Novel Additively Manufactured and Internally Cooled Airfoils for Increasing Small Industrial Gas Turbine Efficiency

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NETL Support Contractor

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Outline

1. Introduction and Motivation
2. Materials and Methods
3. Results and Discussion
4. Conclusions
Introduction and Motivation

- Small (<20 MW) industrial gas turbines produce roughly 2 GW of electricity in U.S. combined heat and power (CHP) applications.\(^1\)
- Blades and vanes in this turbine class are internally cooled.\(^2\)
- Others have used cooling technology curves to compare cooling technologies.\(^3\)
- Experimentally measured technology curves for an entire airfoil are rarely reported.

### Energy, Emissions, & Environment:
- 35-50% reduction in GHG emissions
- 2% point improvement in efficiency

### Cost & Competitiveness:
- 25% reduction in payback period

### Technical & Scientific:
- Novel internal cooling channel designs
- AM alloy powder enhancements

### Other Impacts:
- Thermal energy storage can reduce levelized cost of electricity (LCOE) by 7-10% AND reduce variable grid demand

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Materials and Methods

Test Setup

NETL Conjugate Aerothermal (CAT) Rig

Operation:
• Steady state
• Tests over 10-20 min intervals, 1 Hz sampling frequency

Measurements:
• Infrared (IR) blade surface temperature*
• *w/calibrated radiation model

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant mass flow</td>
<td>1-5 g/s</td>
</tr>
<tr>
<td>Coolant inlet temperature</td>
<td>325 K</td>
</tr>
<tr>
<td>Hot gas mass flow</td>
<td>0.64 kg/s</td>
</tr>
<tr>
<td>Hot gas inlet temperature</td>
<td>650 K</td>
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</table>
Test Approach

Performance Comparison via Technology Curves

\[ \phi = \frac{T_g - T_{w,ext}}{T_g - T_{c,in}} \]

\[ HLP = \frac{\dot{m}_c c_p}{h_{ext} A_{ext}} \]

\[ \eta_c = \frac{\phi_{avg}}{HLP(1 - \phi_{avg})} \]
Materials and Methods

Test Airfoils

Baseline vane
Baseline blade
NETL double wall (stacked design)
Lattice airfoil
Incremental impingement
Measurement Approach and Uncertainty Quantification

- IR measurements with FLIR Model A8300sc
- Camera calibrated with IR-564/301 from Infrared Systems Development Corporation
- Radiation transport model accounts for IR reflections, window transmission, and surface curvature
- Model calibrated in situ to determine reflection and transmission constants
- Uncertainty determined using Kline and McClintock approach

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Uncertainty</th>
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</thead>
<tbody>
<tr>
<td>Temperature (IR Camera)</td>
<td>0.25% (measured value)</td>
</tr>
<tr>
<td>Temperature (Thermocouple)</td>
<td>Maximum of 2.2 K or 0.75% of measured value</td>
</tr>
<tr>
<td>Mass Flow Coolant</td>
<td>0.25% of measured value</td>
</tr>
<tr>
<td>Mass Flow Hot Gas</td>
<td>0.5% of measured value</td>
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<tr>
<td>Differential Pressure</td>
<td>0.2% of measured value</td>
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<table>
<thead>
<tr>
<th>Measurement</th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
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<tbody>
<tr>
<td>$\phi_{avg}$</td>
<td>± 0.019</td>
<td>± 0.025</td>
<td>± 0.016</td>
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<tr>
<td>$\phi_{99}$</td>
<td>± 0.023</td>
<td>± 0.029</td>
<td>± 0.019</td>
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<tr>
<td>$\eta_c$</td>
<td>± 0.040</td>
<td>± 0.108</td>
<td>± 0.004</td>
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<tr>
<td>$HLP$</td>
<td>± 0.007</td>
<td>± 0.034</td>
<td>± 0.001</td>
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Coupon for flat surface IR calibration
Geometry used to model surface emissivity
Results and Discussion

Temperature Maps

Heat load parameter (HLP)

<table>
<thead>
<tr>
<th>HLP = 1.0</th>
<th>Baseline Blade</th>
<th>Baseline Vane</th>
<th>Double Wall</th>
<th>Incremental Imping.</th>
<th>Lattice</th>
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<tr>
<th>HLP = 2.0</th>
<th>Baseline Blade</th>
<th>Baseline Vane</th>
<th>Double Wall</th>
<th>Incremental Imping.</th>
<th>Lattice</th>
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Temperature (K)

Replicates
Pressure Drop and LE/MC/TE Average Temperatures

Leading edge (LE)

Mid-chord (MC)

Trailing edge (TE)

Baseline blade
Cooling Technology Curves

Overall Cooling Effectiveness vs. Heat Load Parameter

Advanced Target
Baseline Target
Internal Cooling Efficiency

\[ \Delta P \sim f(\text{HLP}) \]

\[ \eta_c \sim f(\text{HLP}) \]

- Lattice
- NETL Double Wall
- Baseline Vane
- Baseline Blade
- Incremental Imping.
• Advanced design objectives:
  • Operate at advanced condition
  • Achieve $\eta_c \geq \eta_c,\text{base}$.
• Baseline blade:
  • $\eta_c$: 0.61 decreases to 0.48 to achieve $\phi_{avg} = 0.37$ (100 K above the baseline target)
• NETL double wall:
  • $\eta_c$: 0.95 decreases to 0.7 to achieve $\phi_{avg} = 0.37$
• $\eta_c$ for NETL double wall at +100 K firing temperature is 10% points higher than the baseline blade at the current state-of-the-art

<table>
<thead>
<tr>
<th>Cooling Design</th>
<th>Minimum HLP</th>
<th>Cooling Effectiveness $\phi_{Avg}$</th>
<th>Internal Cooling Efficiency $\eta_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Blade</td>
<td>1.38</td>
<td>3.22</td>
<td>0.46</td>
</tr>
<tr>
<td>Baseline Vane</td>
<td>0.77</td>
<td>1.81</td>
<td>0.37</td>
</tr>
<tr>
<td>NETL Double Wall</td>
<td>0.57</td>
<td>1.36</td>
<td>0.35</td>
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<tr>
<td>Lattice</td>
<td>0.93</td>
<td>1.89</td>
<td>0.41</td>
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<tr>
<td>Incremental impingement</td>
<td>1.26</td>
<td>2.83</td>
<td>0.46</td>
</tr>
</tbody>
</table>
Conclusions

- Efficiency of CHP gas turbines (<20 MW) can be improved through additively manufactured (AM) airfoil cooling schemes.
- Cooling performance of five AM airfoils was determined.
- Tests indicated that enhanced airfoil cooling schemes allow a 100 K increase in firing temperature.
- The NETL Double Wall was uniformly cooled, had the highest performance, and achieved an internal cooling efficiency 10 percentage points higher than baseline blade.
- Design considerations for AM included modifications to eliminate overhangs and allow powder removal.
Acknowledgments

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