Development of Criteria for Flashback Propensity in Jet Flames for High Hydrogen Content and Natural Gas Type Fuels

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Vincent McDonell

UTSR Workshop
Georgia Tech, Atlanta, GA
November 4, 2015

Conducted under Department of Energy University Turbine Systems Research
Contract Number DE-FE0011948; Steven Richardson PM
Outline

• Motivation
• Background
• Project Goals
• Experiment
• Test Procedures
• Results
• Summary
Motivation
**Motivation**

- Integrated Gasification Combined Cycle (IGCC)
- Steam reforming of natural gas or liquid hydrocarbons
- Waste Treatment – Digester Gas
- Biomass
- “Power to Gas”

<table>
<thead>
<tr>
<th>Source</th>
<th>H₂</th>
<th>CO</th>
<th>CH₄</th>
<th>CO₂</th>
<th>N₂</th>
<th>C₂</th>
<th>C₃</th>
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<tr>
<td>High H₂</td>
<td>90-100</td>
<td>0-10</td>
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<tr>
<td>Process and refinery gas</td>
<td>25-55</td>
<td>0-10</td>
<td>30-65</td>
<td>0-5</td>
<td>0-25</td>
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<td>Gasified coal/petcoke (O₂ Blown)</td>
<td>35-40</td>
<td>45-50</td>
<td>0-1</td>
<td>10-15</td>
<td>0-2</td>
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<td>Gasified biomass</td>
<td>15-25</td>
<td>15-35</td>
<td>0-5</td>
<td>5-15</td>
<td>30-50</td>
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<tr>
<td>Digester gas</td>
<td>0-1</td>
<td>50-75</td>
<td>25-50</td>
<td>0-10</td>
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<td>Power to Gas</td>
<td>0-20?</td>
<td>75-80</td>
<td></td>
<td>0-5</td>
<td>0-1</td>
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High hydrogen content fuels
Motivation

• Impact of Alternative Fuels on gas turbine combustion
  – Emissions

  – Operability issues
    • Lean Blow Off (Static stability)
    • Flashback
    • Combustion Dynamic (Dynamic stability)

  High hydrogen content fuels
Motivation

Premixer/Injector: 90/10 H2/NG

Before Flashback

After Flashback
Background
Flashback

- Flame propagation from the combustion zone into premixing section of combustors

  - Flashback in the core flow
  - Combustion induced vortex breakdown (CIVB)
  - Flashback due to combustion instabilities
  - Flashback in the wall boundary layer
    Propagation of flame upstream of the flow inside the boundary layer

Structure of Burner Flames

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Topic</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis, B., &amp; Von Elbe, G.</td>
<td>Stability and structure of burner flames</td>
<td>1943</td>
</tr>
<tr>
<td>Putnam, A. A., &amp; Jensen, R. A.</td>
<td>Application of dimensionless numbers to flash-back and other combustion phenomena</td>
<td>1949</td>
</tr>
<tr>
<td>Thomas, N.</td>
<td>Structure and stability of burner flames</td>
<td>1949</td>
</tr>
<tr>
<td>Wohl, K.</td>
<td>Quenching, flash-back, blow-off-theory and experiment</td>
<td>1953</td>
</tr>
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</table>

Critical boundary layer velocity gradient

- Laminar flow

\[
U = \frac{8}{\pi} \frac{(D^2 - d^2)}{D^4} \bar{u}
\]

Laminar velocity profile

\[
g_c = \frac{(V_{\text{flow}})_{y=\delta_b}}{\delta_b} = \frac{S_L}{\delta_p}
\]

\[
g = \frac{8\bar{u}}{D}
\]

\[
Pe_j = \frac{D \times V}{\alpha}
\]

\[
Pe_F = \frac{D \times S_L}{\alpha}
\]

Putnam and Jensen (1949)

\[
\delta_p \approx \delta_q = K \frac{\alpha}{S_L}
\]

K=2: Flame thickness
## Effects of Various Factors

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Year</th>
</tr>
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<tbody>
<tr>
<td>Grumer, J.</td>
<td>Predicting burner performance with interchanged fuel gases</td>
<td>1949</td>
</tr>
<tr>
<td>Grumer, J., &amp; Harris, M. E.</td>
<td>Predicting interchangeability of fuel gases interchangeability of oil gases or propane-air fuels with natural gases</td>
<td>1952</td>
</tr>
<tr>
<td>Grumer, J., &amp; Harris, M. E.</td>
<td>Flame-stability limits of <strong>methane, hydrogen, and carbon monoxide mixtures</strong></td>
<td>1952</td>
</tr>
<tr>
<td>Grumer, J., &amp; Harris, M. E.</td>
<td>Temperature dependence of stability limits of burner flames</td>
<td>1954</td>
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<tr>
<td>Dugger, G. L.</td>
<td>Flame stability of preheated propane-air mixtures</td>
<td>1954</td>
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<tr>
<td>Grumer, J., &amp; Harris, M. E.</td>
<td>Flame-stability limits of <strong>ethylene, propane, methane, hydrogen, and nitrogen mixtures</strong></td>
<td>1955</td>
</tr>
<tr>
<td>Bollinger, L. E., &amp; Edse, R.</td>
<td>Effect of <strong>burner-tip temperature</strong> on flashback of turbulent hydrogen-oxygen flames</td>
<td>1956</td>
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<tr>
<td>Fine, B.</td>
<td>Stability limits and burning velocities for some laminar and turbulent propane and hydrogen flames at reduced pressure</td>
<td>1957</td>
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<tr>
<td>Kurz, P. F.</td>
<td>Stability limits of flames of ternary hydrocarbon mixtures</td>
<td>1957</td>
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<tr>
<td>Kurz, P. F.</td>
<td>Some factors influencing stability limits of Bunsen flames</td>
<td>1957</td>
</tr>
<tr>
<td>Berlad, A. L., &amp; Potter Jr, A. E.</td>
<td>Relation of boundary velocity gradient for flash-back to burning velocity and quenching distance</td>
<td>1957</td>
</tr>
<tr>
<td>Fine, B.</td>
<td>Flashback of laminar and turbulent burner flames at reduced pressure</td>
<td>1958</td>
</tr>
<tr>
<td>Fine, B.</td>
<td>Effect of Initial Temperature on Flash Back of Laminar and Turbulent Burner Flames.</td>
<td>1959</td>
</tr>
<tr>
<td>Yamazaki, K., &amp; Tsuji, H.</td>
<td>An experimental investigation on the stability of turbulent burner flames</td>
<td>1961</td>
</tr>
<tr>
<td>Caffo, E., &amp; Padovani, C.</td>
<td>Flashback in premixed air flames</td>
<td>1963</td>
</tr>
</tbody>
</table>
Effects of Various Factors

- Fuel compositions (natural gas, propane, ethane, hydrocarbons mixtures)
- Preheated temperature
- Limited Pressures
- Burner tip temperature
- Burner diameter
- Some Turbulent flames

\[ g = 0.023 \text{Re}^{0.8} \left( \frac{U}{D} \right) \quad g = 0.03955 \text{Re}^{0.75} \left( \frac{U}{D} \right) \]

Not studied together

Berlad, A. L. and A. E. Potter

Laminar flames
Cooled Tips

Subatm. pressure

Fine, B.

\[ g = A \left( \frac{U_f}{d_q} \right) \quad g = 14.125 \left( \frac{U_f}{d_q} \right)^{1.168} \]

Caffo

\[ g_F = a_{H_2} \times \%H_2 + \sum a_i \times \%C_i \]
Burner Material Effect

Flash Back of Turbulent Hydrogen-Oxygen Flames


- Metal burners
- Oxygen as an oxidizer
- No correlation

Direct impacts on the flame speed and flashback propensity
**Burner Thickness Effect**

- Increase of thickness
  - Constant inside diameter
  - Indicates need for further investigation


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![Critical velocity gradient vs. Percent hydrogen in mixture](image1)

![Burner tip temperature vs. Percent hydrogen in mixture](image2)
### Effects of Various Factors

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<td>Khitrin, L. N.</td>
<td>Peculiarities of laminar-and turbulent-flame flashbacks</td>
<td>1965</td>
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<tr>
<td>Cescotti, R.</td>
<td>Burners and flame technology</td>
<td>1968</td>
</tr>
<tr>
<td>Plee, S. L., &amp; Mellor, A. M.</td>
<td>Review of flashback reported in prevaporizing-premixing combustors</td>
<td>1978</td>
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<tr>
<td>Ball, D. A., &amp; Putnam, A. A.</td>
<td>Relation to burning velocity, quenching distance, and flash-back velocity gradient for low-and intermediate-Btu gases</td>
<td>1978</td>
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<tr>
<td>Putnam, A. A., &amp; Ball, D. A.</td>
<td>Effect of fuel composition on relation of burning velocity to product of quenching distance and flashback velocity gradient</td>
<td>1980</td>
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<tr>
<td>Lee, S. T., &amp; T’ien, J. S.</td>
<td>A numerical-analysis of flame flashback in a premixed laminar system</td>
<td>1982</td>
</tr>
<tr>
<td>Fox, J. S., &amp; Bhargava, A.</td>
<td>Flame speed and flashback gradient for simulated biomass gasification products</td>
<td>1984</td>
</tr>
<tr>
<td>Karim, G. A., &amp; Kibrya, M. G.</td>
<td>Flashback limits and flame propagation through a premixed stream of fuel and air near the lean flammability limit</td>
<td>1984</td>
</tr>
</tbody>
</table>

\[
g = 0.023 \text{Re}^{0.8} \left( \frac{U}{D} \right)
\]

\[
g_c = \frac{S_L}{\delta_b}
\]

\[
Pe_f = \frac{\delta_b}{D} \text{Re}^{1.8} \Pr
\]

\[
\delta_b = K \frac{\alpha}{S_L}
\]

\[
\text{Re} = \text{const.} Pe_f^{1.10}
\]

**Methane**

\[
D_{\text{Ug}} = 8.0 \text{Re}^{0.23} \delta
\]

\[
\text{tip Temperature/Materials?}
\]

\[
\frac{Pe_f^2}{Pe_j} = \frac{(\frac{D^*S_L}{\alpha})^2}{\frac{D*V}{\alphaV}} = \frac{S_L^2D}{V} \frac{D}{V} \left( \frac{\alpha}{S_L} \right) = \frac{\tau_{\text{flow}}}{\tau_{\text{reaction}}} = Da
\]
Different Flashback Mechanisms

- **Swirling Flows**: Combustion induced vortex breakdown (CIVB)
- **Flashback in the core flow**
- **Syngas**

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<thead>
<tr>
<th>Authors</th>
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<tbody>
<tr>
<td>Kroner, M., and Fritz, J.</td>
<td>Flashback limits for combustion induced vortex breakdown in a swirl burner</td>
<td>2002</td>
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<td>Kroner, M., and Fritz, J.</td>
<td>Flashback limits for combustion induced vortex breakdown in a swirl burner</td>
<td>2003</td>
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<tr>
<td>Davu, D., Franco, R.</td>
<td>Investigation on flashback propensity of syngas premixed flames</td>
<td>2005</td>
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<tr>
<td>Xu, G., Tian, Y.</td>
<td>Flashback limit and mechanism of methane and syngas fuel</td>
<td>2006</td>
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<tr>
<td>Burmberger, S., Hirsch, C.,</td>
<td>Designing a radial swirler vortex breakdown burner</td>
<td>2006</td>
</tr>
<tr>
<td>Noble, D. R., Zhang, Q.</td>
<td>Syngas Mixture Composition Effects Upon Flashback and Blowout</td>
<td>2006</td>
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<tr>
<td>Noble, D. R., Q. Zhang,</td>
<td>Syngas fuel composition sensitivities of combustor flashback and blowout.</td>
<td>2006</td>
</tr>
<tr>
<td>Song, Q., Fang, A.</td>
<td>Dynamic and flashback characteristics of the syngas premixed swirling combustors</td>
<td>2008</td>
</tr>
<tr>
<td>Littlejohn, D., Cheng, R. K.</td>
<td>Laboratory investigations of a low-swirl injector with H2 and CH4 at gas turbine conditions</td>
<td>2009</td>
</tr>
<tr>
<td>Shelil, N., Bagdanavicius, A.</td>
<td>Premixed swirl combustion and flashback analysis with hydrogen/methane mixtures</td>
<td>2010</td>
</tr>
<tr>
<td>Jejurkar, S. Y., &amp; Mishra, D. P.</td>
<td>Flame stability studies in a hydrogen-air premixed flame annular microcombustor</td>
<td>2011</td>
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</table>
Synthesis Gas

<table>
<thead>
<tr>
<th>Authors</th>
<th>Title</th>
<th>Year</th>
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<tr>
<td>Wang, Q., McDonell, V.</td>
<td>Correlating flashback tendencies for premixed injection of hydrogen and methane mixtures at elevated temperature and pressure</td>
<td>2009</td>
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<tr>
<td>Daniele, S., Jansohn, P.</td>
<td>Flashback propensity of syngas flames at high pressure: diagnostic and control</td>
<td>2010</td>
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<tr>
<td>Eichler, C., &amp; Sattelmayer, T.</td>
<td>Experiments on flame flashback in a quasi-2D turbulent wall boundary layer for premixed methane-hydrogen-air mixtures</td>
<td>2011</td>
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<tr>
<td>Eichler, C., &amp; Sattelmayer, T.</td>
<td>Experimental investigation of turbulent boundary layer flashback limits for premixed hydrogen-air flames confined in ducts</td>
<td>2011</td>
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<tr>
<td>Dam, B., Love, N.</td>
<td>Flashback propensity of syngas fuels.</td>
<td>2011</td>
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<tr>
<td>Shaffer, B., Duan, Z.</td>
<td>Study of Fuel Composition effects on flashback using a confined jet flame burner</td>
<td>2013</td>
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<tr>
<td>Lin, Y. C., Daniele, S.</td>
<td>Turbulent flame speed as an indicator for flashback propensity of hydrogen-rich fuel gases</td>
<td>2013</td>
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<tr>
<td>Duan, Z., Shaffer, B.</td>
<td>Study of fuel composition, burner material, and tip temperature effects on flashback of enclosed jet flame</td>
<td>2013</td>
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<tr>
<td>Duan, Z., Shaffer, B.</td>
<td>Influence of burner material, tip temperature, and geometrical flame configuration on flashback propensity of H2-air Jet flames</td>
<td>2014</td>
</tr>
</tbody>
</table>

- High Hydrogen fuels/Syngas
- Advanced visualization/diagnostics
- Computational Fluid Dynamics
Systematic Studies

- Atmospheric studies\(^1,2\) found burner material, tip temperature/inlet temperature and flame confinement impact flashback propensity, while flame enclosure diameter and tube diameter play a negligible role.
- Empirical correlations improved if burner tip temperature is used rather than the inlet temperature.

\[ \frac{u_t}{S_L} \]

\[ \frac{I_t}{\delta_t} \]

Distributed reactions

Corrugated flamelets

Wrinkled flamelets

Typical Gas Turbine Combustor

Limited insight into gas turbine related conditions
Gas Turbine Premixer Conditions

- Daniele et al. (2010,2013) investigated flashback propensity of syngas flame at gas turbine conditions
  - Systematic studies were not carried out
  - Limited data set

Goals and Objectives
Goals

• Develop and validate a comprehensive model for prediction of flashback under gas turbine premixer conditions
  – The model will incorporate effect of ambient pressure as well as thermal coupling between the flame and the burner rim.

• Provide detailed insight towards understanding flashback propensity in jet flames at gas turbine related conditions
# Objectives & Timeline

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<th>Milestone Title</th>
<th>Planned Completion Date</th>
<th>Actual Completion Date</th>
<th>Verification Method</th>
<th>Comments</th>
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<td>Project Management</td>
<td>8/2016</td>
<td></td>
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<tr>
<td>Test Plan Fuels/Modules</td>
<td>12/2013 1/2014</td>
<td>3/2014</td>
<td>Consensus from OEMs and DOE on plan</td>
<td>Complete</td>
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<tr>
<td>Draft</td>
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<tr>
<td>Final</td>
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<tr>
<td>Diagnostics/Rig Setup and Commissioned</td>
<td>5/2014</td>
<td>10/2014</td>
<td>Comparison of commissioning data with literature data</td>
<td>Complete</td>
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<tr>
<td>Experimental Studies</td>
<td>4/2015 12/2015</td>
<td>8/2015 8/2015</td>
<td>Comparison of commissioning data with literature data</td>
<td>90% Complete</td>
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<tr>
<td>Phase I</td>
<td></td>
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<td>Phase II</td>
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<td>Analysis and Model Development</td>
<td>7/2015 1/2016 4/2016</td>
<td>8/2015 current</td>
<td>Predicted vs Actual Results, Goodness of Fit</td>
<td>EM: 90% Complete</td>
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<td>Empirical Model I</td>
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<td>Empirical Model II</td>
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<td>Physics Base Model</td>
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</table>
Experiment
Experimental Setup

- Pressure: 15 atm
- Preheat temperature: 1100 K
- Air flow rate: 1.5 kg/sec continuous
- Fuel: High-pressure supply
  - Liquid fuels
  - Gaseous fuel blends
  - Natural Gas: 0.1 kg/sec, 35 atm
- Optical access
- Water quench system
Experimental Setup

Premixed Jet Flame

1. Venturi fuel/air mixing
2. Perforated plate
3. Interchangeable burner head
4. Pilot fuel, ignited with YAG laser
5. Thermocouples

Fuel injection

Air

Pilot fuel, ignited with YAG laser

Thermocouples

UTSR Workshop, Atlanta, GA, November 4, 2015
Experimental Setup

Nd:YAG laser

Burner
Testing
Test Parameters

- **Pressure**
  - 3 atm to 9 atm

- **Preheated temperature**
  - 300 K to 700 K

- **Fuel compositions**

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume percent</th>
<th>Heat Capacity [J/(g*C)]</th>
<th>Heat Conductivity [W/(m*k)]</th>
<th>Density [g/cm^3]</th>
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<tbody>
<tr>
<td>H2</td>
<td>100</td>
<td>0.500</td>
<td>21.5</td>
<td>8.0</td>
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<tr>
<td>CH4</td>
<td>0</td>
<td>0.385</td>
<td>385.0</td>
<td>7.9</td>
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<td>Ceramiic</td>
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<td>0.456</td>
<td>0.9</td>
<td>4.0</td>
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</table>
Testing

P=7 atm
$T_u=500 \text{ K}$, Inlet temperature
$U_b=35 \text{ m/s}$, Bulk Velocity
Hydrogen fuel
Stainless steel Burner head
Flashback Monitoring

- **Flashback strategy**

  Constant air mass flow rate
Results & Analysis
Results

Higher velocity gradient → Higher flashback propensity

Equivalence Ratio

Critical Velocity Gradient (1/s)

Raw Data

[Graph showing data points and a question mark]
Results

higher velocity gradient → higher flashback propensity

Critical Velocity Gradient (1/s)

Raw Data

Higher velocity gradient → Higher flashback propensity
## Analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td><strong>Flow characteristics</strong></td>
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<tr>
<td>$\bar{U}$</td>
<td>bulk velocity of the mixture</td>
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<tr>
<td>$u'$</td>
<td>turbulent intensity</td>
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<td><strong>Thermodynamics properties of flow</strong></td>
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<tr>
<td>$\rho_u$</td>
<td>density based on unburnt conditions</td>
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<td>$\mu_u$</td>
<td>kinetic viscosity based on unburnt conditions</td>
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<td>$T_u$</td>
<td>Unburnt temperature</td>
</tr>
<tr>
<td>$P_u$</td>
<td>Unburnt pressure</td>
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<tr>
<td>$\alpha_u$</td>
<td>thermal diffusivity based on unburnt conditions</td>
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<tr>
<td>$C_{P_u}$</td>
<td>thermal capacity based on unburnt conditions</td>
</tr>
<tr>
<td>$k_u$</td>
<td>thermal conductivity based on unburnt conditions</td>
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<tr>
<td>$D_u$</td>
<td>Mass diffusivity of fuel composition into the mixture</td>
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<thead>
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<td><strong>Premixed flame characteristics</strong></td>
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<td>$T_f$</td>
<td>adiabatic flame temperature based on unburnt conditions</td>
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<td>$S_{L_u}$</td>
<td>laminar flame speed based on unburnt conditions</td>
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<tr>
<td>$LHV$</td>
<td>lower heating value based on unburnt conditions</td>
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<tr>
<td>$T_{tip}$</td>
<td>Measured burner tip temperature</td>
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<tr>
<td>$g_c$</td>
<td>critical velocity gradient when flashback happens</td>
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<tr>
<td>$h'$</td>
<td>convective heat transfer coefficient</td>
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<td><strong>Ambient conditions</strong></td>
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<tr>
<td>$T_0$</td>
<td>ambient temperature</td>
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<tr>
<td>$P_0$</td>
<td>ambient pressure</td>
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<td><strong>Burner properties</strong></td>
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<tr>
<td>$k'$</td>
<td>thermal conductivity of the burner material</td>
</tr>
<tr>
<td>$d$</td>
<td>diameter of the burner</td>
</tr>
<tr>
<td>$\theta'$</td>
<td>thickness of the burner wall</td>
</tr>
</tbody>
</table>
Analysis

• Non-dimensional groups

\[ g_c \approx \frac{S_L}{\delta_p} \]

\[ \delta_p \approx \delta_q = 2\sqrt{b} \frac{\alpha}{S_L} \]

\[ \Pi_1 = Da = \frac{S_L^2}{\alpha \cdot g_c} \]

\[ g = \frac{1 f \bar{U}^2}{8 v} \]

\[ \frac{1}{\sqrt{f}} = 2.0 \log(Re_D \sqrt{f}) - 0.8, \]

\[ 3.1 \times 10^3 < Re_D < 3.2 \times 10^6 \]

\[ f = \frac{0.3164}{Re_D^{0.25}}, \quad 4 \times 10^3 < Re_D < 10^5 \]

\[ \Pi_1 = f(\Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6) \]

\[ \Pi_2 = \frac{T_u}{T_0}, \Pi_3 = Le, \Pi_4 = \frac{T_{tip}}{T_0}, \Pi_5 = \frac{d \cdot S_L}{\alpha}, \Pi_6 = \frac{P_u}{P_0} \]

\[ \Pi_5 = Pe_F = \frac{d \cdot S_L}{\alpha} \]

\[ Da = \text{Const.} \cdot Le^{1.68} \cdot Pe_F^{1.91} \cdot \left( \frac{T_u}{T_0} \right)^{2.57} \cdot \left( \frac{T_{tip}}{T_0} \right)^{-0.49} \cdot \left( \frac{P_u}{P_0} \right)^{-2.1} \]
Model Performance

\[ Da = \text{Const.} \cdot \text{Le}^{1.68} \cdot Pe_f^{1.91} \cdot \left( \frac{T_u}{T_0} \right)^{2.57} \cdot \left( \frac{T_{\text{tip}}}{T_0} \right)^{-0.49} \cdot \left( \frac{P_u}{P_0} \right)^{-2.1} \]

- Predicted Damköhler Number
- Actual Damköhler Number

SS, H\textsubscript{2}
Model Performance

\[
Da = \text{Const}.Le^{1.68} \cdot Pe_f^{1.91} \cdot \left(\frac{T_u}{T_0}\right)^{2.57} \cdot \left(\frac{T_{\text{tip}}}{T_0}\right)^{-0.49} \cdot \left(\frac{P_u}{P_0}\right)^{-2.1}
\]
Model Performance

\[ Da = \text{Const.} \cdot Le^{1.68} \cdot Pe_f^{1.91} \left( \frac{T_u}{T_0} \right)^{2.57} \left( \frac{T_{\text{tip}}}{T_0} \right)^{-0.49} \left( \frac{P_u}{P_0} \right)^{-2.1} \]
**Interpretation**

- **SS Burner Head**
  - Effect of Inlet Temp, Bulk Velocity, and Pressure on Equivalence Ratio at Flashback
  - Measurements vs Model

\[ \phi_{FB} = P^{-m} \]

![Graph showing equivalence ratio vs pressure for different inlet temperatures and bulk velocities. The graph includes data points for T=300 K, U=30 m/s, T=500 K, U=40 m/s, and T=500 K, U=30 m/s. The equivalence ratio values range from 0.2 to 0.7, and the pressure range is from 2 to 8 atm. The slope m values are 0.43, 0.45, and 0.49.]
Interpretation

• SS Burner Head
  – Impact of Pressure, Inlet Temperature, and Equivalence Ratio on Tip Temperature at Flashback
    • Model vs Measurements
Interpretation

• SS Burner Head
  - Effect of Pressure and Equivalence Ratio on Bulk Velocity at Flashback (Prediction)

```
<table>
<thead>
<tr>
<th>Pressure (atm)</th>
<th>Flashback Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
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</tr>
<tr>
<td>7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
```

$$U_f = \phi \cdot P^{0.20}$$

$$U_f = \phi \cdot P^{0.22}$$

$$U_f = \phi \cdot P^{0.23}$$
Validation

• Comparison to Other Data Sets in Literature
  – Danielle, et al., 2010
  • Syngas/Air jet flames studied in context of global consumption based turbulent flame speed measurements

Validation

\[ Da = Const. \cdot Le^{1.68} \cdot Pe_f^{1.91} \cdot \left( \frac{T_u}{T_0} \right)^{2.57} \cdot \left( \frac{T_{tip}}{T_0} \right)^{-0.49} \cdot \left( \frac{P_u}{P_0} \right)^{-2.1} \]

- SS, H₂
- Copper, H₂
- Ceramic, H₂
- Daniele et al., H₂-CO
Validation

• Comparison to Page, et al., 2012

Capstone C65 Microturbine Combustor


Flashback Detection

2 planes of Injectors

Bottom Plane

Hot Products
Recuperator Wall
Outer Liner
Inner Liner

Back of Combustion Liner

Pressure Probe

TC-Cold

TC-Air

TC-Hot

2.54 cm
Validation

\[ Da = \text{Const.} \cdot Le^{1.68} \cdot Pe_f^{1.91} \cdot \left( \frac{T_f}{T_0} \right)^{2.57} \cdot \left( \frac{T_{\text{tip}}}{T_0} \right)^{-0.49} \cdot \left( \frac{P_f}{P_0} \right)^{-2.1} \]
Validation

\[ Da = \text{Const.} \cdot \text{Le}^{1.68} \cdot \text{Pe}^{1.91} \cdot \left( \frac{T_u}{T_0} \right)^{2.57} \cdot \left( \frac{T_{\text{tip}}}{T_0} \right)^{-0.49} \cdot \left( \frac{P_u}{P_0} \right)^{-2.1} \]
Summary

- Boundary layer flashback experiments have been carried out at elevated pressures and temperatures for various bulk velocities, burner materials, and equivalence ratios
  - Buckingham Pi theorem applied to develop correlation
    \[
    Da = Const. Le^{1.68} Pe_f^{1.91} \left( \frac{T_u}{T_0} \right)^{2.57} \left( \frac{T_{tip}}{T_0} \right)^{-0.49} \left( \frac{P_u}{P_0} \right)^{-2.1}
    \]

- The resulting correlation was applied to current data as well as literature data and found to provide reasonable ability to predict flashback tendencies for the parameters studied
Experimental Setup

- Velocity profile using LDV

  Fully developed turbulent flow

![Graph showing normalized axial velocity (U/Um) vs. normalized radial distance (r/R) for different flow rates: Q=40.2308 scfm, Q=49.22471 scfm, Q=58.75896 scfm, and Numerical Method (RANS). The graph indicates a venturi setup with a 40 cm vertical measurement.]
Fuel/Air Mixing

Mixing performance
• Computational modeling

contour of molar concentration for pure hydrogen fuel

Homogeneous mixture at premixing tube outlet
Results

- SS, H₂
- Copper, H₂
- Ceramic, H₂
- Daniele et al., H₂-CO
- Page et al., H₂-CO
- Page et al., H₂-NG
- Copper, NG
Alternative Formulation

- **Lin and Danielle (2013)**
  
  \[ g_c = \frac{S_T}{(Le \times \delta_{L0})} \]

  - Proposed correlation based on turbulent flame speed
    
    \[ \frac{S_T}{S_L} \approx \left( \frac{P}{P_0} \right)^m \left( \frac{u'}{S_L} \right)^n \]

  - Facilitates incorporation of turbulence levels
    
    \[ g_c = f \left( Le, S_L, u', \frac{P}{P_0}, \alpha \right) \]
Results

Pressure
• 3 atm to 7 atm

Preheated temperature
• 300 K to 500 K

Fuel
• Hydrogen
• Daniele et al. 2010
• Methane-Hydrogen

Burner materials
• Stainless steel
• Copper

\[ Da = \text{Const} \cdot Pe_F^{1.93} \cdot Le^{1.9} \cdot \left( \frac{T_u}{T_0} \right)^{2.1} \cdot \left( \frac{T_{tip}}{T_u} \right)^{-0.32} \cdot \left( \frac{P_u}{P_0} \right)^{-1.56} \]
Results

Combustion regimes

\[ Da = \text{Const} \cdot Pe_{F}^{2.2} \cdot Le^{-9.11} \cdot \left( \frac{T_{u}}{T_{0}} \right)^{1.68} \cdot \left( \frac{T_{tip}}{T_{u}} \right)^{-0.37} \cdot \left( \frac{P_{u}}{P_{0}} \right)^{-1.64} \]
Test Plan
Test Plan Approach

- To help guide the Test Plan, additional analysis of flashback of jet flames was carried out to generate a clearer set of required information to accomplish the project goals
Test Plan Analysis

- Atmospheric studies identified burner material, tip temperature/inlet temperature and flame confinement have a strong impact on flashback propensity, while flame enclosure diameter and tube diameter play a negligible role.
- Better correlations can be obtained if the burner tip temperature is used as the representative temperature rather than the inlet temperature.
  - $T_{\text{tip}}$-based SL able to determine flashback propensity in terms of critical velocity gradient (Duan et al. 2013)

\[
g_{c,\text{tip}} = \left( 155 + 546.4\alpha_{\text{tip}} + 5363.19d_{q,\text{tip}} - 0.71T_{\text{tip}} - 1.1S_{L,\text{tip}} + 1.1\alpha_{\text{tip}}T_{\text{tip}}^2 \
- 763.3d_{q,\text{tip}}S_{L,\text{tip}} - 0.0023T_{\text{tip}}S_{L,\text{tip}} \right)
\]
Test Plan Analysis

- **Primitive Variable Correlation**
  - Able to collapse materials effect

\[ g_{c,\text{tip}} = (155 + 546.4\alpha_{\text{tip}} + 5363.19d_{q,\text{tip}} - 0.71T_{\text{tip}} - 1.1S_{L,\text{tip}} + 1.1\alpha_{\text{tip}}T_{\text{tip}} - 763.3d_{q,\text{tip}}S_{L,\text{tip}} - 0.0023T_{\text{tip}}S_{L,\text{tip}})^2 \]

- **STUDY OF FUEL COMPOSITION, BURNER MATERIAL, AND TIP TEMPERATURE EFFECTS ON FLASHBACK OF ENCLOSED JET FLAME**
Test Plan Analysis

• Primitive variable approach shows reasonable performance but lacks elegance

• To address this
  – Determine *non-dimensional groups* involved in flashback propensity to capture all effects of various parameters
    • Buckingham Pi theorem
  – Find a comprehensive model to predict flashback propensity under various conditions
  – Verify the developed model for previous relevant data in the literature
## Test Plan Analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{U}$</td>
<td>bulk velocity of the mixture</td>
</tr>
<tr>
<td>$u'$</td>
<td>turbulent intensity</td>
</tr>
</tbody>
</table>

### Thermodynamics properties of flow

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_u$</td>
<td>density based on unburnt conditions</td>
</tr>
<tr>
<td>$\mu_u$</td>
<td>kinetic viscosity based on unburnt conditions</td>
</tr>
<tr>
<td>$T_u$</td>
<td>Unburnt temperature</td>
</tr>
<tr>
<td>$P_u$</td>
<td>Unburnt pressure</td>
</tr>
<tr>
<td>$\alpha_u$</td>
<td>thermal diffusivity based on unburnt conditions</td>
</tr>
<tr>
<td>$C_Pu$</td>
<td>thermal capacity based on unburnt conditions</td>
</tr>
<tr>
<td>$k_u$</td>
<td>thermal conductivity based on unburnt conditions</td>
</tr>
<tr>
<td>$D_u$</td>
<td>Mass diffusivity of fuel composition into the mixture</td>
</tr>
</tbody>
</table>

### Premixed flame characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_f$</td>
<td>adiabatic flame temperature based on unburnt conditions</td>
</tr>
<tr>
<td>$S_{L_u}$</td>
<td>laminar flame speed based on unburnt conditions</td>
</tr>
<tr>
<td>$LHV$</td>
<td>lower heating value based on unburnt conditions</td>
</tr>
<tr>
<td>$T_{tip}$</td>
<td>Measured burner tip temperature</td>
</tr>
<tr>
<td>$g_c$</td>
<td>critical velocity gradient when flashback happens</td>
</tr>
<tr>
<td>$h'$</td>
<td>convective heat transfer coefficient</td>
</tr>
</tbody>
</table>

### Ambient conditions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>ambient temperature</td>
</tr>
<tr>
<td>$P_0$</td>
<td>ambient pressure</td>
</tr>
</tbody>
</table>

### Burner properties

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k'$</td>
<td>thermal conductivity of the burner material</td>
</tr>
<tr>
<td>$d$</td>
<td>diameter of the burner</td>
</tr>
<tr>
<td>$\theta'$</td>
<td>thickness of the burner wall</td>
</tr>
</tbody>
</table>
Test Plan Analysis

- Non-dimensional groups

\[
\begin{align*}
\Pi_2 &= \text{Re} = \frac{\text{UD}}{\nu} \\
\Pi_3 &= Le_u = \frac{\alpha_u}{D_u} \\
\Pi_4 &= \text{Pr} = \frac{\nu}{\alpha} \\
\Pi_5 &= \frac{P_u}{P_0} \\
\Pi_6 &= \frac{T_u}{T_0} \\
\Pi_7 &= \frac{\theta'}{d}
\end{align*}
\]

Pressure effect

Momentum equation

\[ Da = f \left( \text{Re}, \text{Pr}, Le_u, \frac{P_u}{P_0}, \frac{T_u}{T_0}, \frac{\theta'}{d} \right) \]

Flashback characteristic

Energy equation

Effect of mass diffusivity in energy equation

Burner properties
Test Plan Analysis

- Thermal conductivity of burner is significant in determining flashback propensity
  - Rate of flame regression into the premixing section differs for different burner material

- A comprehensive parameter survey based on Buckingham Pi theorem results in a physical correlation for flashback propensity prediction

\[
Da = C_0 \cdot Le^{-6.12} \cdot \left(\frac{T_u}{T_0}\right)^{-1.71} \cdot \left(\frac{T_{\text{tip}}}{T_u}\right)^{-3.69} \cdot \left(\frac{\alpha}{d \cdot S_L}\right)^{-1.89} \cdot f_2\left(\frac{\theta'}{d}\right) \cdot f_3\left(\frac{P_u}{P_0}\right)
\]
Test Plan Analysis

- Correlation Performance
  - Dataset from Duan, et al. 2013


\[
Da = \text{Const.} \cdot \text{Le}^{-6.12} \cdot \left(\frac{T_u}{T_0}\right)^{-1.71} \cdot \left(\frac{T_{\text{tip}}}{T_u}\right)^{-3.69} \cdot Pe_f^{-1.89} \cdot \left(\frac{\theta'}{d}\right) \cdot f_1\left(\frac{P_u}{P_0}\right) \cdot f_2\left(\frac{P_u}{P_0}\right)
\]
Test Plan Analysis


\[ Da = \text{Const.} \cdot Le^{-6.12} \cdot \left( \frac{T_{AFT}}{T_u} \right)^{-2.75} \cdot Pe_f^{-1.89} \cdot \left( \frac{P_u}{P_0} \right)^{-2.10} \]

Guidance from Test Plan Analysis

• Based on Analysis:
  – Further investigation of effects of thermo-physical features of burner material on flashback propensity
    • More systematic study
  – Extend the investigation on jet flame flashback to more gas turbine related conditions
    • More systematic study
  – Framework to evaluate model performance as data are gathered is in place

• Eventually apply methodologies to develop/understand strategies to prevent flashback event and mitigate its damage
Experiments
Measurement Plan

• Fuel Composition Variation
  – Effect of Pressure
  – Effect of Preheat Temperature

• Effect of Burner Head
  – Burner Material
  – Burner Thickness
Experiment Set-up
Experiment Set-up

- Air and fuel mixing through a Venturi mixer
- Flow straightening via honeycomb materials
- Interchangeable burner head
- Consistent burner rim temperature measurement
- Hydrogen pilot ignited with YAG laser to initiate reaction

- Overall setup is similar to that used in Beerer et al. (2014)

Experiment Set-up

Premixed Jet Flames

- Venturi fuel/air mixing
- Fuel injection
- Perforated plate
- Top test section face
- Graphite gaskets
- Quartz liner
- Interchangeable burner head
- Pilot flame
- Springs
- Thermocouples
- Observation window
- Exhaust section

Air inlet
Experiment Set-up

YAG laser

Burner
Experiment Set-up

- Velocity profile using LDV

![Graph showing normalized axial velocity and normalized radial distance.](image)

- Venturi

- Q = 40.2308 scfm
- Q = 49.22471 scfm
- Q = 58.75896 scfm
- Numerical Method (RANS)

- Setup showing LDV measurement and a piece of equipment with a note of 5mm.
Experiment Set-up

- Injector (80% completed)
- Fuel system (80% completed)
- Air system (80% completed)
- Preheating (100% completed)
- Water quenching system (80% completed)
- Air Mass Flow rate Control (70% completed)
- Fuel Mass Flow rate Control (70% completed)
- Hardware Setup (80% completed)
- Software Setup (50% completed)
- YAG laser (50% completed)
Test Parameters

- **Pressure**
  - 1 atm to 10 atm

- **Preheated temperature**
  - 300 K to 800 K

- **Fuel compositions**

- **Burner materials**

- **Burner thickness**

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Capacity [J/(g*C)]</th>
<th>Heat Conductivity [W/(m*k)]</th>
<th>Density [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>100</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>CH₄</td>
<td>0</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>SS-304</td>
<td>0.5</td>
<td>21.5</td>
<td>8</td>
</tr>
<tr>
<td>Copper</td>
<td>0.385</td>
<td>385</td>
<td>7.94</td>
</tr>
<tr>
<td>Quartz</td>
<td>0.7</td>
<td>1.4-2.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>

- \( \Pi_5 = \frac{P_u}{P_0} \)

- \( \Pi_6 = \frac{T_u}{T_0} \)

- \( \Pi_7 = \frac{\theta'}{d} \)

- \( \Pi_1 = Da = \frac{S_L^2}{\alpha \cdot g_c} \)
Fuel/Air Mixing

Computational Fluid Dynamics (CFD)
- Mixing profile

Reaction Kinetic Simulation
- Adiabatic Flame Temperature
- Laminar Flame speed

- Venturi gas mixer
Next Steps

Physical Modeling and Interpretation (60% completed)
Verifying the developed model for previous data in the literature

Experiment Set-up (60% completed)
Flashback diagnostic system
  • Thermocouple (TC)
  • Pressure Transducer (PT)
  • High Speed Imaging

Flashback Data Acquisition (ongoing)

Computational Modeling (30% completed)
CFD modeling
  • Combustion modeling of the premixed jet flame
  • Flashback

Data Analysis and Correlation Development (0% completed)
  • Single factor correlation
  • General factor correlation
  • Non-dimensional groups
  • Comparison between current study and previous research

Conclusion and Suggestion (0% completed)