Characterization of the Influence of Moderate Pressure Fluctuations on the Cooling Performance of Advanced Combustor Cooling Concepts in a Reacting Flow

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- Lean combustion concepts are prone to combustion and thus pressure fluctuations.

- Combustor liner must resist heat load with a sparse cooling film in comparison to conventional combustors.

- *Moderate* pressure fluctuations will be part of the regular operating envelope of a lean combustor even with applied damping devices.

- The impact of pressure fluctuations on different cooling concepts is of special interest for the combustor designer.

- An investigation of different acoustic-focused and cooling optimized cooling concepts in a realistic environment was conducted.
Generation of pressure fluctuations by self-induced combustion instabilities
Scheme of Test Section in HPCR

Turbulence level $Tu = 22\%$
Pressure Fluctuations in Test Section

- Pressure in test section: $p=5\text{bar}$
- Near wall hot gas temperature: $T_g\approx 1520\text{K}$
- Near wall hot gas velocity: $u_g=23\text{m/s}$
- Level of pressure fluctuations is affected by combustor preheat temperature $T_3$
- Fuel: Diesel
- Constant adiabatic flame temperature in combustor

Amplitude of pressure fluctuations is $\approx 2.5\%$ of overall pressure
Test Samples I, Acoustic Focused

Cooling hole angle $\beta=90^\circ$

\[
\frac{n_{\text{eff}}}{n_{\text{imp}}} = 3
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity $k$ [W/(m*K)]</th>
<th>Wall thickness $t/d$ [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel</td>
<td>14…20</td>
<td>1.4</td>
</tr>
<tr>
<td>Copper</td>
<td>190…240</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Test Samples II, Cooling Optimized

Cooling hole angle $\beta=30^\circ$

\[
\frac{n_{\text{eff}}}{n_{\text{imp}}} = 1
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity $k$ [W/(m*K)]</th>
<th>Wall thickness $t/d$ [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nimonic</td>
<td>14…20</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Impact of Pressure Fluctuations

Acoustic Design

Inconel

- \( \Delta p_{rel,c} = 3\% \)
- \( T_c = 470\text{K} \)
- \( M = 2.2 \)
- \( l = 1.6 \)

\[
\eta_{tot} = \frac{T_{gas} - T_{wall}}{T_{gas} - T_{cool}}
\]
Impact of Pressure Fluctuations

Acoustic Design
Inconel

- $\Delta p_{rel,c}=3\%$
- $T_c=470\text{K}$
- $M=2.2$
- $l=1.6$

- Strongest effect of pressure fluctuations upstream where film is thin
Influence of Cooling Air Pressure Drop

Acoustic Design

Inconel

$T_c=540K$

- Strongest effect of pressure fluctuations at low cooling air pressure drop

$$Str_c=2\pi*f*t/u_c$$

$$Str_c*Ma_c<0.04$$

$Str_c*Ma_c\leq1$ indicates an effect of the pressure period on the cooling air jet flow

Ligrani et al. 1996

Longitudinal coordinate x/d [1]

Total cooling effectiveness $\eta_{tot}$ [1]

Impingement jets

$\Delta p_{rel,c}=4\%$, stable, $M=2.4$, $l=2.1$

$\Delta p_{rel,c}=2.1\%$, stable, $M=1.7$, $l=1.1$

$\Delta p_{rel,c}=4\%$, unstable, $M=2.4$, $l=2.1$

$\Delta p_{rel,c}=2.1\%$, unstable, $M=1.7$, $l=1.1$
Acoustic Design

Thermocouples in impingement cavity
Temperature in Impingement Cavity

\[ \Theta_{cav} = \frac{T_{cav} - T_c}{T_h - T_c} \]

Temperature in cavity indicates back flow of hot gas flow under pressure fluctuations at low cooling air pressure drops.

Acoustic Design

Inconel

\[ T_c = 540K \]
Spatially Resolved Fourier Transformation

- Reduce frame size of infra red camera → frame rate approx. $f = 2.9\text{kHz}$
- Acquire series of images
- Perform Fourier transformation for time series at each camera pixel
- Extract amplitude of temperature fluctuations at frequency of pressure fluctuations ($f \approx 620\text{Hz}$)
- Mapping of amplitudes
Distribution of Temperature Fluctuations

Acoustic Design

Inconel

- \( \Delta p_{rel,c} = 2.1\% \)
- \( T_c = 540 \text{K} \)
- \( M = 1.7 \)
- \( l = 1.1 \)
- \( f \approx 620 \text{Hz} \)

- Temperature fluctuations on perimeter of cooling holes indicate back flow of hot gas flow under pressure fluctuations
- Cooling jets interact with hot gas flow upstream 1\text{st} and 2\text{nd} row of holes

\( \Delta p_{rel,c} = \frac{p_{rel,c} - p_{dyn}}{p_{dyn}} \times 100\% \)
Influence of Cooling Air Pressure Drop

• Under stable conditions cooling air pressure drop has small effect on cooling effectiveness → high thermal conductivity
• At low cooling air pressure drop strong impact of pressure fluctuations → back flow of hot gas & high thermal conductivity

$T_c = 470 K$

Longitudinal coordinate $x/d$ [1]

Total cooling effectiveness $\eta_{tot}$ [1]

$\Delta p_{rel,c} = 4\%$, stable, $M=2.6$, $I=2.1$

$\Delta p_{rel,c} = 2.1\%$, stable, $M=1.8$, $I=1.0$

$\Delta p_{rel,c} = 4\%$, unstable, $M=2.6$, $I=2.1$

$\Delta p_{rel,c} = 2.1\%$, unstable, $M=1.8$, $I=1.0$

Impingement jets

Acoustic Design
Copper

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Influence of Cooling Air Pressure Drop

Cooling optimized Nimonic

\[ T_c = 470K \]

- Strong effect of pressure fluctuations on cooling effectiveness at low cooling air pressure drop
Distribution of Temperature Fluctuations

Cooling optimized Nimonic

- $\Delta p_{rel,c}=2.1\%$
- $T_c=470K$
- $M=4.1$
- $l=5.2$
- $f\approx 620Hz$
- The cooling effectiveness of all investigated cooling concepts was deteriorated by moderate pressure fluctuations in the hot gas flow.

- Film fluid was flowing back into the cavity during a pressure fluctuation period especially at low cooling air pressure drops.

- The cooling optimized concept revealed a strong impact of pressure fluctuations on the cooling effectiveness.

- High temperature fluctuations on lateral surface of inclined cooling holes.
- Approach is made to isolate the effect of pressure fluctuations on film cooling effectiveness.

- Investigation is extended towards
  - Cooling concepts with integrated damping devices
  - Single skin effusion cooling concepts.