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Fundamental Processes and Design Considerations for the NexGen Fire Test Burner: Experiments and High-Fidelity Simulations

Prashant Khare, PhD
Assistant Professor
Department of Aerospace Engineering
University of Cincinnati

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Acknowledgments
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- Steve Summer, Rob Ochs, and other researchers at FAATC for inputs

Team: San Mou Jeng (Co-PI), Ryan Hasselbeck (staff), Manu Kamin (PhD student) and Prashant Khare (PI)

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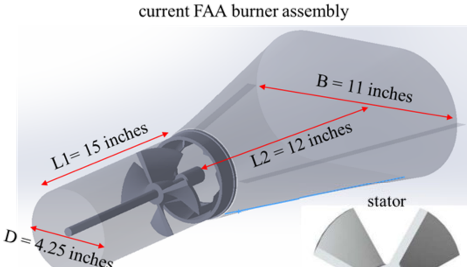
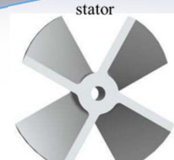
Computations: Overall Goals

- **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**

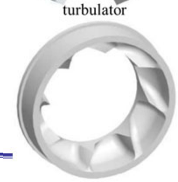
current FAA burner assembly



stator



turbulator



Objectives of this presentation

- Cold flow computations without fuel spray in current geometry
  – Identify the detailed flow physics for 2 inlet velocities
  – compare our results with measurements from Dr. Ochs' thesis
- Preliminary analysis with fuel sprays
  – liquid jet in crossflow configuration

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

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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

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.

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LES: Dispersed Phase Formulation

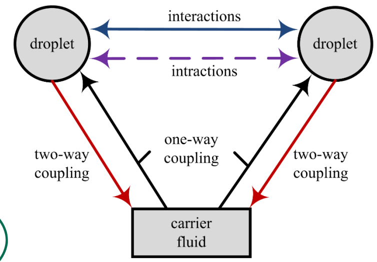
Spray Dynamics

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

Basset-Boussinesq-Oseen (BBO) equation

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

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



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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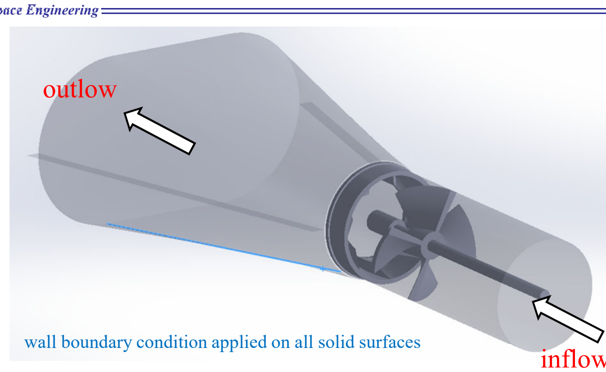
Cold Flow: FAA Burner Geometry

Case I: inlet airflow @ 10m/s

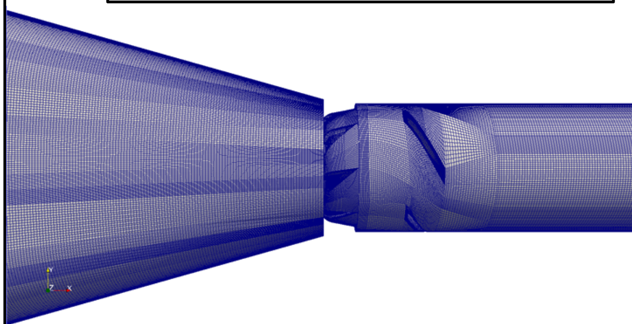


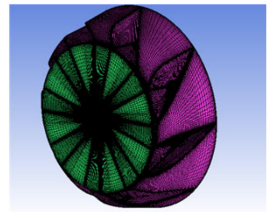
Inflow velocity : 10 m/s
Inlet air temperature : 300 K
Inlet air pressure: 1 atm
Reynolds number : 66,200

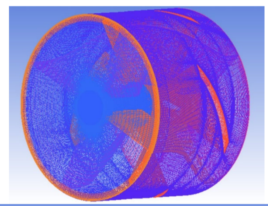
Computational Grid

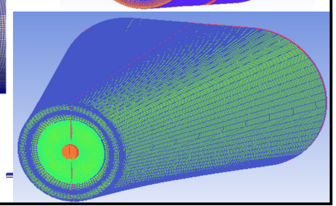
- Block structured grid with only hexahedral elements.
- Multi-block grid for massively parallel computing
- Smallest grid size based on y+ = 5 ≈ 0.14mm

Total number of grid points : 21.2 million
Total number of grid blocks : 1960
Smallest grid size: 0.4 mm









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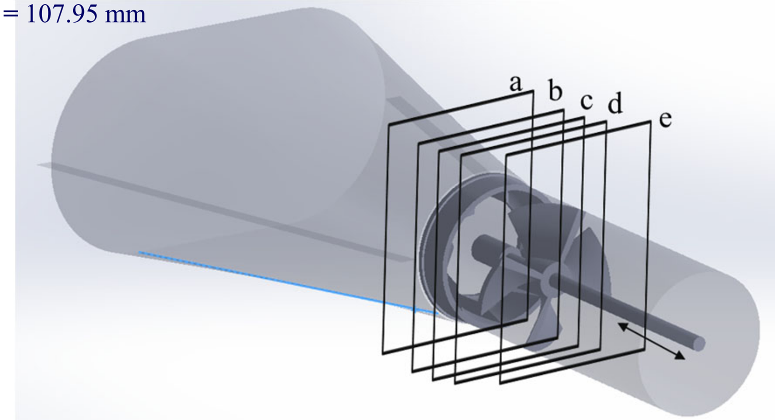
Locations of cross sectional planes for instantaneous visualization

Reference position: turbulator plane

d = 107.95 mm



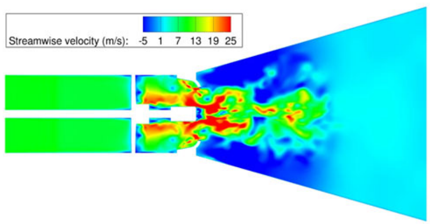
Locations a, b, c, d and e (combustion chamber, after turbulator, turbulator plane, after stator and stator plane respectively)

a : x/d = -0.5, b : x/d = 0, c : x/d = 0.1, d : x/d = 0.5, x/d = 0.65

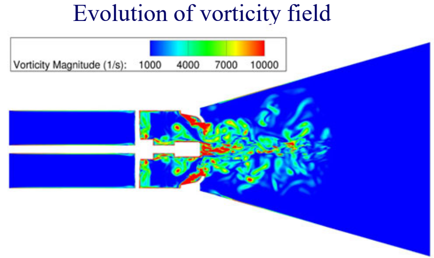
Streamwise Velocity (video)

Detailed Flow Dynamics

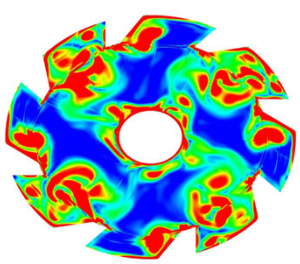
streamwise velocity evolution

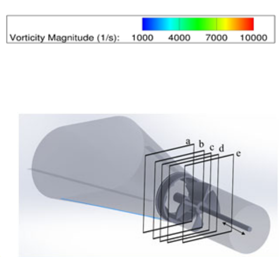


Evolution of vorticity field

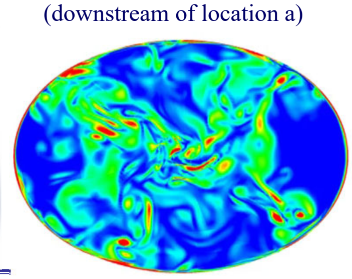


vorticity field - turbulator (location c)





vorticity field - burner cone (downstream of location a)



Mean Velocity
Center and Off-Center Planes

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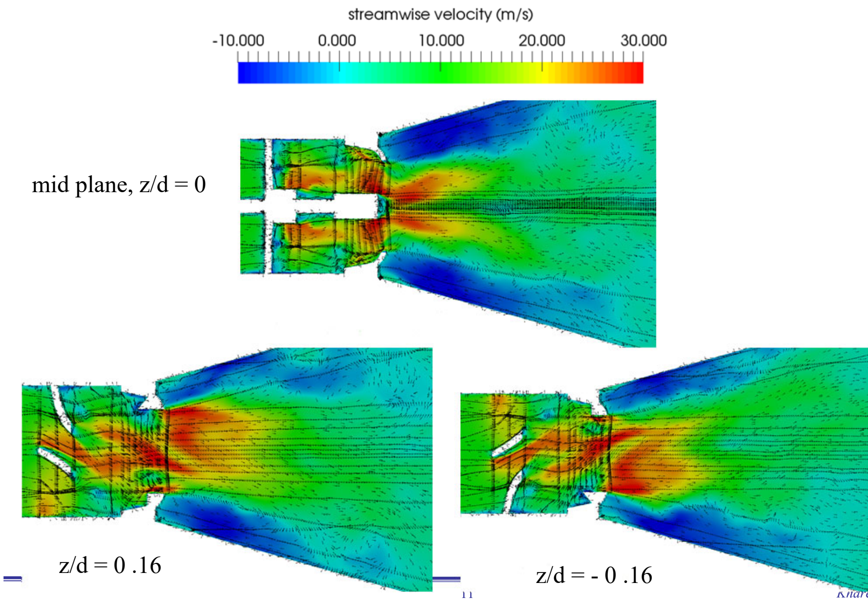

Mean Velocity
Streamwise Sectional Planes

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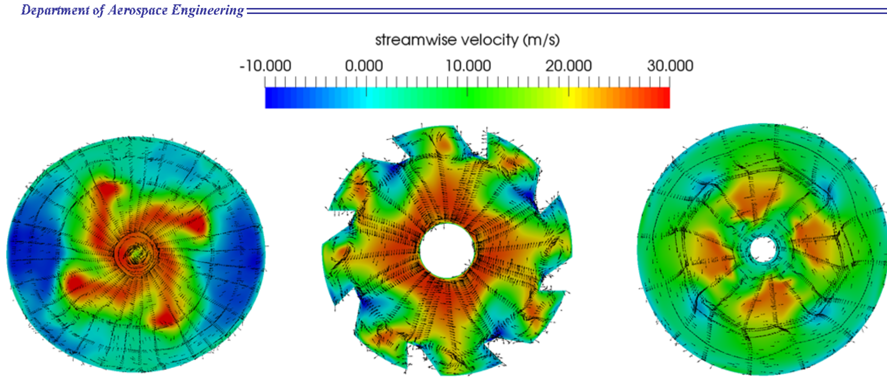
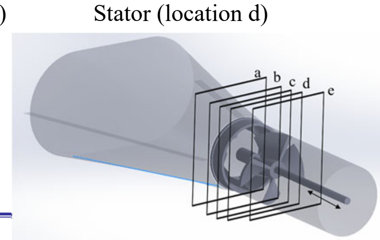


Burner cone (location a) Turbulator (location c) Stator (location d)



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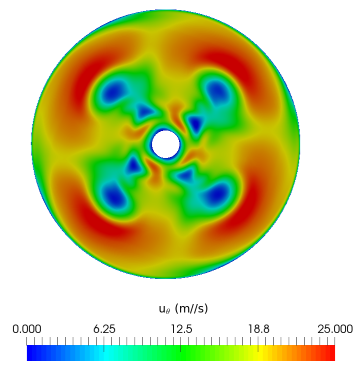
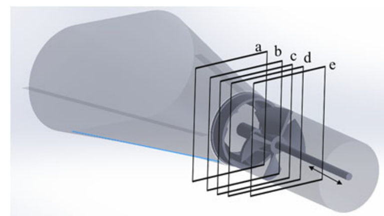
Swirl Number



Contour of mean azimuthal velocity downstream of the stator (location d)



- The azimuthal velocity component suggests that stator is seen to impart swirl to incoming flow
- Swirl number S = 0.76 based using the expression below:

$$S = \frac{\int \rho U_x U_\theta r dA}{R \int \rho U_x^2 dA}$$

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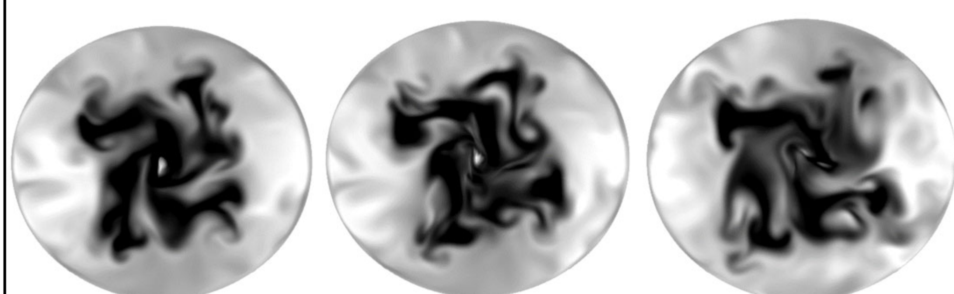
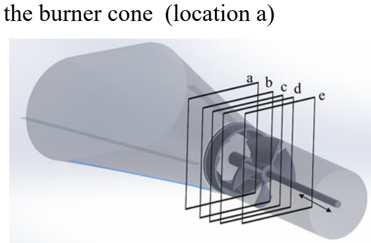
POD Analysis using Method of Snapshots



Sample instants of streamwise velocity contours in the burner cone (location a)

- Snapshots of instantaneous velocity fields is obtained at the fixed cross sectional location in the burner cone.
- A few sample instants are as shown in figure above, which is at a cross sectional plane in the burner cone



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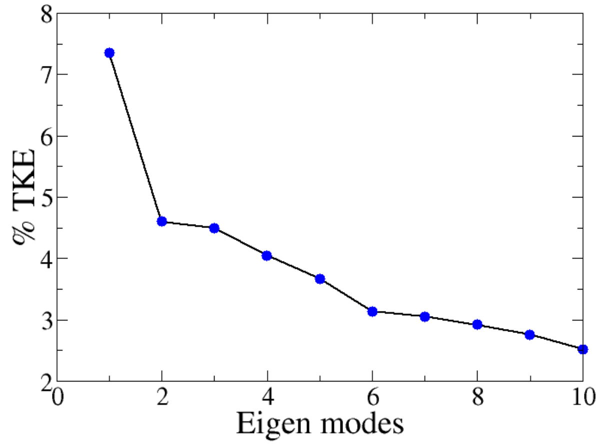
Distribution of Energy Content



- Above plot shows the energy content per eigen mode.
- Only first 10 eigen modes (out of 83) that have significant percentage of total energy content are shown here.

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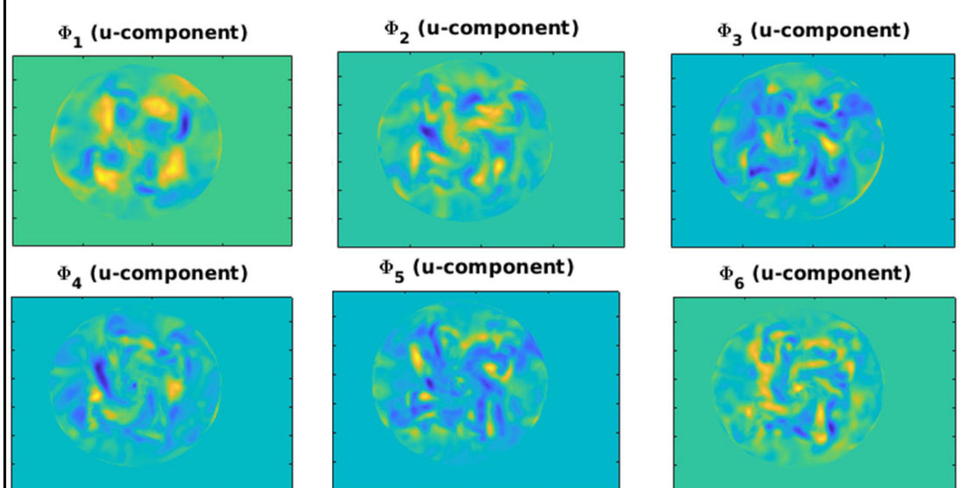
POD Eigen Modes



visualization of the energy content of the first 6 modes

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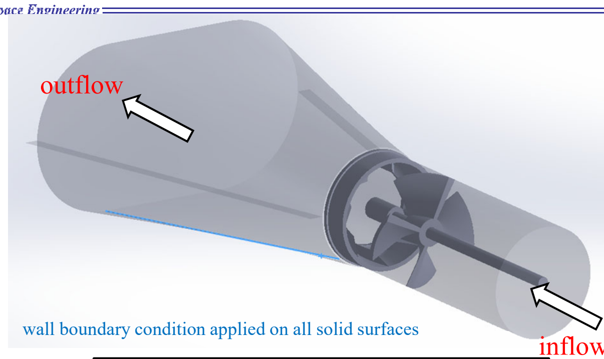
Cold Flow: FAA Burner Geometry

Case II: inlet airflow @ 3.86m/s



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.

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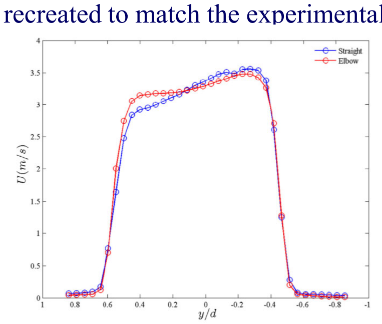
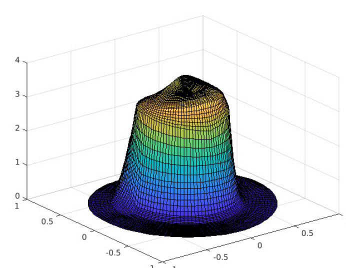
Inlet Velocity Profile

- 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



Inlet velocity profile reconstructed for simulation

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Streamwise Velocity Dynamics (video)

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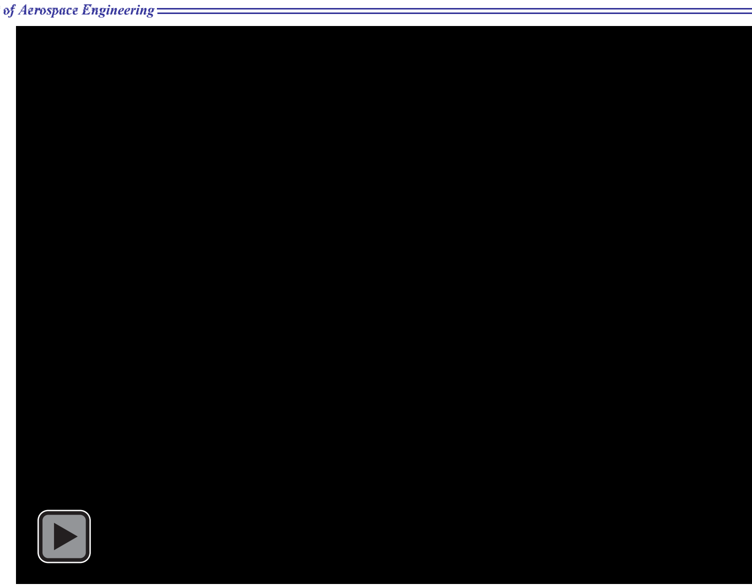
Vorticity Dynamics (video)



Preliminary Comparison with Measurements

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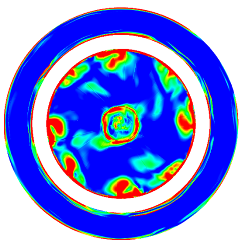
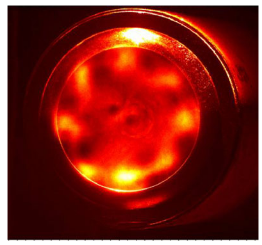
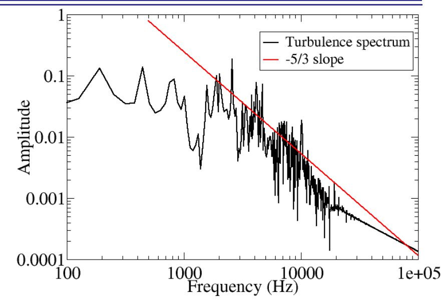
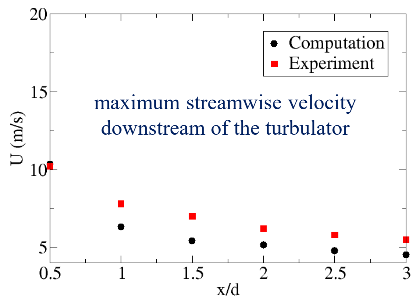
present



experiment







- experiment was conducted the burner cone and the simulations are conducted with the cone
- the recirculation zones at the burner cone lead to reduction in maximum sectional velocities

Fuel Spray: Code Validation I

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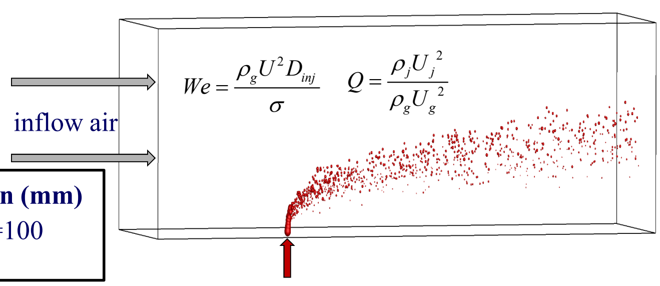

$$We = \frac{\rho_g U^2 D_{inj}}{\sigma} \qquad Q = \frac{\rho_j U_j^2}{\rho_g U_g^2}$$

computation domain (mm)
H=25.8, W=28.9, L=100
D_{inj} = 0.254 mm

Case A (air at room temperature)	Case B (air at 573 K)
Inflow Air - U_g=116m/s, 1 atm, 300 K	**Inflow Air -** U_g=166m/s, 1 atm, 573 K
Liquid jet - T=298K, U_j=12.01 m/s	**Liquid jet** - T= 298K, U_j=12.36 m/s
We = 68 **, Q** = 9	**We** = 68.3 **, Q** = 9

Mesh size : 1.6 million
Minimum grid size = 0.02 mm

*Stenzler et al., Atomization and Sprays , 2006

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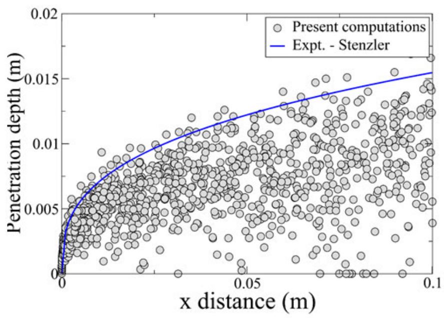
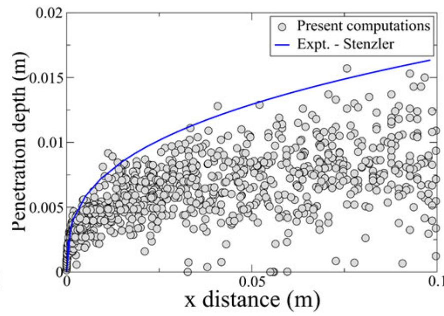
Comparison with Experiments

liquid penetration trajectory



Case A : air temperature = 300 K



Case B : air temperature = 573 K

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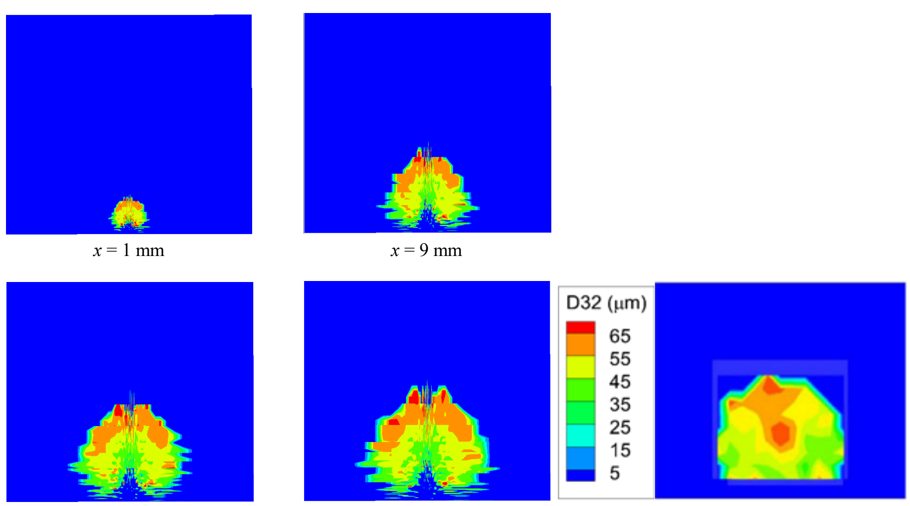
Comparison with Experiments

sauter mean diameter

Case A : SMD distribution at various streamwise locations



x = 1 mm; *x* = 9 mm; *x* = 18 mm; *x* = 25.4 mm; *x* = 25.4 mm, experiment

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Conclusions & Upcoming Tasks

- Conducted high-fidelity cold flow simulations for two different flow conditions on the current FAA burner geometry using LES
- Analyzed the resulting flow field by visualizing the flowfiled at different spatial locations
- Conducted POD analysis to identify the dominant modes
- Validated the spray formulation using liquid jet in crossflow configuration

Upcoming Tasks

- Continue analysis of the second case
- Conduct cold flow simulations on the geometry modification informed by experiments
- Conduct cold flow simulations with fuel spray for the above two geometries

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Thank you for your attention.

Prashant Khare, PhD
Assistant Professor
Department of Aerospace Engineering
University of Cincinnati
Tel: (513) 556-5248
Email: Prashant.Khare@uc.edu
Web: http://khare.uc.edu