Development and Evaluation of a Novel Fuel Injector Design Method using Hybrid-Additive Manufacturing

Program Monitor: Mark Freeman

Project Review – November 7, 2019

PI: Jacqueline O’Connor
Co-PIs: Guha Manogharan, Yuan Xuan

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Hanjie Lee, Dave Voss
Overview of presentation

— Background
— Technical approach
— Project objectives
— Project structure
— Next steps
Overview of presentation

— Background
— Technical approach
— Project objectives
— Project structure
— Next steps
Project origin: Discussions with industry about issues related to combustion operability and fuel injector manufacturing

“Why do fuel injectors have to look like fuel injectors?”
Current fuel injector designs do well at flame stabilization for a moderate range of fuel compositions, operating conditions.
Recent work by PI and collaborators has showed that a stable flow can be “designed” using hydrodynamic stability analysis.

**Time-averaged flow**

**Coherent response**

**Flow parameter variation**
Fuel injectors are notoriously difficult to manufacture and can be comprised of dozens of components, assembled by hand.

- Complex aerodynamic surfaces
- Small orifices with specified surface finish
- Internal flow passages
Goal of this project is to create a design optimization paradigm that marries combustion physics and manufacturing.
The team is comprised of three PIs and two grad students from Penn State and industrial partners Solar Turbines

PI: Jacqueline O’Connor  
Associate Professor of ME  
Combustion/Gas Turbines

Co-PI: Guha Manogharan  
Assistant Professor of ME  
Design +Hybrid-Additive Manufacturing

Co-PI: Yuan Xuan  
Assistant Professor of ME  
Combustion simulation

Solar Turbines  
A Caterpillar Company
Overview of presentation

— Background
— Technical approach
— Project objectives
— Project structure
— Next steps
Technical approach uses an optimization framework for incorporating combustion and manufacturing constraints

1. Flame dynamic stability through flow response modeling
2. Flame static stability through computational fluid dynamics
3. Fuel flexibility through computational fluid dynamics
4. Additive manufacturing considerations for laser powder bed fusion
5. Surface finishing considerations for abrasive flow machining

Re-design objectives and constraints

Define design objectives, constraints → Design optimization tool → Detailed design for manufacture → CFD for flow generation → LHSAs for stability analysis → TEST PART → PRINT PART

Is flame stable?

NO → Re-design objectives and constraints

YES
Parametric design-process planning advanced manufacturing approach is proposed for fuel-injector applications.
Overview of presentation

— Background
— Technical approach
— Project objectives
— Project structure
— Next steps
Project objectives center around four gaps in the fuel injector design process to help industry

- Integrate issues related to flame static and dynamic stability more seamlessly into the design process
- Incorporate the use of hydrodynamic stability analysis for prediction of dynamic stability issues for efficient computational prediction
- Incorporate high-fidelity, multi-physics modeling into optimization processes
- Link post-processing steps of the AM component into the design optimization process
An initial proof of concept exercise showed that hydrodynamic stability + CFD could be used for optimization.

Step 1: CFD captures experimental trends

Step 2: LHSA results from CFD and experiment match

Step 3: Optimization of flow stability ($\omega_i$) on parameter $S$

$$L(S, \lambda) = \omega_i(S) - \lambda(\omega_i(S) - \epsilon)$$

$$\frac{\partial L}{\partial S} = 0 \rightarrow \frac{\partial \omega_i}{\partial S} (1 - \lambda) = 0 \rightarrow \lambda = 1$$

$$\lambda \omega_i(S) = \epsilon$$

Result: Optimizer stepped towards stability condition

<table>
<thead>
<tr>
<th>Iteration</th>
<th>$S$</th>
<th>$\omega_r$</th>
<th>$\omega_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.56</td>
<td>3.40</td>
<td>-0.68</td>
</tr>
<tr>
<td>2</td>
<td>0.57</td>
<td>3.38</td>
<td>-0.69</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>3.03</td>
<td>-0.28</td>
</tr>
<tr>
<td>4</td>
<td>0.65</td>
<td>3.03</td>
<td>-0.27</td>
</tr>
</tbody>
</table>
Overview of presentation

— Background
— Technical approach
— Project objectives
— Project structure
— Next steps
Project objectives center around four gaps in the fuel injector design process to help industry

— Task 1: Project management and planning
— Task 2: Establish baseline
— Task 3: Develop design optimization tool
— Task 4: Implement optimization process on baseline configuration
— Task 5: Design process improvement
— Task 6: Integration of improved design process
— Task 7: Final process testing and technology transfer
Novel contribution: Design optimization tool that will incorporate physics-based constraints
Novel contribution: Integrated Design-AM-Post Processing Framework

Gas Turbine

Hot-section

(Source: www.solarturbines.com)

NURBS curves

(image of knots $\xi_i$)

(control points)

(Source: Vin Phu Nyugen, et. al. (2013))

(Source: Solar Turbines (2011))

(Source: Li Junye, et. al. (2015))

Adjoint based design
Parametric design-process planning advanced manufacturing approach is proposed for fuel-injector applications.

1. Sample of targeted AM geometry
   (Engineering Specifications: Tolerance and Surface Finish)

2. Sample representation of part feature decomposition (NURBS curve)

3. Sample analysis of AM build orientation

4. Sample AM build orientation and fabrication

5. Sample AM heat-treatment

6. Sample AM surface post-processing

7. CT Scan – AM quality control

8. Surface roughness evaluation

Laser-Powder Bed Fusion AM

Abrasive Flow Machining

Electrochemical Machining

Residual Stress Annealing
Novel contribution: NURBS based design approach

- Non-Uniform Rational Basis Splines
- Super set of all curves
- Advantages
  - Can approximate most curves and surfaces mathematically
  - Flexibility
  - Computational efficiency
  - Local propagation (segments)
  - Maintains continuity requirements (slope and curvature)
Project impact stems from multi-disciplinary team and technology transfer to industry partner for future designs

- Gas turbine operability
- Combustion simulation
- Hybrid manufacturing
- Material post-processing
- Design optimization

- Combustor design
- Manufacturing at scale
- Process integration
Questions?

Development and Evaluation of a Novel Fuel Injector Design Method using Hybrid-Additive Manufacturing

Program Monitor: Mark Freeman

PI: Jacqueline O’Connor
Co-PIs: Guha Manogharan, Yuan Xuan

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Hanjie Lee, Dave Voss
Backup slides
Combustion dynamics is one of the most expensive problems in the gas turbine industry

- Damages expensive hardware
- Reduces operability
- Increases emissions (NO$_x$, CO)

Combustion dynamics is a coupling between combustor acoustics and flame heat release rate fluctuations.
Initially, some perturbation in heat release rate causes gas expansion from the flame.
The gas expansion does compression work, locally adding energy to the acoustic field (a pressure anti-node)

\[ \int PdV \]

- Flame Heat Release Fluctuations \((q')\)
- Combustor Acoustic Fluctuations \((p',u')\)
The energized acoustic field then produces a disturbance, which can excite further heat release rate oscillations.
Combustion instability is a phenomena better heard or “felt” than analyzed for better understanding.
In real devices the feedback from acoustics to the flame typically includes a “coupling mechanism”
Velocity coupling: acoustic fluctuations produce vortex roll-up in the flowfield, resulting in flame disturbances
Velocity coupling: acoustic fluctuations produce vortex roll-up in the flowfield, resulting in flame disturbances.
Velocity coupling: acoustic fluctuations produce vortex roll-up in the flowfield, resulting in flame disturbances

What if we could stop the feedback loop not by changing the flame or acoustics, but changing the flow?
What if we could stop the feedback loop not by changing the flame or acoustics, but changing the flow?

Suppression through changes in shear layer receptivity
Swirling flows are hydrodynamically unstable and susceptible to acoustic forcing in different ways throughout the flow.

Billant et al., JFM, 1998, Huang et al., AIAA J., 2006
Structure of swirling flows change significantly with swirl number, inducing vortex breakdown and PVC.

<table>
<thead>
<tr>
<th>Swirl Number</th>
<th>0.00</th>
<th>0.18</th>
<th>0.38</th>
<th>0.56</th>
<th>0.79</th>
<th>1.05</th>
<th>1.43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow State</td>
<td>No VB</td>
<td>No VB</td>
<td>No VB</td>
<td>Intermittent VB</td>
<td>Weak PVC</td>
<td>PVC</td>
<td>Strong PVC</td>
</tr>
<tr>
<td>PVC Frequency</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>770–815 Hz</td>
<td>840 Hz</td>
<td>1060 Hz</td>
</tr>
</tbody>
</table>
Harmonic reconstruction of forced response indicates variation in shear layer receptivity with swirl number, frequency.
Acoustic to vortical transfer function shows significant amplification of disturbances except at high swirl number.

### Acoustic to Vortical TF

- **Velocity coupling possible**
- **No velocity coupling**

### Vorticity SNR

- **600 Hz**
- **1800 Hz, 1%**
- **1800 Hz, 2%**
PVC is present in the flowfield at the three highest swirl numbers; PVC is has significant turbulent kinetic energy
Stable design through flow design – use of hydrodynamic instability tools to tune flowfield receptivity

Collaborators: Santosh Hemchandra and Kiran Manoharan, IISc-Bangalore

Weakly non-linear stability calculation

\[ q(r, z, \theta, t) = \bar{q}(r, z) + q'_o(r, z, \theta, t) + q''(r, z, \theta, t) \]

\[ \mathcal{B} \frac{\partial q}{\partial t} + \mathcal{N}[q]q + S\mathcal{N}^s[q]q + S^2\mathcal{N}^{ss}[q]q = \mathcal{L}_v q + S\mathcal{L}_v^s q \]

\[ \text{max}(\exp \left[-\int_0^x k_z^+(\omega, x') dx'\right]) \]

\[ \frac{f_{\delta_{OSL}}}{U_o} \]
LES results of turbulent swirling flows

Comparison with measurements for $S = 0.56$

Other simulation results with higher Swirl numbers

$S = 0.76$

$S = 0.81$
Hydrodynamic stability analysis – proof of concept

Table 2. Results of proof-of-concept optimization study.

<table>
<thead>
<tr>
<th>S</th>
<th>$\omega_r$</th>
<th>$\omega_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.56</td>
<td>3.40</td>
<td>-0.68</td>
</tr>
<tr>
<td>0.57</td>
<td>3.38</td>
<td>-0.69</td>
</tr>
<tr>
<td>0.6</td>
<td>3.03</td>
<td>-0.28</td>
</tr>
<tr>
<td>0.65</td>
<td>3.03</td>
<td>-0.27</td>
</tr>
</tbody>
</table>