Revolutionizing Turbine Cooling with Micro-Architectures Enabled by Direct Metal Laser Sintering

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Objectives

• Explore innovative cooling architectures enabled by additive manufacturing techniques for improved cooling performance and reduced coolant waste.

• Leverage DMLS to better distribute coolant through microchannels, as well as to integrate inherently unstable flow devices to enhance internal and external heat transfer.

• Demonstrate these technologies
  1. at large scale and low speed.
  2. at relevant Mach numbers in a high-speed cascade.
  3. finally, at high speed and high temperature.

• Complement experiments with CFD modeling to explore a broader design space and extrapolate to more complex operating conditions.
Integration of Promising Designs in NGV

Reverse Cooling on PS:
- Fed by upstream microchannel
- Better surface coverage with lower massflow?

Fluidic Oscillator Impingement Cooling on LE:
- Eliminate showerhead
- Lower massflow required?
- Microchannel exhaust

Microchannels in TE:
- Improved coverage with lower massflow required?
- Weight savings with skin cooling?

Sweeping Fluidic Oscillator Film Cooling:
- Improved coverage with lower massflow required?
Turbine Heat Transfer Facilities

• For innovative concepts to be viable, must be vetted in facilities that simulate the real operating environment

• Graduated complexity
  – Low speed, large scale
  – High speed, smaller scale
  – High speed, high temp \( (T_w/T_b) \), small scale

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Replaceable endwall plate

Traverse slot

Adjustable tailboards

Inlet and outlet pressure taps

Stagnation Pressure and temperature

Turbulence Grid

Choke bars array

Screens

Honeycomb

Infrared Camera

Pitot Probe & Thermocouple

Region for area-average data

Freestream air from blower and heater

Film Cooling Model

Leading edge boundary layer suction

Flow Conditioning Suction

Coolant air from vortex tubes
Sweeping Jet Impingement Cooling

**Design Variables**

- Jet-to-wall spacing (H/D)
- Exit fan angle (∅)
- Aspect ratio (AR)
- Hole pitch (P/D)
- Reynolds number (Re)
Overview

- **Goal:** Study the potential for using **sweeping jets for impingement** heat transfer in leading edge internal cooling applications.

- **Progression:**
  - **Flat plate** experiments to determine the effect of Re, $z/d_h$
  - **Computational studies** to determine the effect of exit nozzle angle, impingement surface curvature, and reduced frequency
  - **Low speed** wind tunnel experiments with engine-relevant Biot number
    - Array of sweeping jets in a **faired cylinder**
    - Array of sweeping jets in a linear cascade **nozzle guide vane**
  - **Transonic** cascade

![Diagram of sweeping jets and Mach number](image)
Flat Plate Impingement Experiments with Solo Fluidic Oscillator

- Test jets mounted in a temperature-controlled chamber for transient tests
- Results compared to a circular L/D=1 orifice jet at similar test conditions

- Surface temperature was measured with IR thermography, and heat flux was measured locally with heat flux gauges

- Test matrix:
  - Reynolds numbers: 20,000 to 35,000
  - Jet-to-wall spacings: 5 to 7 (z/dh)
  - Exit nozzle angles: 70° and 102°
  - Hydraulic diameter d_h = 4.11 mm
  - AR = 1 for all fluidic oscillators
Heat Flux Gauge Impingement Measurements

- Unsteadiness evident in local heat transfer (HFG power spectra and IR)
- Validation of oscillation frequency (to within 5%), bi-stable flow field, and spreading angle

Sweeping Jet Velocity Contour

\[ \beta \approx 60^\circ \]
Results for Sweeping Impingement Jet

- Sweeping jet impingement Nu depends on jet Re^{0.5}
- Sweeping jet impingement heat transfer is not symmetric between lobes of high heat transfer
- Changing fluidic oscillator exit angle drastically changes the sweeping jet impingement heat transfer profile
- Heat transfer on flat plate underperformed compared to the circular jet

Opportunities for Design Optimization!!!
Impingement Study (CFD)

- CFD calculations performed with FO and round jet to investigate the external flow field and heat transfer parameters.
- **Unsteady RANS** \((k - \omega)\) **SST model**
- \(Re = 35:\)

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**Impingement wall**

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**CFD Grid**
External Flow Field (Iso-surface of $Q$-criterion)

- CFD showed complicated flow structure due to entrainment that leads to a pulsing action of the jet.

- Iso-surfaces are colored by Mach number and impingement surface is colored by local Nu number.

$$Q = \frac{1}{2}(\Omega_{ij} - \xi_{ij})$$
**Surface Nusselt Number**

- Sweeping action of the jet enhances cooling in the lateral direction.
- The time-averaged Nu contour shows **two distinct lobe** of cold regions that were confirmed by heat flux gauge data.
Effect of $\theta$ and H/D for Impingement Cooling (CFD)

- 72 cases were examined.
- $\theta = 0^\circ, 20^\circ, 40^\circ, 55^\circ, 70^\circ, 85^\circ, 100^\circ, 130^\circ$.
- $m = 50, 75, 100 slpm$
- H/D = 3, 5, 8
- Unsteady RANS ($k - \omega$ SST turbulence)
- $Re_D \sim 17500, 26000, 35000$
Time Averaged Nu Distribution

- Time averaged contours show the effect of exit fan angle on local Nu distribution.
- Large fan angle shows increased spreading of coolant. However, the peak value of Nu drops significantly due to mixing.
Area Averaged Nu Distribution

- Results are shown as a function of exit angle.
- Area averaged Nu drops linearly (up to $\theta = 85^\circ$) as the exit angle increases for all massflow rates for H/D = 5.
- Recall $\theta=0$ is essentially steady jet.

Oscillating jet always has lower area-averaged Nu compared to $\theta = 0$
The time averaged Nu distribution is not the whole story. In order to show the actual benefit of the sweeping action, a new parameter has been defined as ‘**Surface Uniformity Index (\(\gamma\))**’.

\[ \gamma = 1 - \frac{\sum \sqrt{(N\nu_i - \overline{N\nu_i}) \cdot A_i}}{N\nu A} \]

\(\gamma = 1\) indicates a perfectly uniform metal temperature.

**Surface Uniformity Index**

At H/D=5, oscillating jet **OUTPERFORMS** \(\theta = 0\) for uniformity.
Leading Edge Model

- Radius of curvature, \( R_{LE} = 17D_h \)
- Leading edge diameter, \( D_{LE} = 101.6\,mm \)
- Span, \( S_{LE} = 380\,mm \)
- LE wall thickness, \( t_{LE} = 1.5\,mm \)
- Exit Fan angle 40°
Leading Edge Wall Thickness (matched Bi number approach)

Adiabatic film effectiveness:
\[ \eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \]

Overall cooling effectiveness:
\[ \phi = \frac{T_\infty - T_{wall,ext}}{T_\infty - T_c} \]

One dimensional heat transfer analysis:
\[ \phi = \frac{1 - \eta}{1 + Bi + \frac{h_e}{h_c}} + \eta \]

\[ Nu_D = 0.3 + \frac{0.62 Re_D^{0.5} Pr^{0.33}}{ \left(1 + \left(\frac{0.4}{Pr}\right)^{0.66}\right)^{0.25} \left[1 + \left(\frac{Re_D}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}}} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi</td>
<td>0.1</td>
</tr>
<tr>
<td>(h_e/h_i)</td>
<td>0.5</td>
</tr>
<tr>
<td>(T_\infty)</td>
<td>310K</td>
</tr>
<tr>
<td>(T_c)</td>
<td>275K</td>
</tr>
</tbody>
</table>

Leading Edge Model (Fluidic Oscillator)

- **Geometric Parameter**

  \[
  Aspect\ ratio\ (AR) = \frac{\text{Throat width (} W_t \text{)}}{\text{Throat height (} H_t \text{)}}
  \]

- **Oscillator Characterization**

  - \( AR = 1.0 \)
  - \( AR = 0.75 \)
  - \( AR = 0.5 \)

<table>
<thead>
<tr>
<th>( AR )</th>
<th>( D_h ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>2.50</td>
</tr>
<tr>
<td>0.75</td>
<td>2.85</td>
</tr>
<tr>
<td>0.50</td>
<td>3.33</td>
</tr>
</tbody>
</table>

Frequency contour
Test Matrix

- 72 tests were conducted.
- Both heat transfer and pressure drop measurements were performed.
- Span averaged and area averaged cooling effectiveness were estimated.

\[ \theta = \frac{T_{\infty} - T_w}{T_{\infty} - T_c} \]

<table>
<thead>
<tr>
<th>Aspect ratio</th>
<th>Pitch (P/D)</th>
<th>H/D</th>
<th>Tu</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4, 6</td>
<td>3, 5, 8</td>
<td>0.5%, 10.1%</td>
</tr>
<tr>
<td>0.75</td>
<td>4, 6</td>
<td>3, 5, 8</td>
<td>0.5%, 10.1%</td>
</tr>
<tr>
<td>0.5</td>
<td>4, 6</td>
<td>3, 5, 8</td>
<td>0.5%, 10.1%</td>
</tr>
</tbody>
</table>
**Effect of H/D**

- Span averaged cooling effectiveness are shown for $AR = 1$, $P/D = 6$.

- Cooling effectiveness decreases with the increases of $H/D$ and turbulence.

- At $H/D = 5$, sweeping jet shows promising performed compared to round jet.
Effect of H/D

- Span averaged cooling effectiveness are shown for AR = 1, P/D = 4
- Area averaged cooling effectiveness shows the effect of turbulence at varying H/D.

![Span averaged effectiveness](image)

![Area averaged effectiveness](image)
**Effect of Aspect Ratio**

- Overall cooling effectiveness contours are shown for sweeping jet and steady jet at three different aspect ratios.

- Area averaged effectiveness implies that aspect ratio of AR = 1 has the best cooling performance.

![Graph showing area averaged effectiveness](image)
Effect of Freestream Turbulence

- Freestream turbulence augments external heat transfer thus a drop in overall cooling effectiveness has been observed.
Effect of Pitch

- At P/D = 4, the interaction between the adjacent jets augments internal heat transfer resulting in an increase in overall cooling effectiveness.

![Area averaged effectiveness](image)

**Overall cooling effectiveness**

- P/D = 4
- P/D = 6
Internal flowfield (CDF)

- CFD shows mutual interaction between adjacent jets over time that induce coolant flow in the spanwise direction.

- CFD also reveals that the jet oscillations are not synchronized with adjacent jets.
Pressure Drop Measurement

- Pressure drop across the device is lower for sweeping jet compared to steady jet for this particular plenum condition.

\[ \Delta P = P_{\text{plenum}} - P_{\text{atm}} \]
Vane Leading Edge Impingement

- Vane was designed at OSU as a research vane
- The vane has a large leading edge radius to facilitate surface temperature measurements
- Models were additively manufactured with stereolithography and fused deposition modeling
- Modular so that multiple impingement and film cooling geometries can be tested

Film cooling hole
Impingement hole

OSU vane

FDM

SLA
Cascade Design

- Tests performed in a linear cascade in an open-loop wind tunnel
- The linear cascade section consists of three-vanes, two passages.

Vane geometry and flow condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>True chord ((C))</td>
<td>15.24 cm (6 in)</td>
</tr>
<tr>
<td>Axial chord ((C_x))</td>
<td>8.33 cm (3.28 in)</td>
</tr>
<tr>
<td>Chord/pitch ((C/P))</td>
<td>1.20</td>
</tr>
<tr>
<td>Span/chord ((S/C))</td>
<td>1.25</td>
</tr>
<tr>
<td>Inlet and exit angles</td>
<td>0° and 70°</td>
</tr>
<tr>
<td>Chord Reynolds number ((Re_{in}))</td>
<td>9.5 x 10^4</td>
</tr>
<tr>
<td>Freestream velocity, ((U_\infty))</td>
<td>9.5 m/s</td>
</tr>
<tr>
<td>Freestream temperature, ((T_\infty))</td>
<td>315 K</td>
</tr>
</tbody>
</table>
Vane Leading Edge Impingement

- Leading edge modules were manufactured by SLA for circular and sweeping jet configurations
- Leading edge thickness was designed to match engine-relevant Biot (0.1-0.3)
- Fluidic oscillator design parameters were taken from the leading edge model study
- Vane surface temperature was measured with IR thermography in the region indicated

<table>
<thead>
<tr>
<th>Geometric parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_h</td>
</tr>
<tr>
<td>1.5 mm</td>
</tr>
</tbody>
</table>

![Geometric parameters graph]
Overall Cooling Effectiveness

Circular Jet

Sweeping Jet

Low Tu (0.3%)

High Tu (6.1%)

\[ \theta = \frac{T_\infty - T_s}{T_\infty - T_{cooled}} \]
Overall Cooling Effectiveness

- Span-averaged $\theta$ profiles show the circular jet cools the surface more effectively.
- Sweeping jet has a broader, more uniform cooling profile.
- Increasing freestream turbulence has a similar effect on both circular and sweeping jets.

![Graphs showing overall cooling effectiveness](https://arc.engineering.osu.edu)
Internal Nusselt Number

- Calculated with a computational thermal inertia method
  - Driving coolant temperature, external temperature, and external heat transfer coefficient are known
  - Measured external surface temperature is applied as a boundary condition on the solid model
  - Internal heat transfer coefficient is guessed, and updated based on how accurate the predicted external temperature is compared to the measured temperature

Low Tu (0.3%)
Pressure Drop

- Sweeping jet has **HIGHER pressure drop** than circular jets
- Opposite of cylinder result
- Could be solved with **improved plenum design**, enabled by additive manufacturing
Reverse Film Cooling
Reverse-oriented Film Cooling

- Reverse film cooling has potential to provide a more uniform coolant spread due to the redirection of the coolant flow by the main flow.

- Reverse cooling was studied experimentally and numerically to gain an understanding of the physics behind the interaction in attempt to increase net heat flux benefit.

- Flat plate wind tunnel testing was performed in an open loop wind tunnel.
Mid-hole PIV Measurements

- Clear high-velocity jetting from the leeward edge of the hole
- Jetted fluid creates a blockage, accelerating the freestream over the hole
- Low velocity fluid above the hole, and large recirculation zone downstream of the hole
Adiabatic Cooling Effectiveness – High Turbulence

Conventional Cylindrical Cooling

Reverse-oriented Cylindrical Cooling

\[ \eta \]

\[ T_u = 13\% \]
\[ M = 0.25 \]

\[ T_u = 13\% \]
\[ M = 0.5 \]

\[ T_u = 13\% \]
\[ M = 1.0 \]
Adiabatic Cooling Effectiveness

- Laterally averaged data compared with conventional cylindrical and 777-shaped holes
- **Reverse cooling shows better performance** near the hole, with good coverage downstream
Area-averaged Heat Transfer Values

- Reverse cooling **augments heat transfer coefficient significantly** compared to conventional cooling cases.

- Reverse cooling provides **net heat flux benefit**, but **less than the conventional holes** due to increased $h$. 
Pressure Loss

- Pressure loss created by reverse cooling holes was calculated with total pressure taps downstream.

- Follows trend of increasing pressure loss with increasing compound angle.
LES Computations – Validation with Experiment

- LES computations of reverse cooling holes and 777-shaped holes were performed, and solutions match experimental data well.

![Graph and diagrams showing LES computations compared to experimental data.](image-url)
LES Computations – Flow Visualizations

Iso-surface of Q-criterion = 1e7 colored by θ

Time Step 100130
Physical Understanding

- Goal of the computations was to gain a better understanding of the hole flow physics so that design changes could be made to improve reverse cooling.

Geometric Optimization Concepts

- Round hole edges to control separation.
- Shape the inlet to induce vorticity to help spread coolant.
- Shape the exit to guide coolant to better coverage.

Some geometries may require reverse flow design.
Sweeping Jet Film Cooling
Preliminary Flow Field Analysis (CFD)

- Unsteady RANS simulation was performed to evaluate the time averaged and time accurate flow field at the down stream of the hole.
- The time averaged flow field is *deceiving* since it would suggest that the SJ vortices mutually induce each other to the wall.
- The jet acts as a *vortex generator* as it interacts with the freestream.

![streamwise vorticity at x/D = 6 & M = 1.97](image-url)
Effect of Exit Fan Angle for Film Cooling (CFD)

- Four different exit angles have been studied for sweeping jet film cooling hole.
- Distance between hole leading edge and trailing edge was kept constant.
Data were averaged over the hole pitch ($P/D = 8.5$).
Hole with 70 degree fan angle shows the highest area averaged film effectiveness.
Effect of Exit Fan Angle (CFD)

- Cross plane velocity fields are shown at $x/D = 6$
- Two CRVPs have been observed for $\phi = 40^\circ$ and $\phi = 100^\circ$ case.

$\phi = 70^\circ$ was considered for final design
Preliminary Hole Design (Flat plate test)

- The SJ hole exhibits **higher span averaged effectiveness** at the **near hole region** ($x/D < 15$).

- SJ hole film effectiveness is more **uniform** along the span.
Vane Flow Visualization

- Water flow visualization shows uniform oscillation at each hole.

**Time accurate**

**Instantaneous**

$\emptyset = 0^\circ$

$\emptyset = 180^\circ$
Measurement Location

- Transient IR measurements were taken at the mid-span of the vane. The measurement area covers five holes.

- Heat transfer measurements were taken at –
  - $Tu = 0.3\%$
  - $M = 0, 0.5, 1.0, 1.5$.

- Wake survey was performed at 0.1C downstream of the vane over a single pitch.

- Wake survey was performed at –
  - $Tu = 0.3\%, 6.1\%$
  - $M = 0, 0.5, 1.0, 1.5$.
Cooling Effectiveness (SJ vs 777) at Tu = 0.3%

- Cooling effectiveness was estimated at three different blowing ratios (M = 0.5, 1.0, 1.5)
  \[ \eta = \frac{T_\infty - T}{T_\infty - T_c} \]

- At low blowing ratio (M = 0.5), a high cooling effectiveness was observed in the near hole region for SJ hole.

- As blowing ratio increases, the cooling effectiveness increases downstream and drops again at the highest blowing ratio (M = 1.5)

- Cooling performance of the 777-shaped hole similar to flat plate.
Cooling Effectiveness (SJ vs 777) at Tu = 6.1%

- Turbulence increases lateral spreading of the coolant for 777 hole.

- Turbulence increases mixing, thus a reduced film effectiveness was observed at all blowing ratios for SJ hole.
Span averaged Cooling Effectiveness

- Span averaged cooling effectiveness was estimated at three different blowing ratios ($M = 0.5, 1.0, 1.5$)

- Sweeping jet hole shows higher cooling effectiveness in the near hole region compared to 777-hole.

Lateral effectiveness

Span averaged (Tu = 0.3%)

Span averaged (Tu = 6.1%)
Area averaged Cooling Effectiveness

- Data were averaged over 20 hole diameter in the streamwise direction and three hole pitch (18D) in the spanwise direction.
- Sweeping jet hole shows higher $\bar{\eta}$ compared to 777-holes at all blowing ratios.
- The area averaged film effectiveness data for SJ are compared with cylindrical hole (CY), shaped hole (SH), and anti-vortex hole (AV) in a similar low speed cascade experiment performed by Ramesh et. al. [2017].
- Note that the vane geometry ($GE E^3$) used in their study is different from the current geometry.
Heat Transfer Coefficient

- Transient experiments were performed at three different blowing ratios ($M = 0.5, 1$ and $1.5$) and $Tu = 0.3\%$.

- The convective heat transfer coefficient was then estimated using Duhamel’s superposition principle.

- SJ shows a **high values of convective heat transfer coefficient** compared to 777-shaped hole.

- The unsteady interaction between the shear layers of two coolant streams probably causes this augmentation of $h$. 
Net Heat Flux Reduction

- Heat transfer augmentation depends on both the heat transfer coefficient ratio and adiabatic film effectiveness.

- Results show approximately 18% improvement in overall cooling benefit at $M = 1.0$ for SJ hole.

\[ \frac{q}{q_o} = \frac{h}{h_o} \left( 1 - \frac{\eta}{\phi} \right) \]

*Here, $\phi = 0.6$*
Total Pressure Loss Measurement (2D Grid)

- A wake survey was performed in a 127 mm x 51 mm plane normal to the vane span at 0.1C downstream of the vane trailing edge.

- A wake total pressure loss coefficient ($\gamma$) was then estimated.

$$\gamma = \frac{Pt_{in} - Pt_{ex}}{\frac{1}{2} \rho U_\infty^2}$$

- SJ hole shows a uniform increase of $\gamma$ along the span due to sweeping action of the coolant.
Total Pressure Loss Measurement

- Span averaged loss coefficient ($\bar{\gamma}$) for SJ and 777-shaped hole.
- The baseline data implies the span averaged loss coefficient ($\bar{\gamma_0}$) without any coolant flow.
- An increase in $\bar{\gamma}$ on the suction side implies additional aerodynamics loss due to coolant flow.
- It is also evident that SJ hole generates more aerodynamic losses compared to 777-hole at all blowing ratios.
Trailing Edge Cooling
Trailing Edge Cooling

Concept to capitalize on AM

Microchannels

Pin-Fin

Ribs

Microchannels provide unparalleled coverage. Bunker (IGTI 2013)

Keep the coolant where it is needed – at the surface!!

Excessive Pressure Drop and Mediocre Cooling 😞
Trailing Edge Cooling AM Concepts

Can we decrease pressure drop without decreasing heat transfer?

- **Elliptical** pin fin decreases pressure loss with comparable thermal performance
- **Dimples** increase Nu while decreasing pressure loss
- **Centerbody** concentrates coolant at the wall
- **Tip clearance** decreases pressure drop and maintains Nu at the wall with the pins.
- **Triangular** pins increase heat transfer augmentation

- **Design concepts enabled by AM**

Preliminary Pressure Drop (CFD vs Exp)

- **PF (CFD)**
- **PF (Exp)**
- **PFC (CFD)**
- **TFC (CFD)**
- **EPFD (CFD)**

**Symbols and Definitions**
- **PF** = Circular pin fin
- **PFC** = Pin fin with clearance
- **TFC** = Triangular pin fin with clearance
- **EPFD** = Elliptic pin fin with dimples

**Graph**
- The graph shows the relationship between massflow rate [g/s] and pressure drop [Pa].
- Different lines and markers represent different types of pin fin configurations and their pressure drop characteristics.

**Legend**
- **PF (CFD)**: Blue line and circle
- **PF (Exp)**: Blue circle
- **PFC (CFD)**: Red line and square
- **TFC (CFD)**: Green line and square
- **EPFD (CFD)**: Black line and square

**Axes**
- **Y-axis**: ΔP [Pa]
- **X-axis**: Massflow Rate [g/s]
What’s Next?
Transonic Cascade Design

Test section

Leading edge and pressure side

Suction side
Vane Integration (Trailing edge)

Suction side film cooling

Leading edge impingement

Trailing edge design
Questions?