
- Flowfield analysis with fuel sprays
  - identify the effect of fuel spray on flow dynamics

* geometry dimensions source - https://www.fire.tc.faa.gov/pdf/materials/NexGenPlans_4_2016.pdf

Approach: Large Eddy Simulation (LES)

Salient features of the in-house LES framework:

- Compressible finite volume solver
- Multi-block structured grid based solver with Message Passing Interface (MPI) for inter-process communication
- LES with dynamic Smagorinsky model for sub-grid scale modeling
- Up to fourth order accurate in space and third order in time
- Scalar or matrix artificial dissipation to assure numerical stability
- All Mach number with preconditioning schemes for steady and unsteady flows

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LES: Gas Phase Formulation

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Favre-filtered conservation equations for gas-phase flowfield

mass
$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i}{\partial x_i} = \tilde{\dot{\rho}}_s$$

momentum
$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial x_i} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial(\bar{\tau}_{ij} - \tau_{ij}^{SGS})}{\partial x_i} + \tilde{\dot{F}}_{s,i}$$

energy
$$\frac{\partial \bar{\rho}\tilde{E}}{\partial t} + \frac{\partial[(\bar{\rho}\tilde{E} + \bar{p})\tilde{u}_i]}{\partial x_i} = \frac{\partial(-\bar{q}_i + \tilde{u}_j\bar{\tau}_{ji} - \sigma_i^{SGS} - H_i^{SGS})}{\partial x_i} + \tilde{\dot{Q}}_s$$

species
$$\frac{\partial \bar{\rho}\tilde{Y}_k}{\partial t} + \frac{\partial(\bar{\rho}\tilde{Y}_k\tilde{u}_i)}{\partial x_i} = \frac{\partial(-\bar{\rho}\tilde{Y}_k\tilde{V}_{i,k} - Y_{i,k}^{SGS} - \theta_{i,k}^{SGS})}{\partial x_i} + \tilde{\dot{w}}_k + \tilde{\dot{S}}_{s,k}$$

Closure requirements

- Subgrid-scale (sgs) turbulence interaction

$$\tau_{ij}^{sgs},\ D_{ij}^{sgs},\ H_i^{sgs},\ \sigma_{ij}^{sgs},\ \Phi_{k,j}^{sgs},\ \theta_{k,j}^{sgs}$$

- Chemical reaction source and thermophysical properties & constitutive laws

$$\bar{\dot{\omega}}_k,\ Z,\ C_p,\ \mu,\ \lambda,\ D_{im}$$

Li, H. G., Khare, P., Sung, H. G., & Yang, V. (2016). A large-eddy-simulation study of combustion dynamics of bluff-body stabilized flames. CST, 188(6), 924-952.
Kamin, M., & Khare, P. (2022). The Effect of Weber Number on Spray and Vaporization Characteristics of Liquid Jets Injected in Air Crossflow. ASME JFE, 144(6), 061108.

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LES: Dispersed Phase Formulation

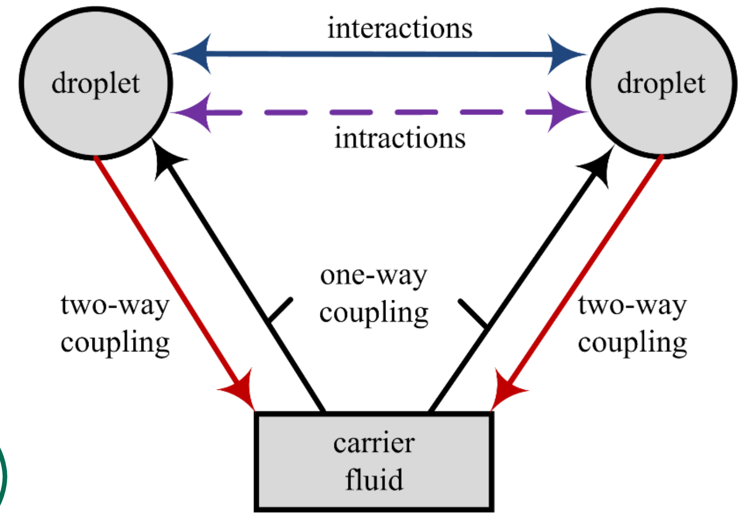
Spray Dynamics

$$\frac{d\boldsymbol{x}_d}{dt} = \boldsymbol{u}_d \qquad m_d \frac{d\boldsymbol{u}_d}{dt} = \boldsymbol{F}_d$$

Basset-Boussinesq-Oseen (BBO) equation

$$\boldsymbol{F}_d = \underbrace{\frac{\pi}{12} d_d^3 \rho \left(\dot{\boldsymbol{u}} - \dot{\boldsymbol{u}}_d \right)}_{\text{virtual mass}} + \underbrace{\frac{\pi}{8} d_d^2 \rho C_d \left| \boldsymbol{u} - \boldsymbol{u}_d \right| \left(\boldsymbol{u} - \boldsymbol{u}_d \right)}_{\text{drag force}} + \underbrace{\frac{\pi}{6} d_d^3 \left(-\nabla p + \nabla \cdot \boldsymbol{\tau} \right)}_{\text{buoyancy}}$$

$$+ \underbrace{\frac{3}{2} d_d^2 \sqrt{\pi \rho \mu} C_B \left[\int_{t_0}^{t} \frac{\dot{\boldsymbol{u}} - \dot{\boldsymbol{u}}_d}{\sqrt{t - \xi}} d\xi + \frac{\left(\boldsymbol{u} - \boldsymbol{u}_d \right)_{t_0}}{\sqrt{t}} \right]}_{\text{Basset force}} + \underbrace{m_d \boldsymbol{g}}_{\text{gravity}} + \underbrace{\boldsymbol{F}_L}_{\text{lift}}$$



one-way: effect of carrier fluid on droplets
two-way: mutual coupling between droplets and carrier fluid
four-way: droplet-droplet intractions and interactions (e.g., collision & coalescence)

Mass and Heat Transfer

$$\frac{dm_d}{dt} = -\dot{m}_d$$

$$m_d C_l \frac{dT_d}{dt} = \dot{Q}_{conv} - \dot{m}_d L_v = h_d \pi d_d^2 (\tilde{T} - T_p) - \dot{m}_d L_v$$

Spray breakup models:

- K-H wave model for primary atomization
- Taylor Analogy Breakup (TAB) model for secondary atomization

Khare, P., Wang, S., & Yang, V. (2015). Modeling of finite-size droplets and particles in multiphase flows. Chinese Journal of Aeronautics, 28(4), 974-982.

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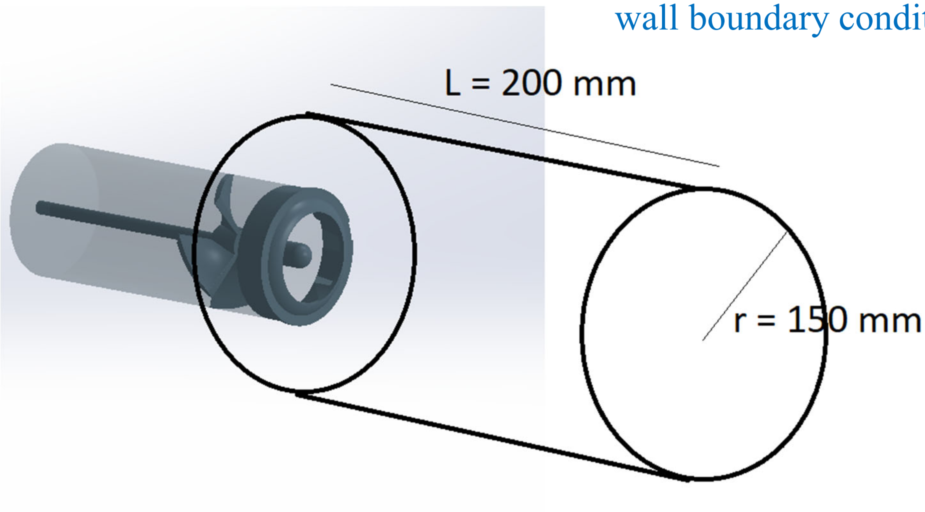
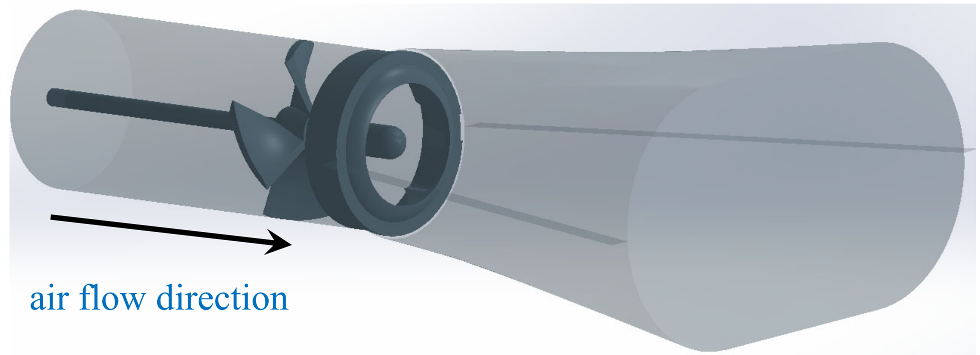
Cold Flow: FAA Burner Geometry
inlet airflow @ 3.86m/s

wall boundary condition applied on all solid surfaces



Case 0: geometry for code validation



Case 1: NexGen geometry

Inlet air temperature : 283 K

Pumped air pressure : 5.15 bar

Inlet air density: 1.2474 kg/m^3

Mass flow rate : 0.0384 kg/s

Equivalent inflow velocity : 3.86 m/s

Reynolds number: 30623

Note: the experiment was conducted the burner cone. A difference in some flow features can be expected as a result.

Ochs, R. I. (2013). Design and Analysis of the Federal Aviation Administration Next Generation Fire Test Burner, Ph.D Thesis, Rutgers University.

Blocking & Grid Generation

- Block structured grid with only hexahedral elements.
- Multi-block grid for massively parallel computing

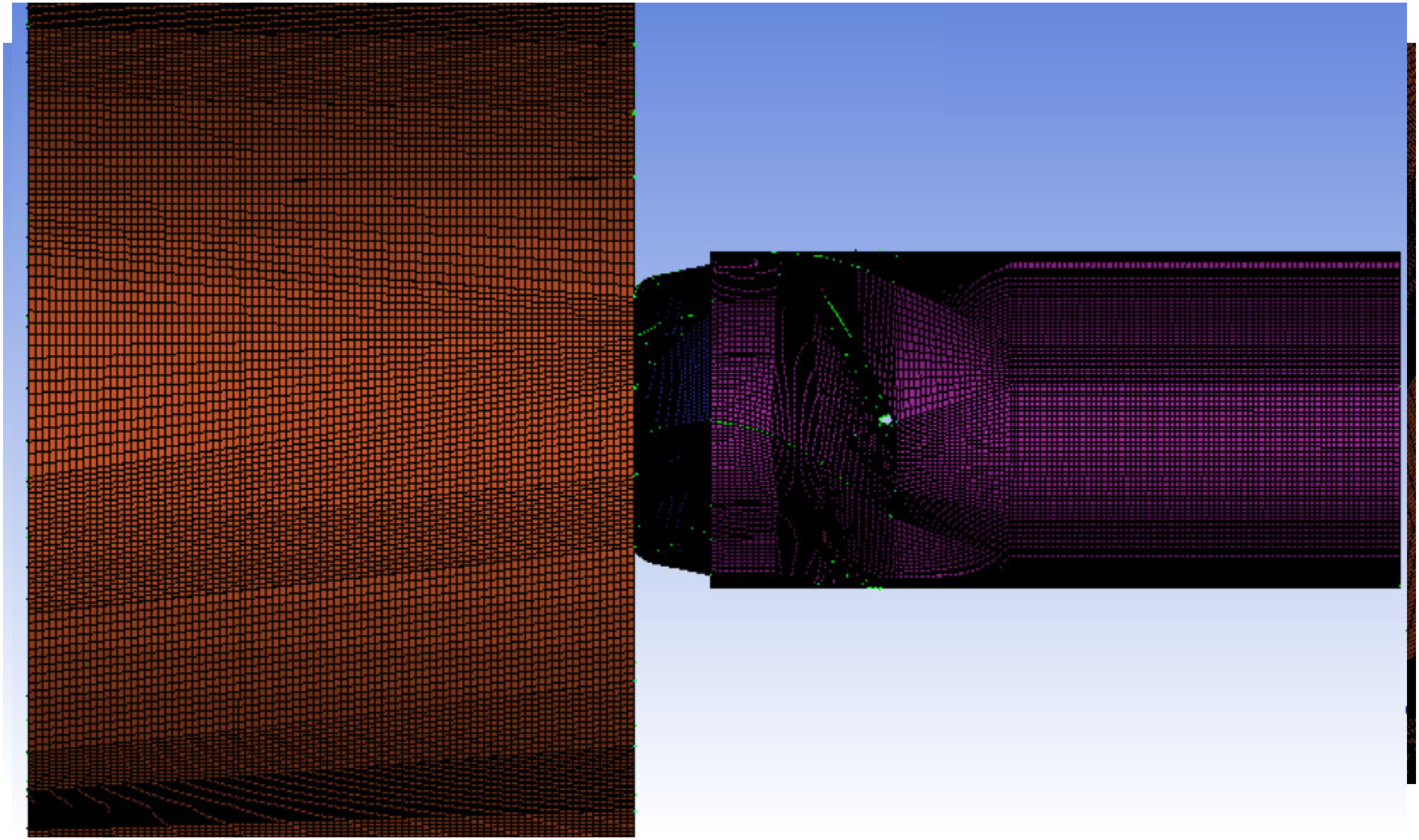
Grid metrics

Validation case (Case 0)	Burner cone case (Case 1)
Total grid points : 122.2 million	**Total grid points:** 193 million
Total number of grid blocks: 4664	**Total number of grid blocks:** 7028
Smallest grid size: 0.04 mm	**Smallest grid size:** 0.04 mm

- Smallest grid size based on y+ = 5 ≈ 0.14 mm close to walls.
- Present grid has extra refinement at the injector center due to the O-grid configuration.
- Grid size approximately 0.65 mm elsewhere
- For reference, Taylor microscale is 0.5 mm and the Kolmogorov scale is 0.017 mm

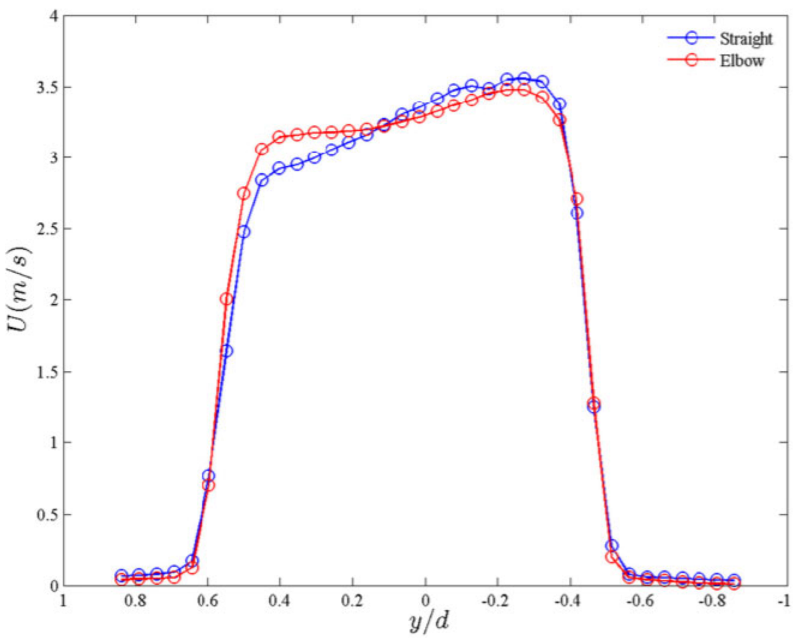
Case 0: model validation

Grid Snapshots



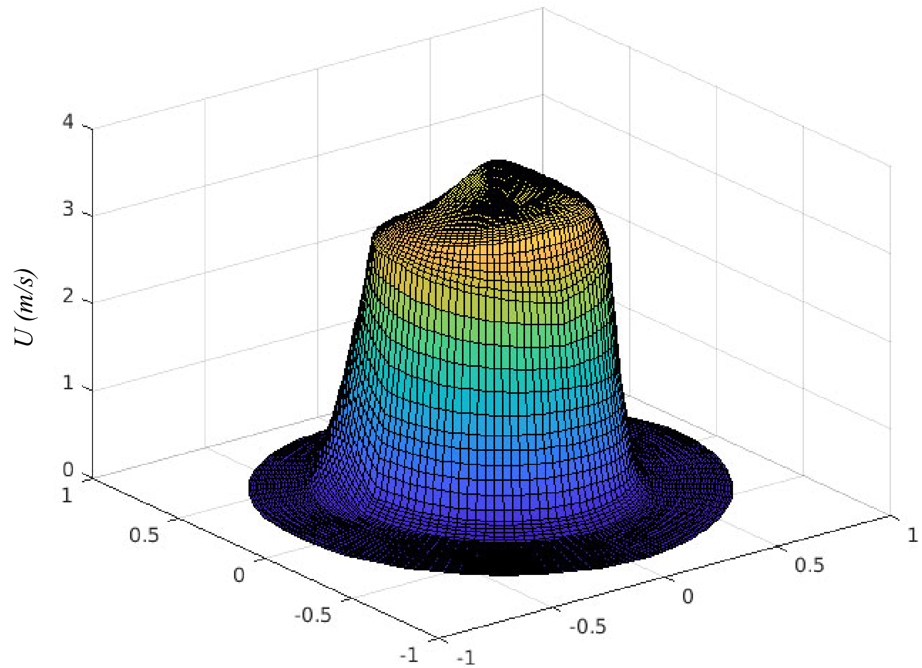
Inlet Velocity Profile

- Asymmetry in the inflow profile within the draft tube
- The asymmetry is therefore accounted for, and a velocity profile is recreated to match the experimental profile.



Inlet velocity profile reported in the experiments

Ochs, R. I. (2013). Design and Analysis of the Federal Aviation Administration Next Generation Fire Test Burner, Ph.D Thesis, Rutgers University.



Inlet velocity profile reconstructed for simulation

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Mean Velocity Magnitude

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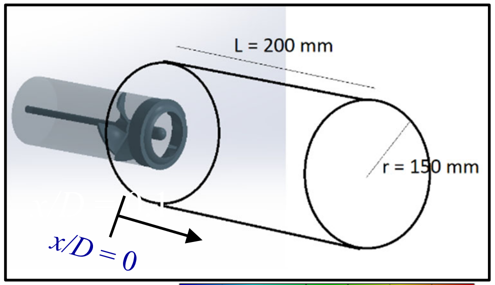
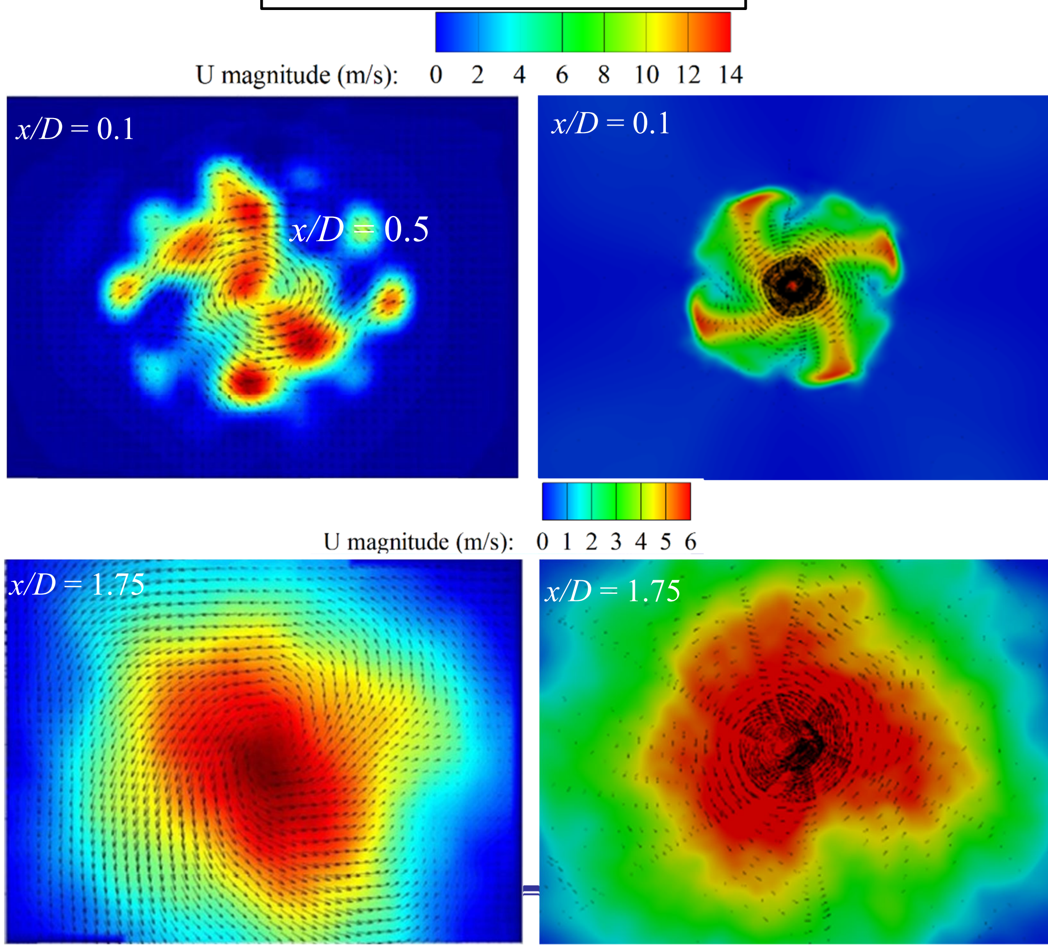
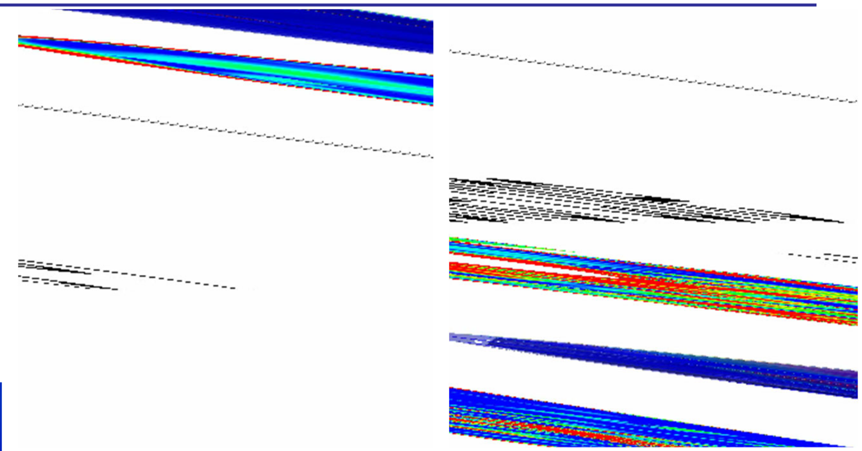
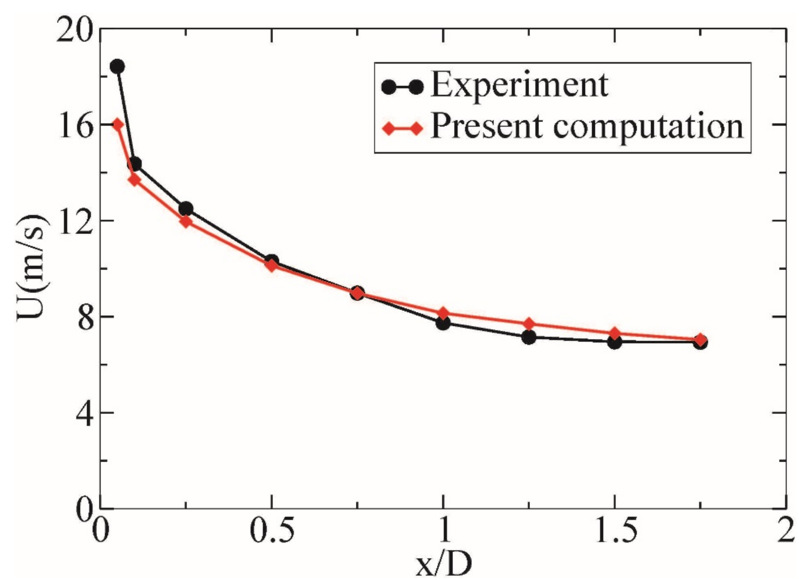




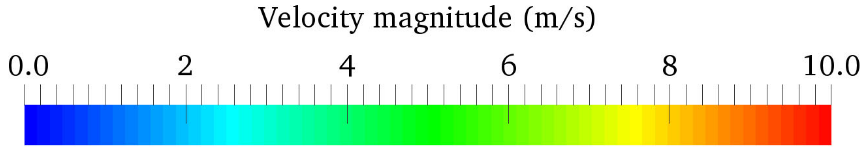


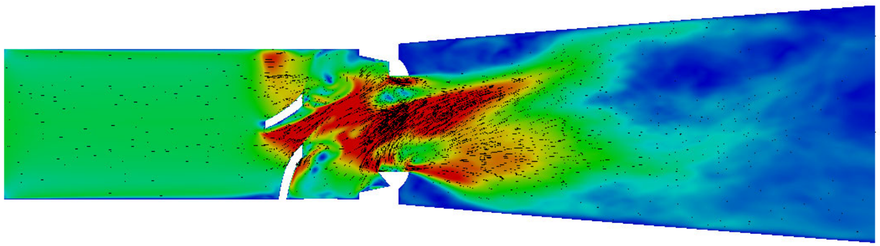
stator turbulator



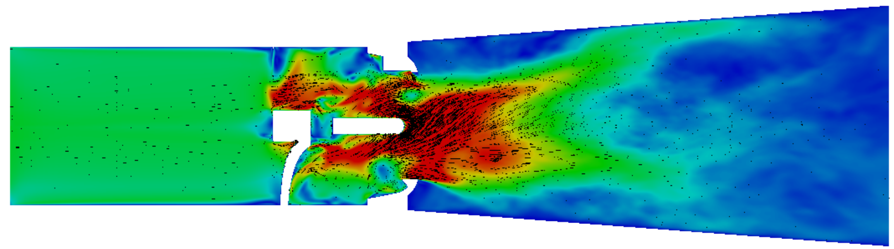
Case 1: cold flow dynamics of NexGen burner

Mean Velocity in Spanwise Planes

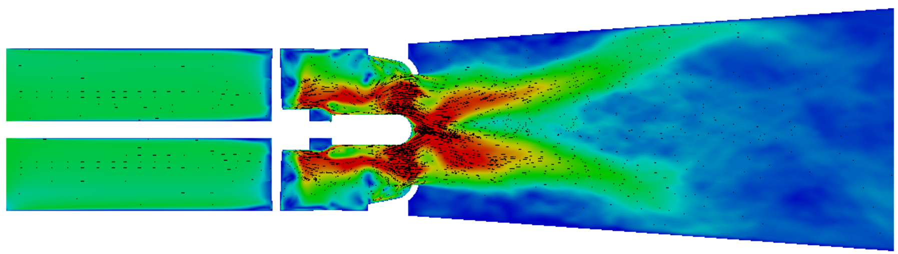




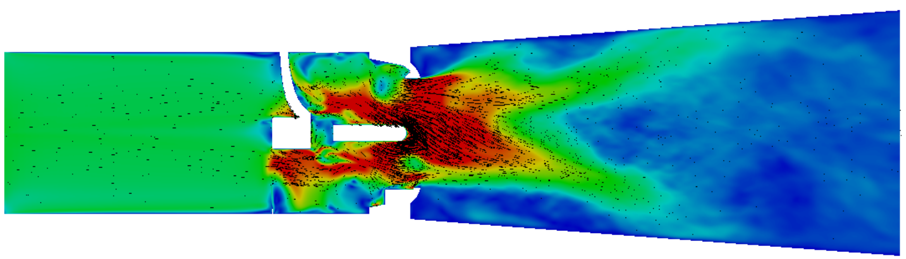
z/D = –0.16 (into the plane)



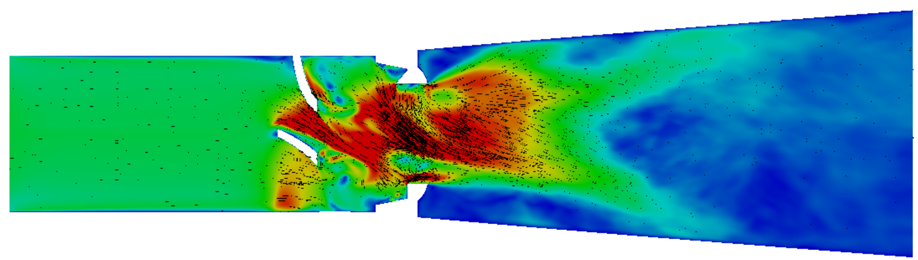
z/D = -0.08 (into the plane)



z/D = 0 (mid-plane)

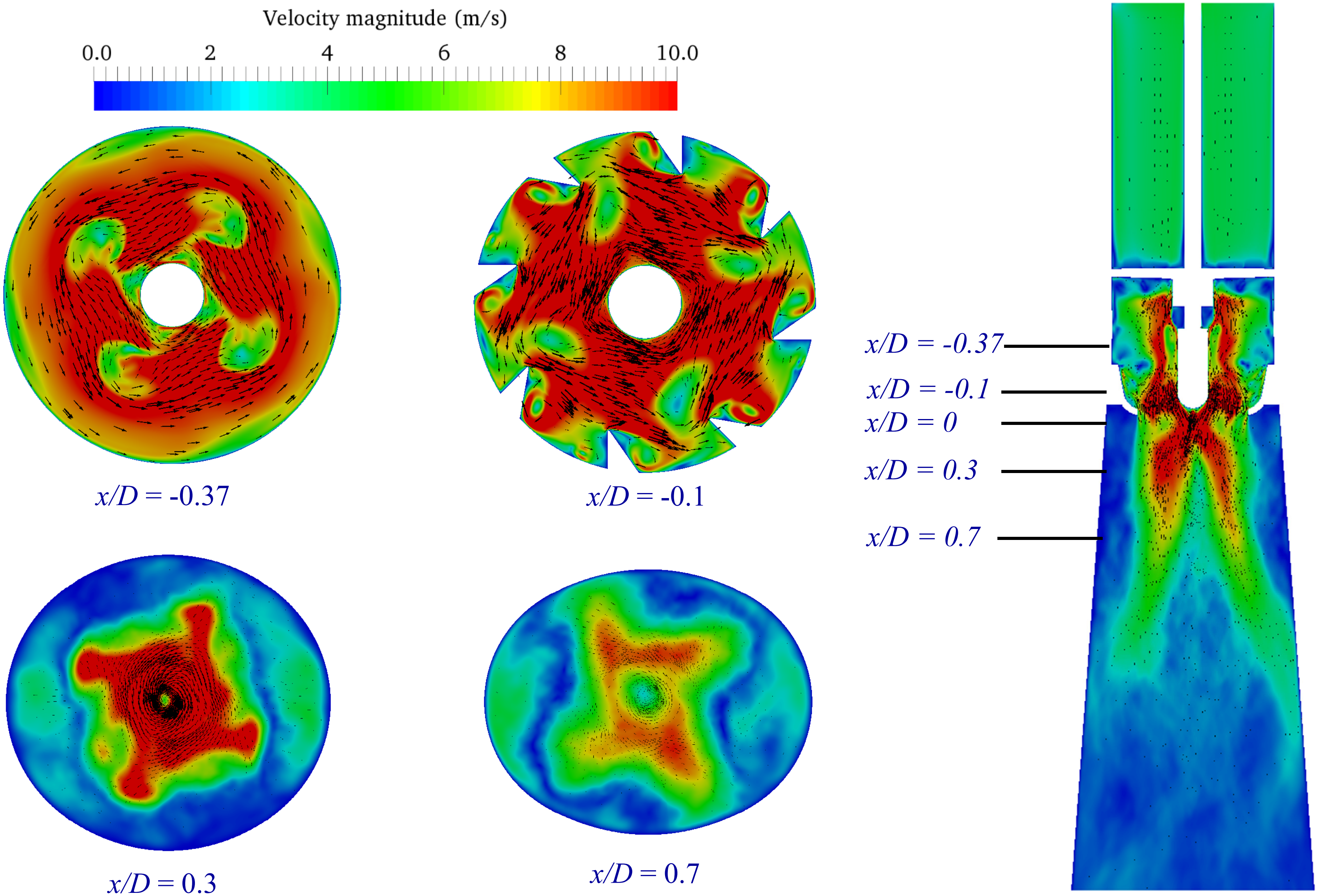


z/D = 0.08 (out of plane)

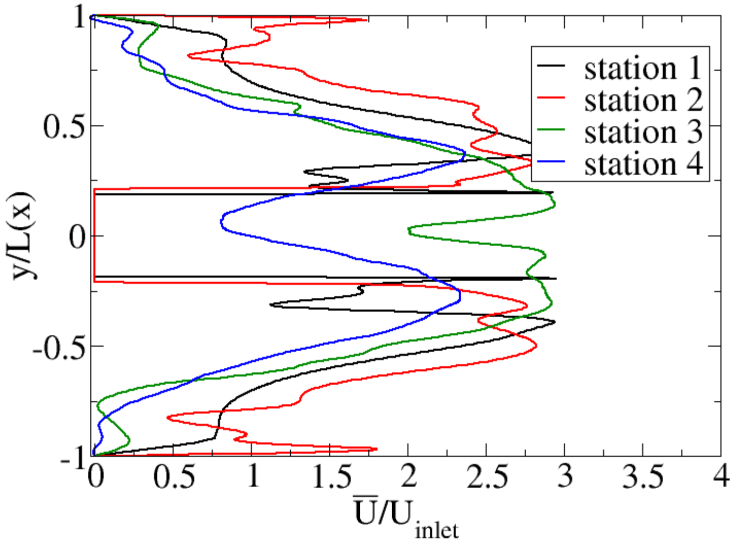


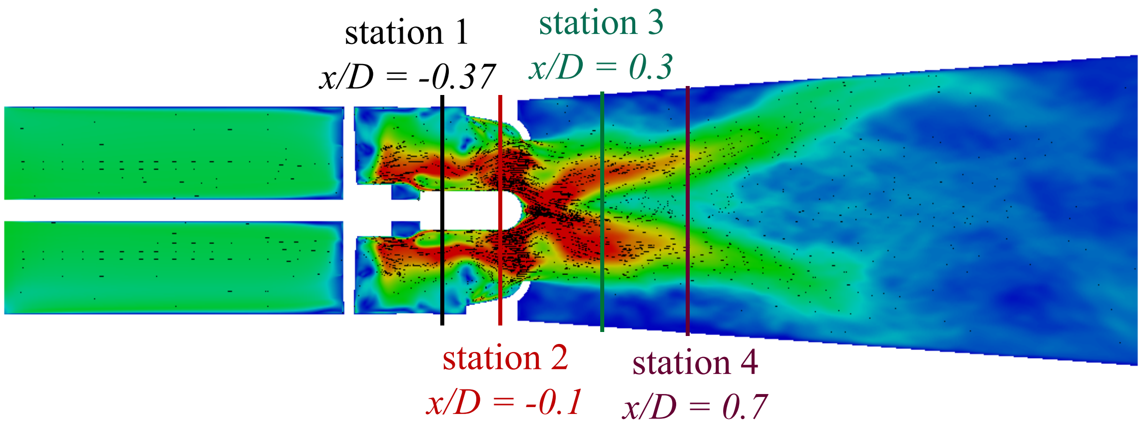
z/D = 0.16 (out of plane)

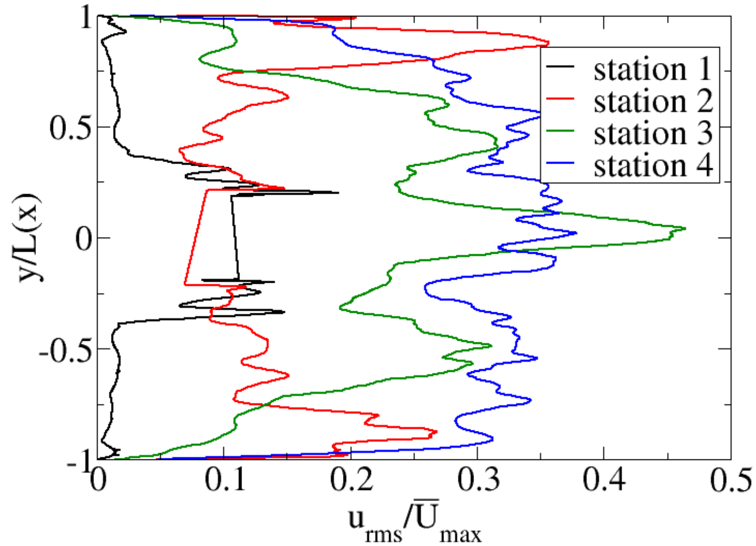
Mean Cross-Sectional Velocities

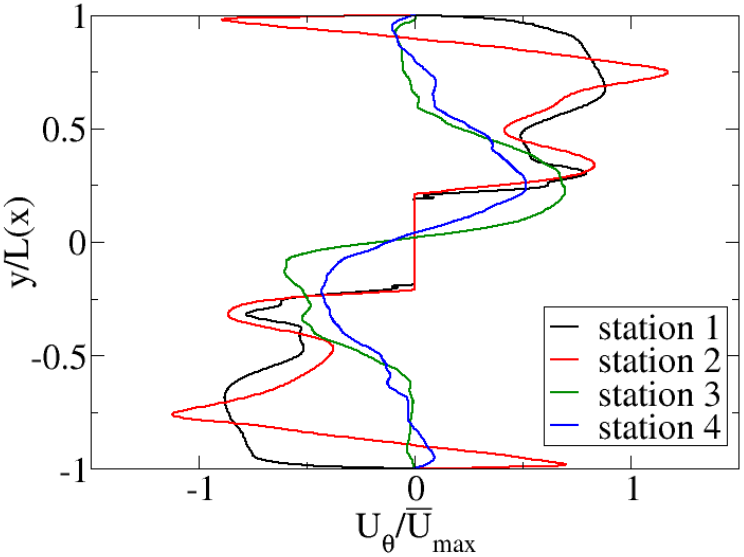


Mean, Azimuthal and rms Velocity



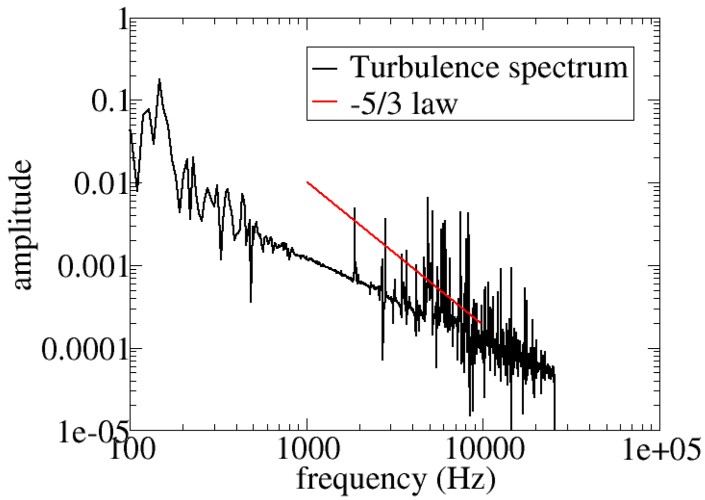




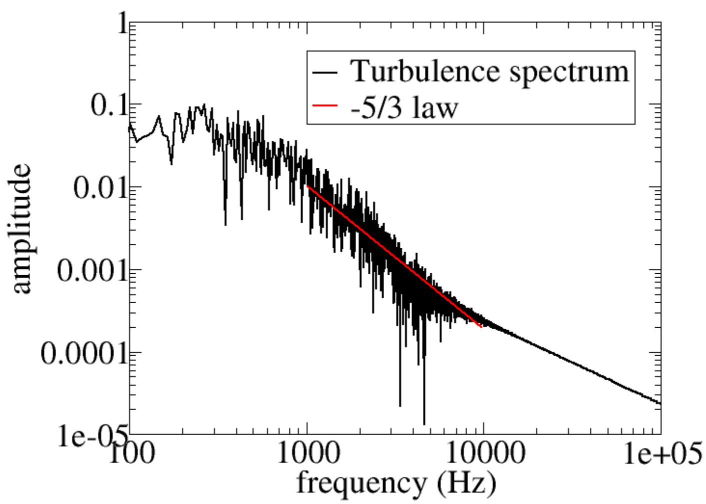


Turbulence Spectrum

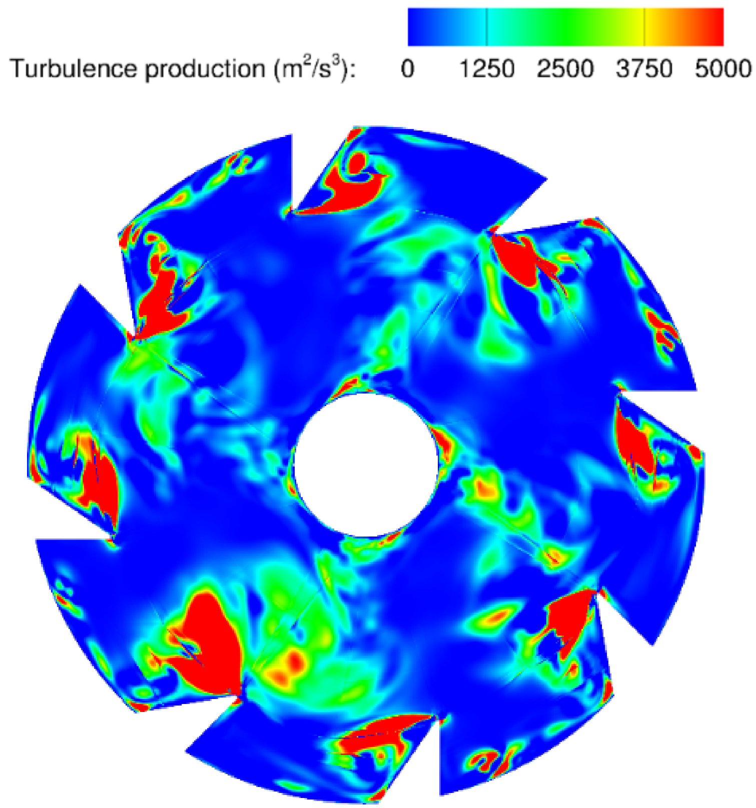
x/D = 0.3 downstream of the stator exit



x/D = 0.5 downstream of the turbulator exit



turbulent shear production $u_i' u_j' \dfrac{\partial \overline{U}_j}{\partial x_i}$



Case 2: cold flow dynamics with fuel spray for NexGen burner

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NexGen Burner with Fuel Spray

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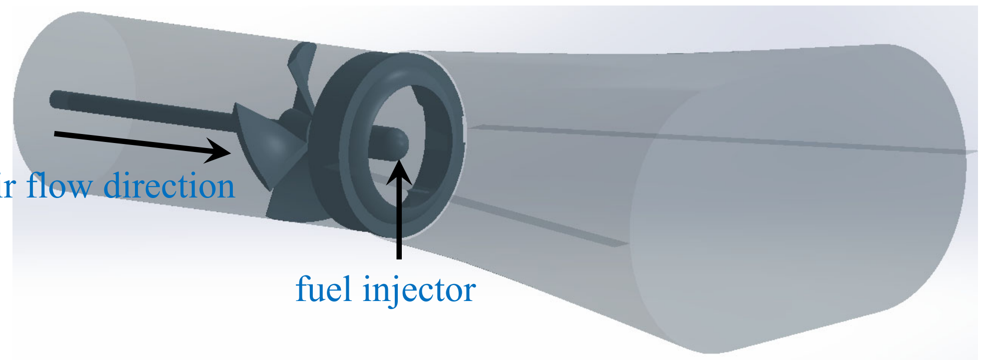
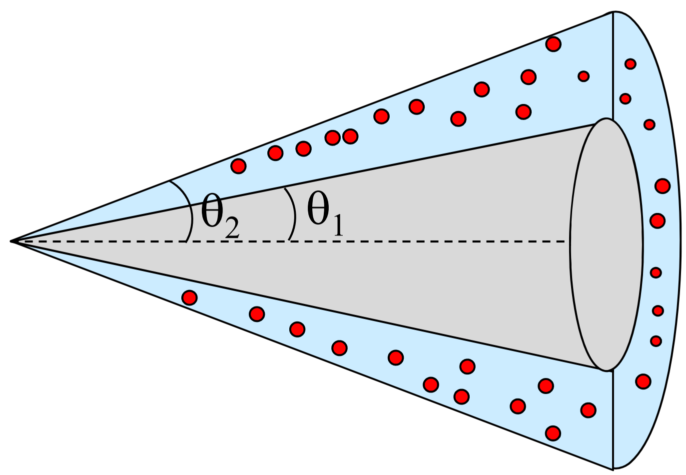
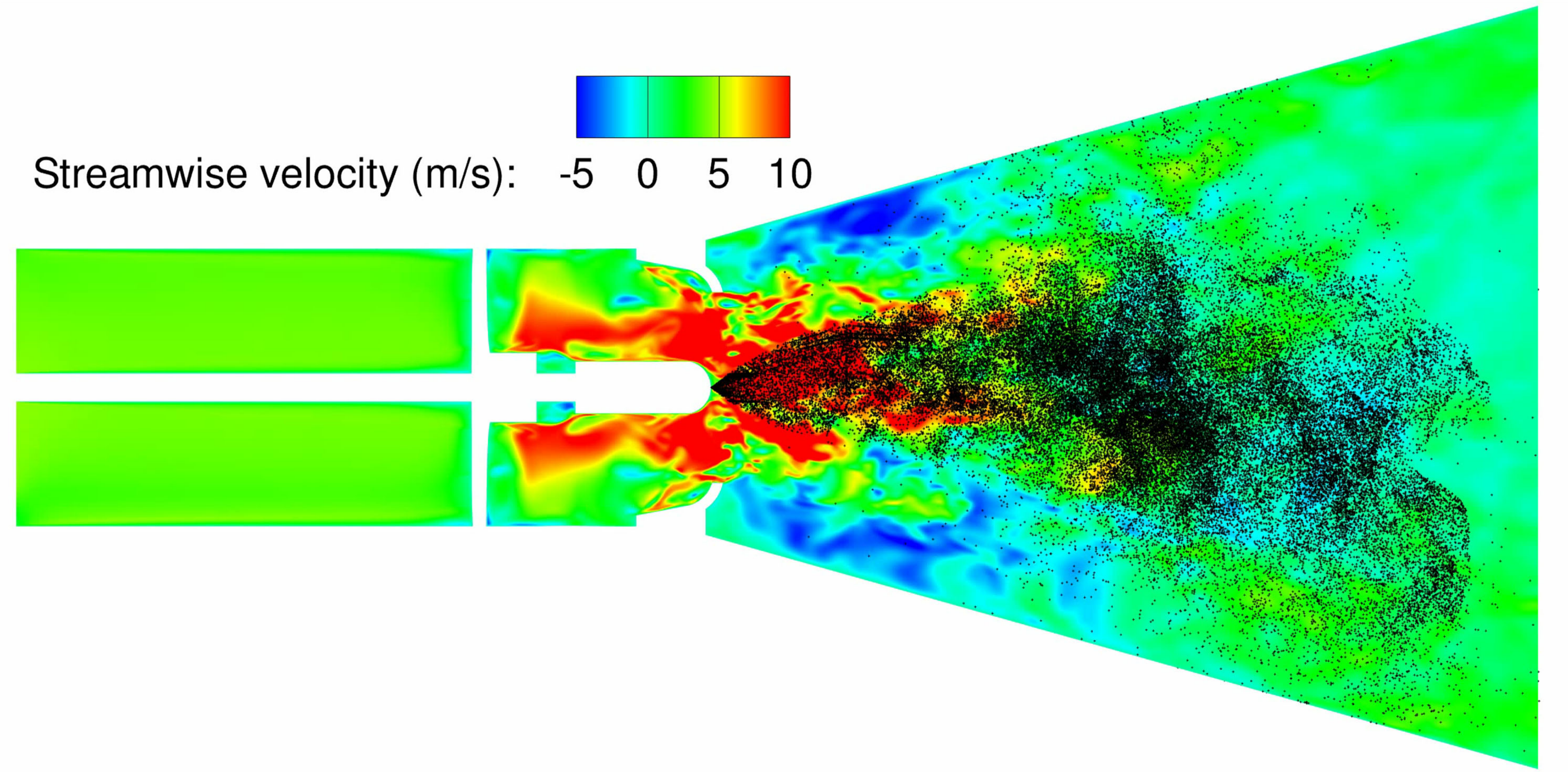
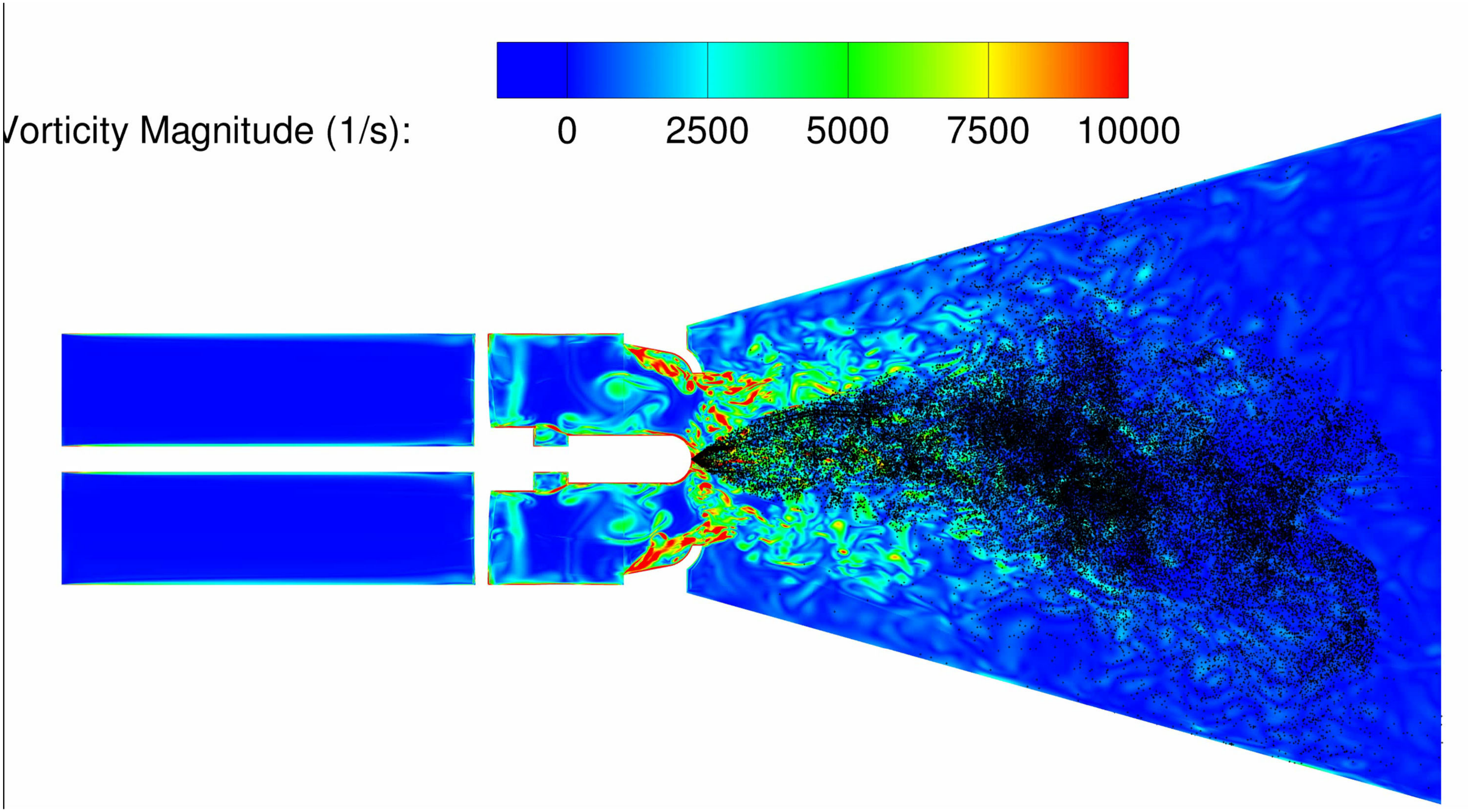
Liquid jet: Jet A
Liquid jet pressure: 100 psi
Liquid temperature: 298 K
Liquid density: 840 kg/m^3
Mass flow rate: 2.5 Gph
SMD (exp.): 40 µm



- Injected spray closely resembles the experimental spray cone characteristics with an SMD of 40 µm
- Primary and secondary atomization not modeled
- Spray injected in the hollow cone defined by half angles of 20^o and 40^o
- Dilute spray assumption
- Finite size formulation to model four way coupling




Streamwise velocity (m/s): -5 0 5 10


Vorticity Magnitude (1/s):
0
2500
5000
7500
10000

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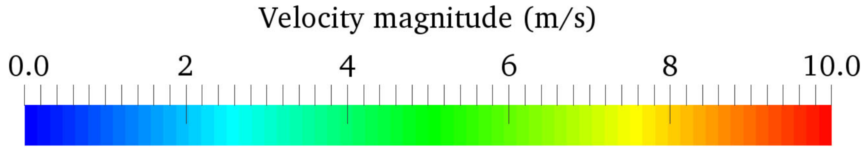
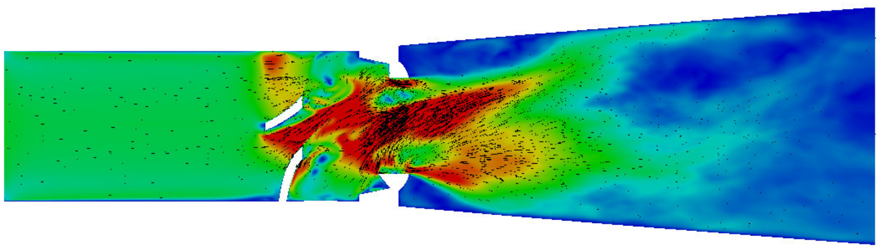
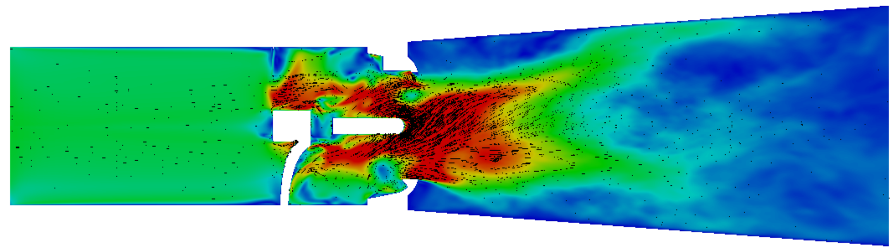
Mean Velocity in Spanwise Planes (without spray)

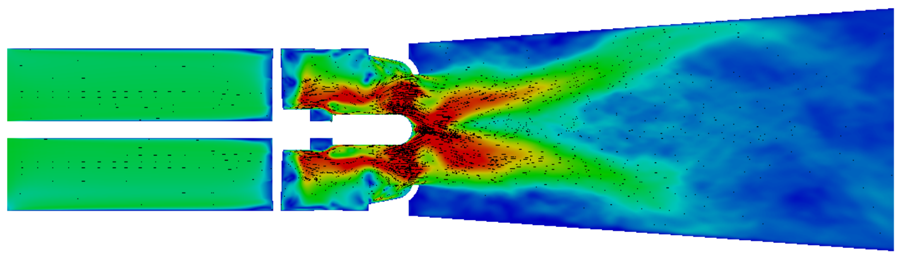




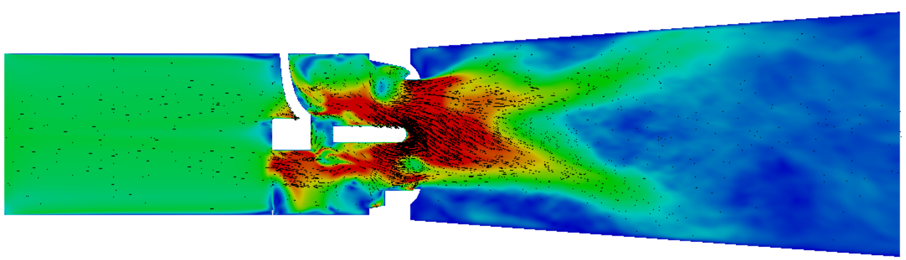
z/D = –0.16 (into the plane)



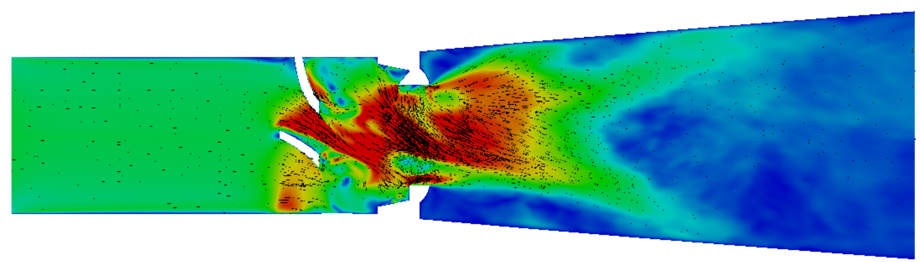
z/D = -0.08 (into the plane)



z/D = 0 (mid-plane)



z/D = 0.08 (out of plane)



z/D = 0.16 (out of plane)

Mean Velocity in Spanwise Planes (with spray)

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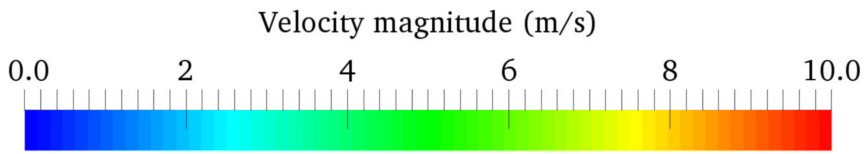
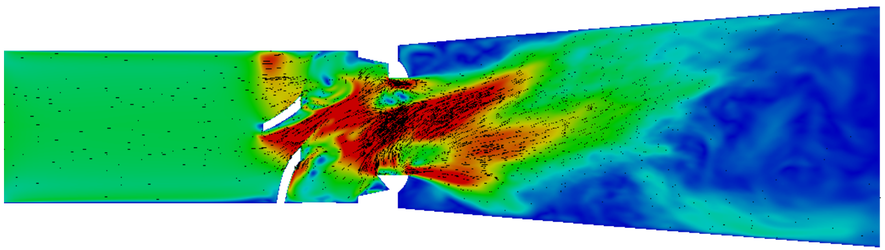
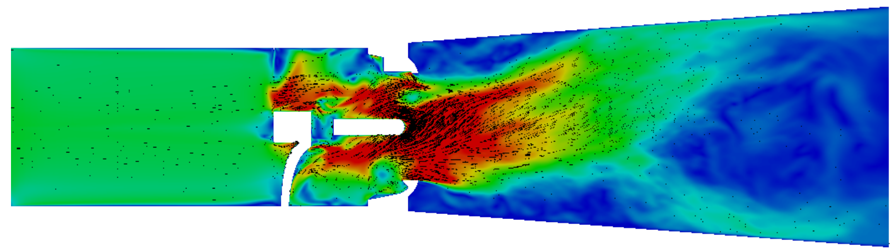
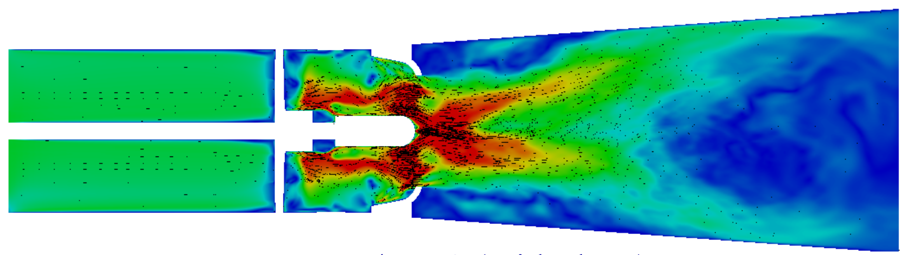




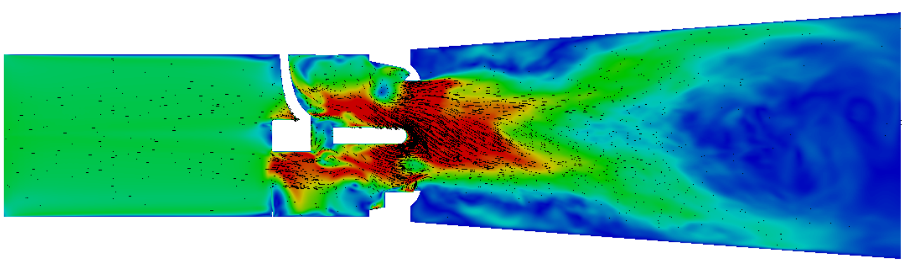
z/D = –0.16 (into the plane)



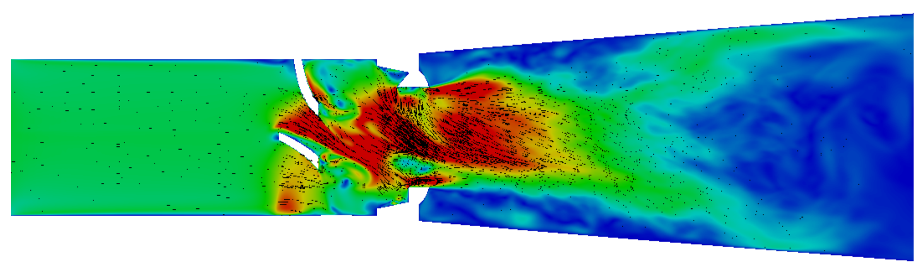
z/D = -0.08 (into the plane)



z/D = 0 (mid-plane)

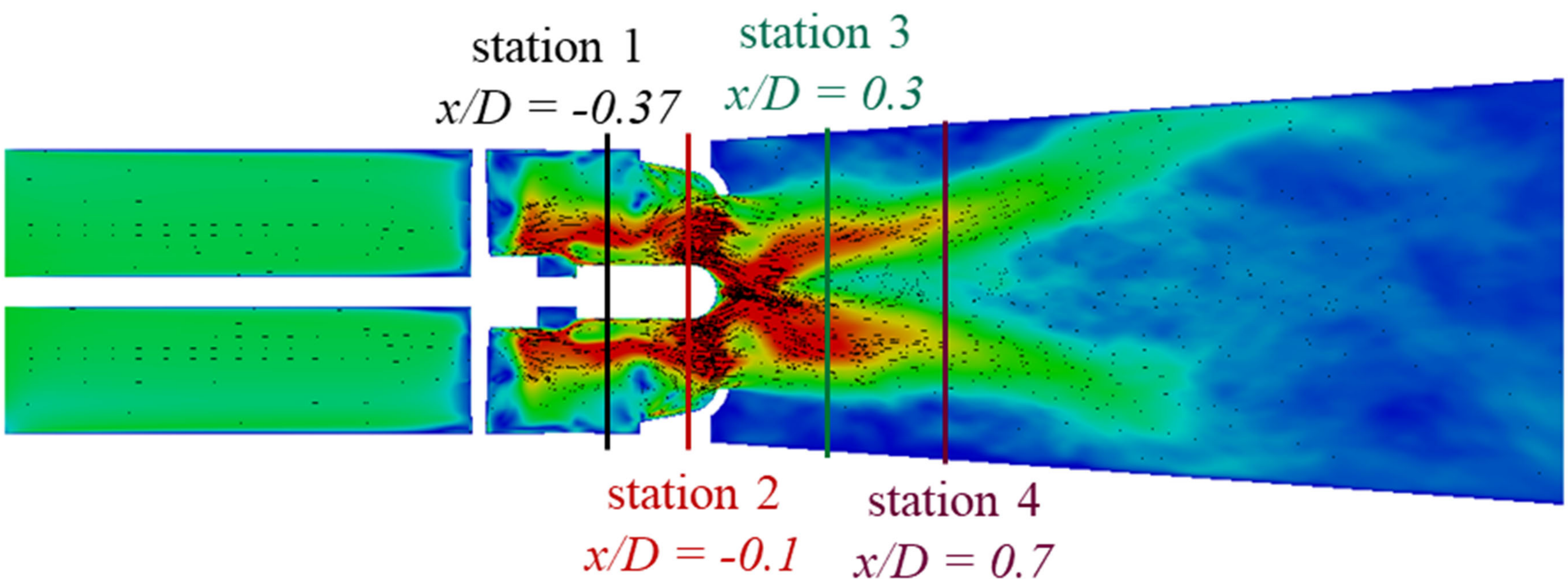


z/D = 0.08 (out of plane)



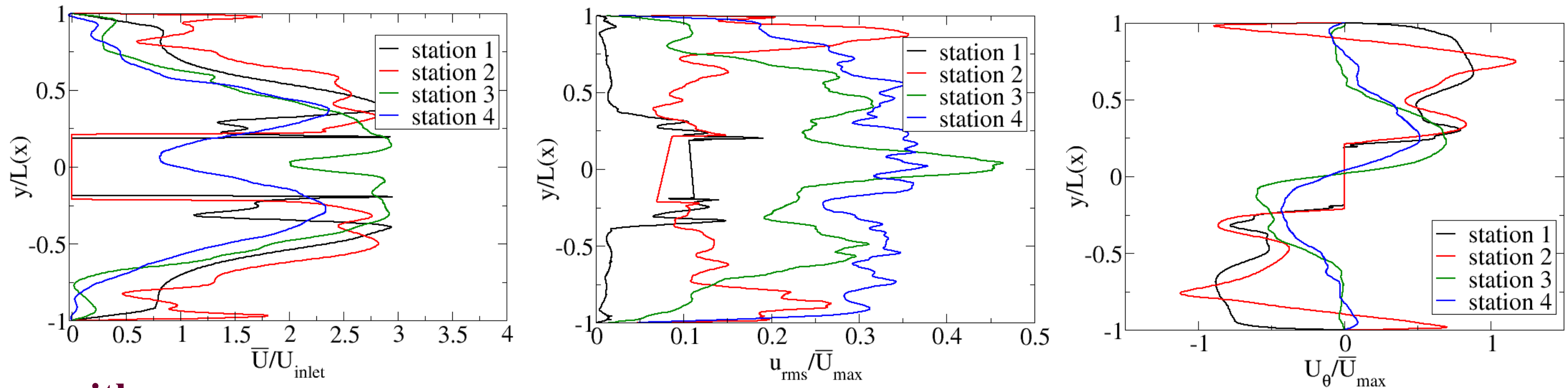
z/D = 0.16 (out of plane)

Recall: Data Extraction Planes

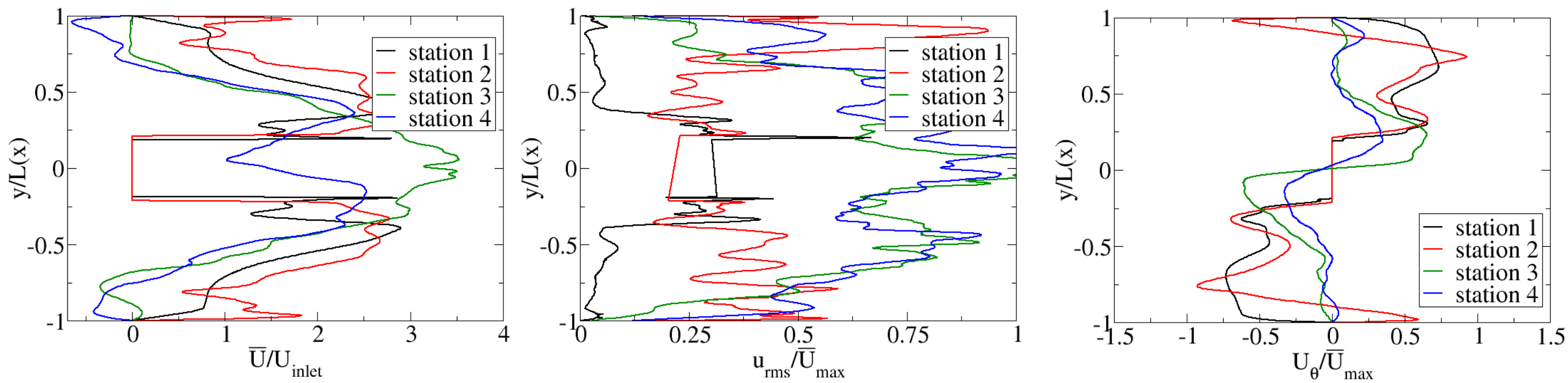


Quantitative Comparison (with and without spray)

without spray



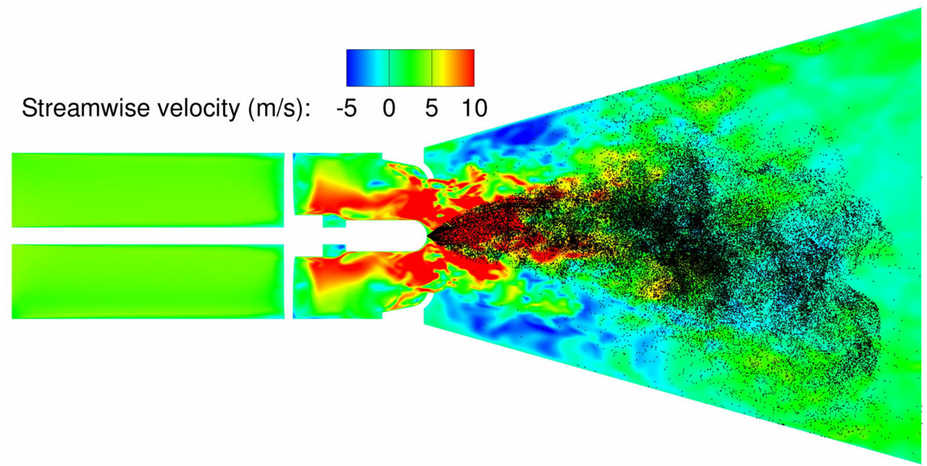
with spray

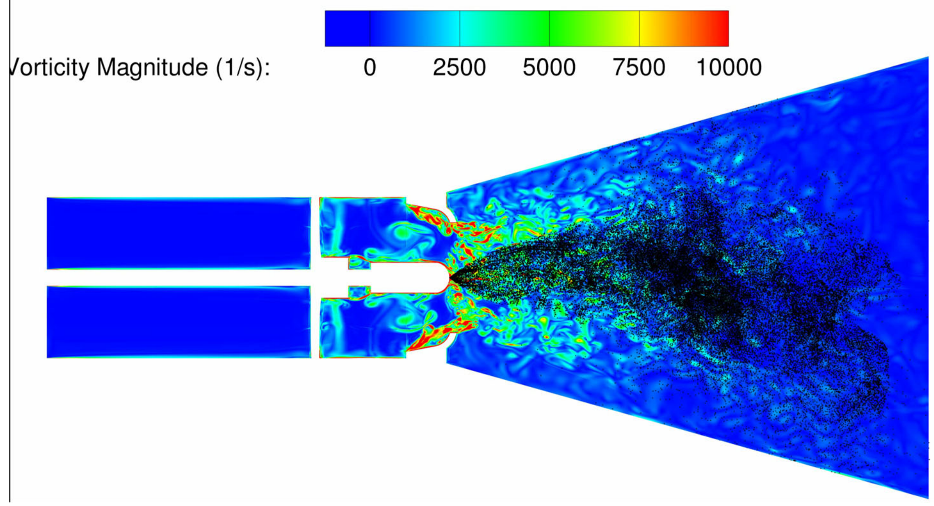


- Recirculation zones near the walls for case with spray
- Larger RMS velocity (stations 3,4) -- enhanced turbulence due to flow-droplet interaction
- Slight drop in peak azimuthal velocity near the walls

Conclusions

- Cold flow computations without fuel spray in current geometry
  - identify the detailed flow physics
  - compare results with experimental measurements
- Identified the effect of fuel spray on flow dynamics
  - flow dynamics in the far field significantly different
- Next steps
  - Identify the effect of vaporizing fuel spray on flow dynamics
  - Identify the reacting flow dynamics
  - Compare and contrast the effect of changes in geometry on flow and combustion physics





Thank you for your attention

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