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University Turbine Systems Research
Project Review Meeting

Oct. 30 – Nov. 1, 2023

Integrated Turbine Component Cooling Designs Facilitated by Additive Manufacturing and Optimization

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UTSR University Turbine Systems Research

TTCRL
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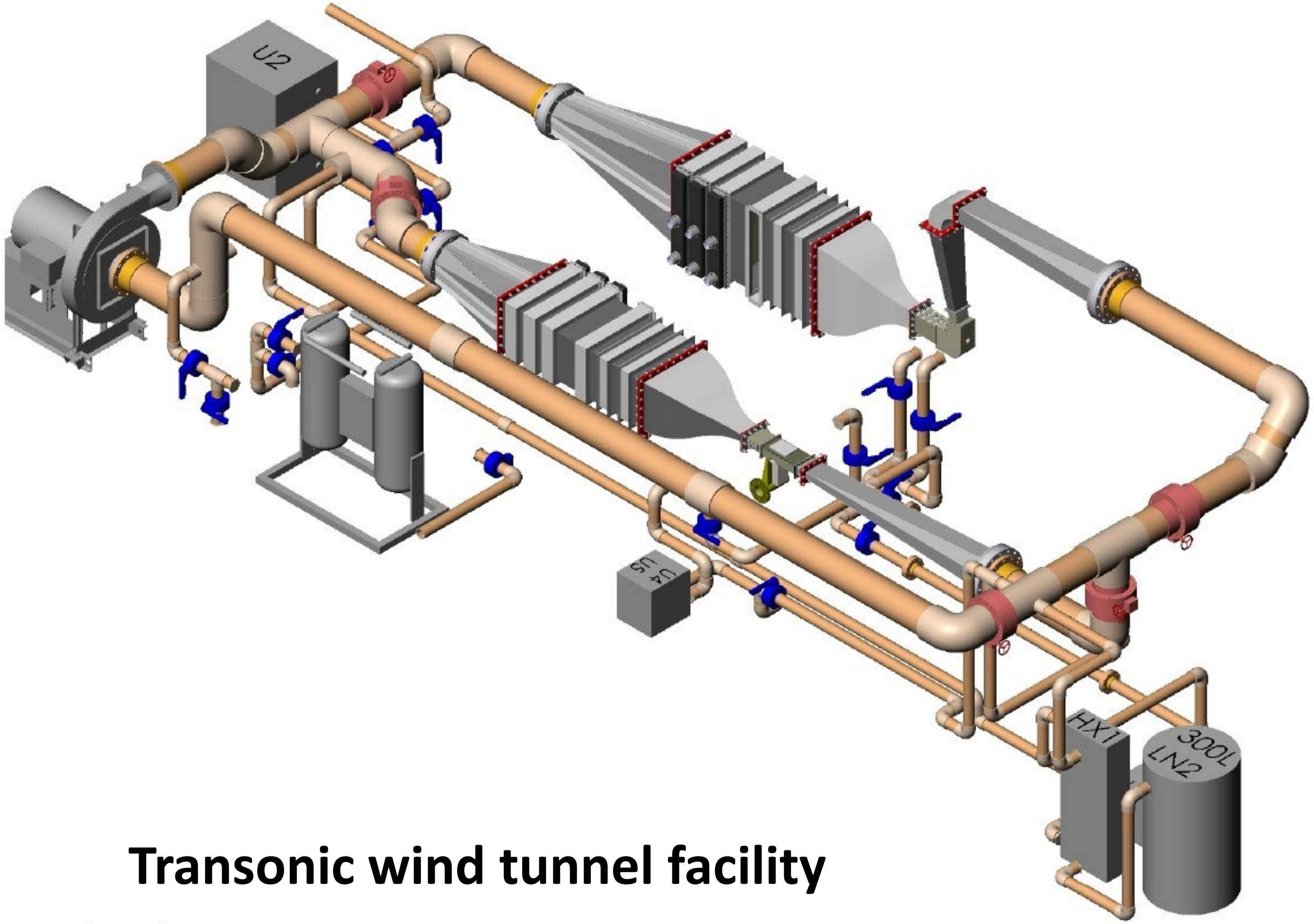
START

Overview of presentation

- Review compressible effects on film cooling
- Transonic Wind Tunnel Facility
- Experimental Methodology
- Results
- Conclusions



Transonic wind tunnel facility

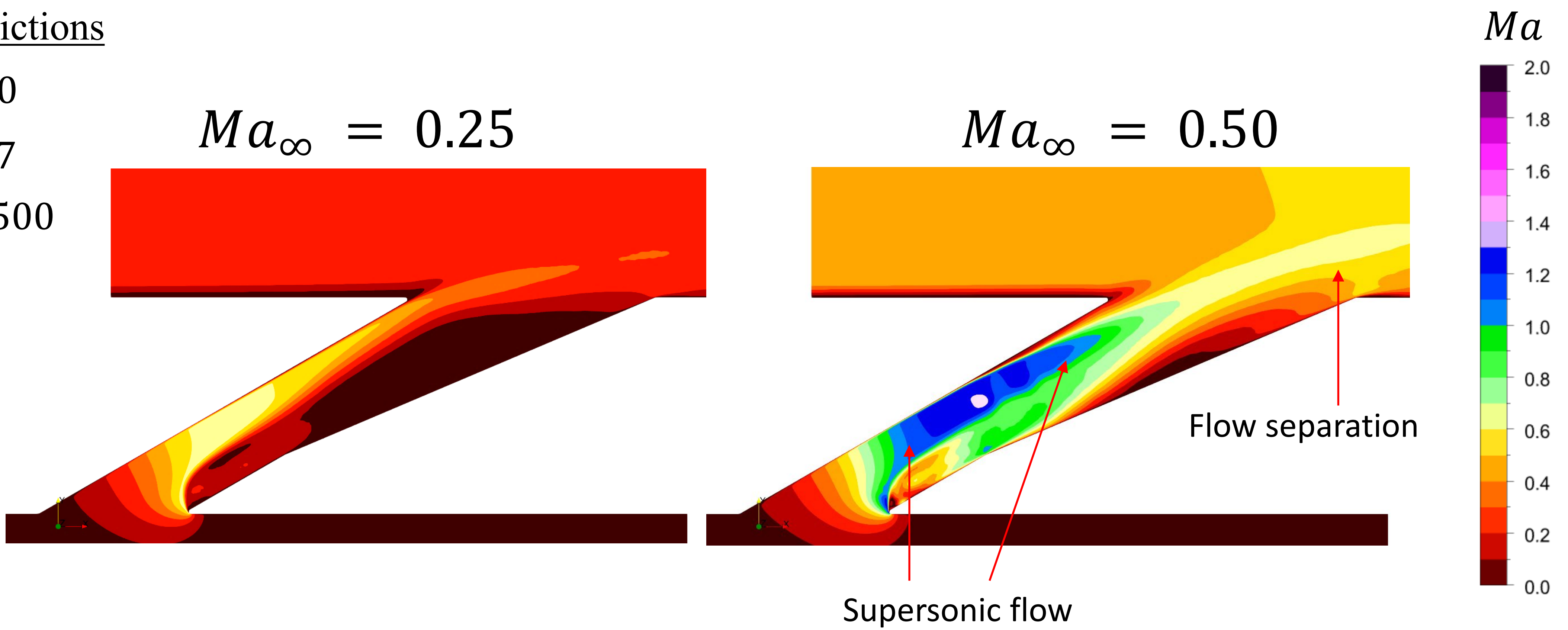
Background – Computational Studies show significant changes in the internal flow in film cooling holes with increasing Mach numbers.

<u>LES predictions</u>

$\mathcal{M} = 2.00$

$\mathcal{T}^o = 0.67$

$Re_d = 5{,}500$

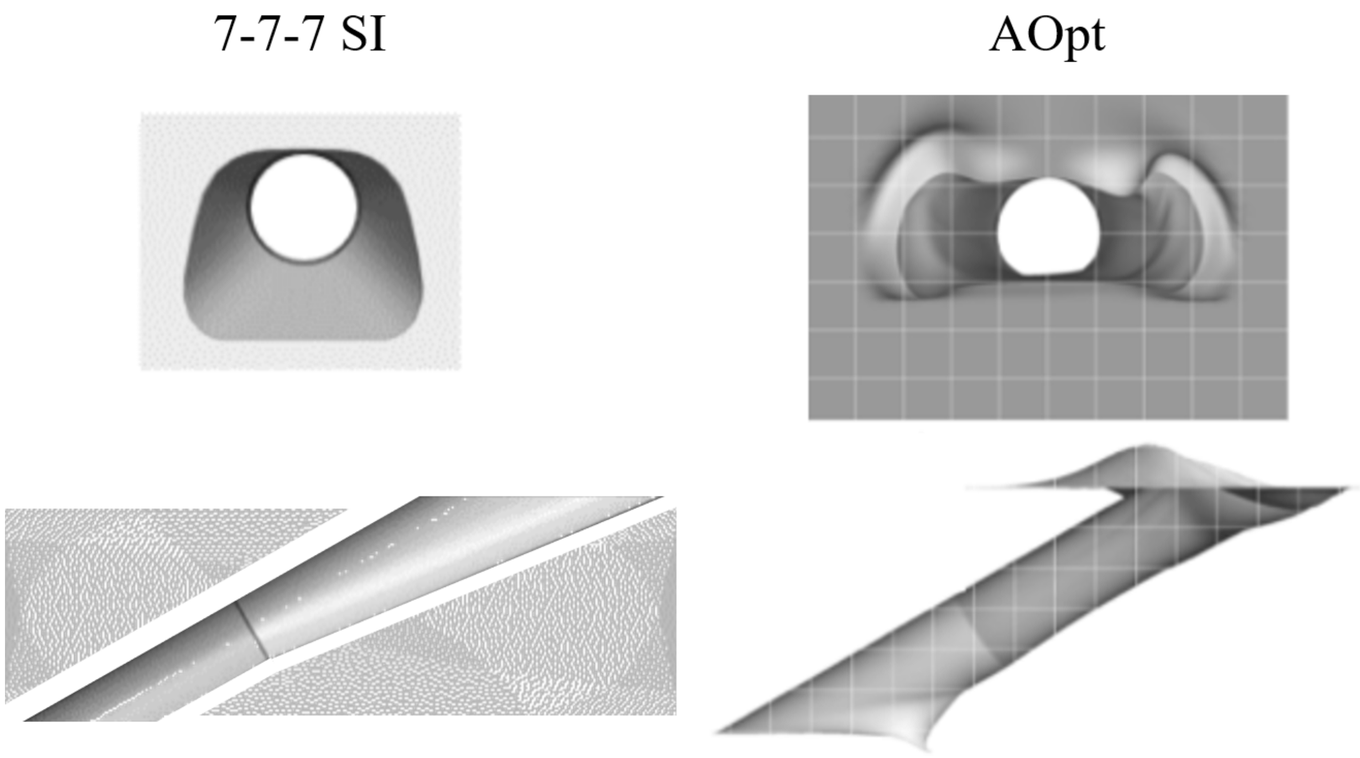


From Oliver et al. (2019)

Objectives of the study

- Characterize the dependence of film cooling performance on mainstream Mach number, Ma_{∞}, for shaped holes.

- Compare the cooling performance for an adjoint optimized hole geometry (AOpt) developed in previous studies at TTCRL[1] with a baseline 7-7-7 SI hole[2].



[1]Jones et al. (2021)
[2]Schroeder and Thole (2021)

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Establishing metric for film effectiveness for compressible flows: four definitions of adiabatic effectiveness were compared

Stagnation Definition

$$\eta^{o} = \frac{T_{\infty}^{o} - T_{aw}}{T_{\infty}^{o} - T_{c}^{o}}$$

Recovery Definition (mainstream only)

$$\eta^{r,\infty} = \frac{T_{\infty}^{r} - T_{aw}}{T_{\infty}^{r} - T_{c}^{o}}$$

Mass Fraction Definition (PSP)

$$\eta^{\chi} = \frac{C_{\infty} - C_{aw}}{C_{\infty} - C_{c}}$$

Recovery Definition (with coolant)

$$\eta^{r} = \frac{T_{\infty}^{r} - T_{aw}}{T_{\infty}^{r} - T_{c}^{r}}$$

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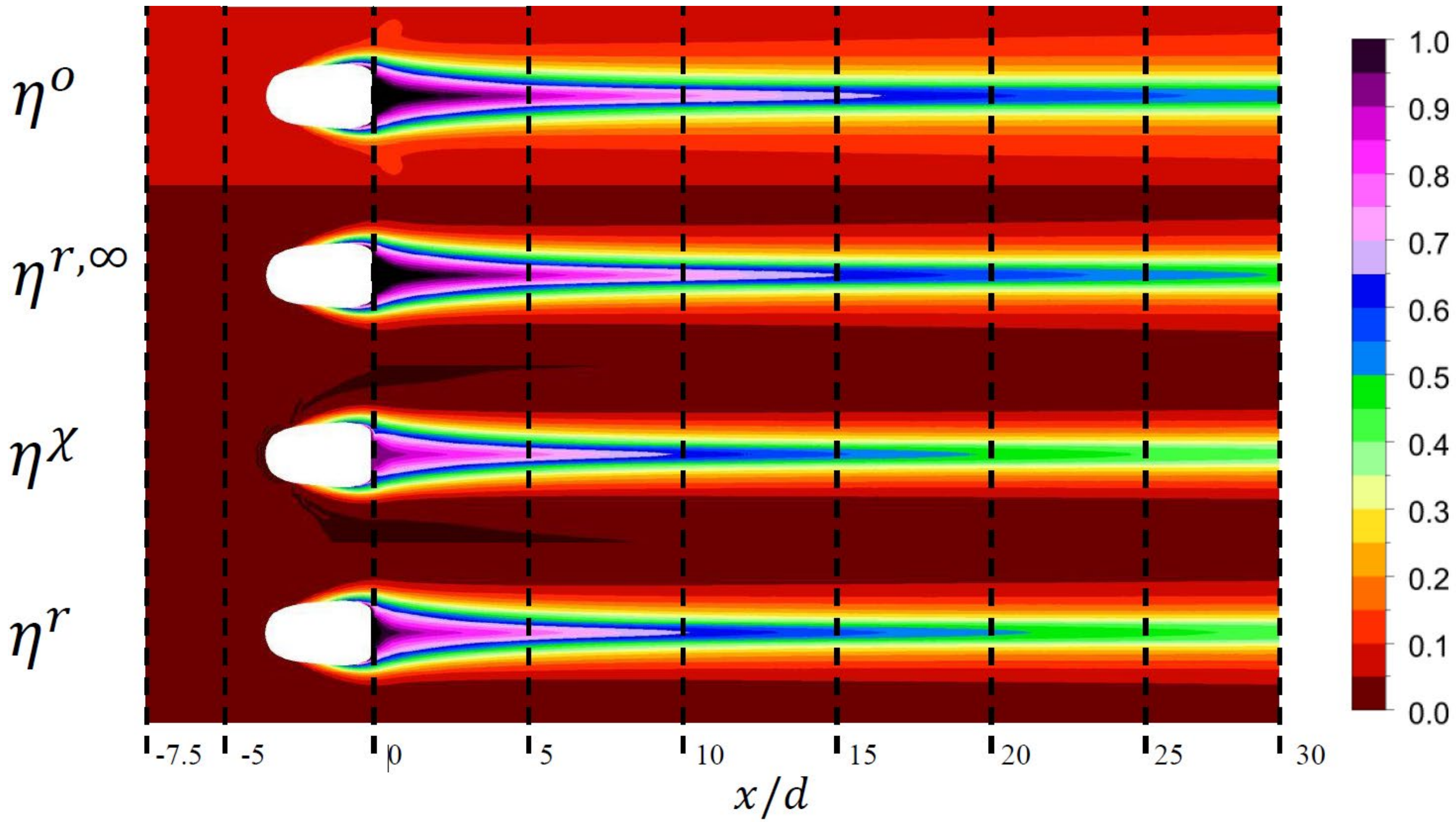
The choice of definition has a clear impact on the interpretation of the film cooling flow

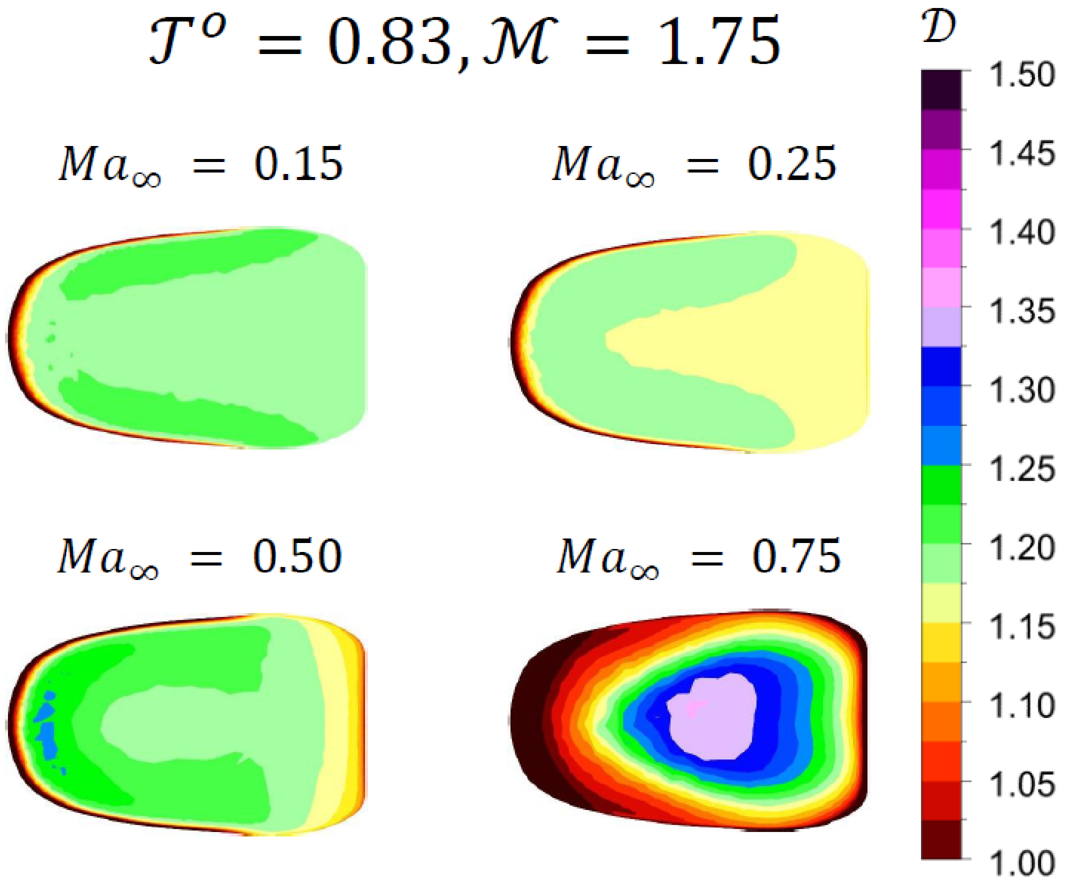
- The stagnation definition shows non-zero values outside the film cooling jet
- The displayed jet profile varies among the three remaining definitions, with η^{χ} and η^{r} being the most similar.

$\mathcal{T}^{o} = 0.83, \mathcal{M} = 1.75, Ma_{\infty} = 0.75$



For high Mach numbers, the definition of coolant density ratio is unclear

- Incompressible film cooling flows observe relatively constant hole exit density, where the density ratio is usually defined
- For incompressible flows, density ratio is analogous to temperature ratio by the ideal gas law, as the hole exit pressure is equivalent to the mainstream pressure.
- These conventions are clearly inaccurate for high-speed flows. Stagnation temperature ratio should be used as an analog to density ratio.



Local hole exit plane density ratio of coolant to mainstream gas from RANS simulations

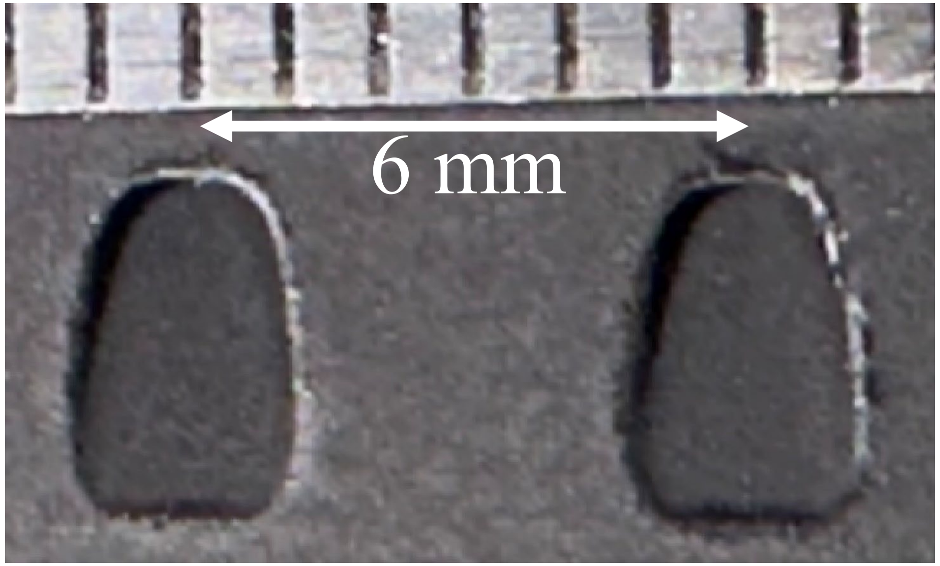
Measurement Range and Test Conditions

- **Measurement Area:**
- **Center 4 film cooling holes with *P/D* = 5.5**
- ***x/D* = 5 to 20**
- ***z/D* = -11 to 11**

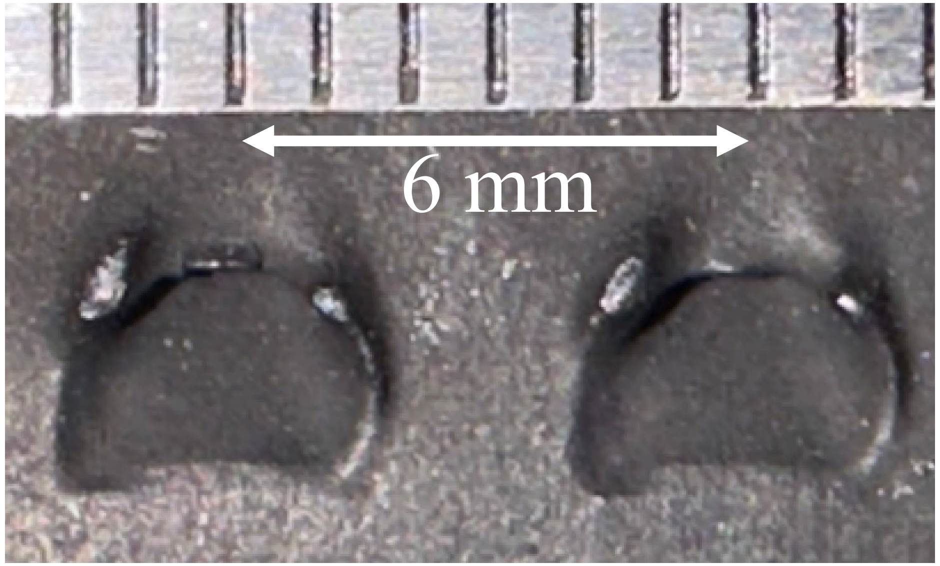
Ma_∞	0.25	0.50
T_∞^o	307 K	315 K
T_c^o	256 K	263 K
$\mathcal{T}^o = T_c^o/T_\infty^o$	0.83	0.83
Re_d	6,000	11,000
$\mathcal{M}$	0.61 – 2.9	0.54 – 2.9
$\mathcal{P}$	1.02–1.54	1.05 – 1.86

Test coupon fabrication using stereolithography (SLA) printer.

7-7-7 Hole Outlet



AOpt Hole Outlet



Engine scale holes were constructed with good precision.

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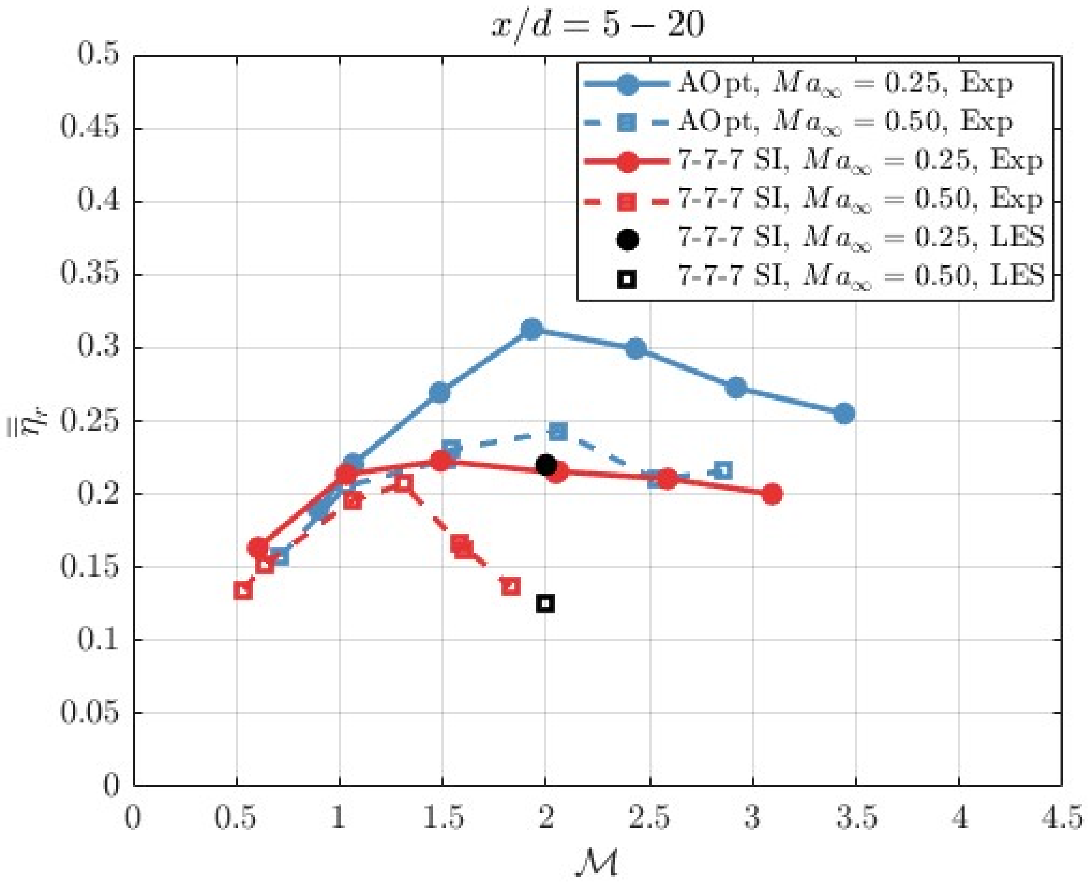
Experimental measurement of adiabatic effectiveness, $\bar{\bar{\eta}}_r$, for mainstream Mach numbers of 0.25 and 0.50 for 7-7-7 and AOpt holes

- Similar performance for $\mathcal{M} < 1$ for all Ma_∞
- For $\mathcal{M} > 1$, significant $\bar{\bar{\eta}}_r$ degradation occurs between $Ma_\infty = 0.25$ and 0.50.
  - Peak performance of the AOpt hole drops by 20%.
  - The 7-7-7 hole's performance experiences a steep decline for $Ma_\infty = 0.50$ which does not occur for $Ma_\infty = 0.25$.
- Adiabatic Effectiveness values predicted with LES computational simulations with the 7-7-7 SI holes matched well with experimental values.



LES study by Oliver et al. (2019) study was conducted at $\mathcal{T}^o$ = 0.67

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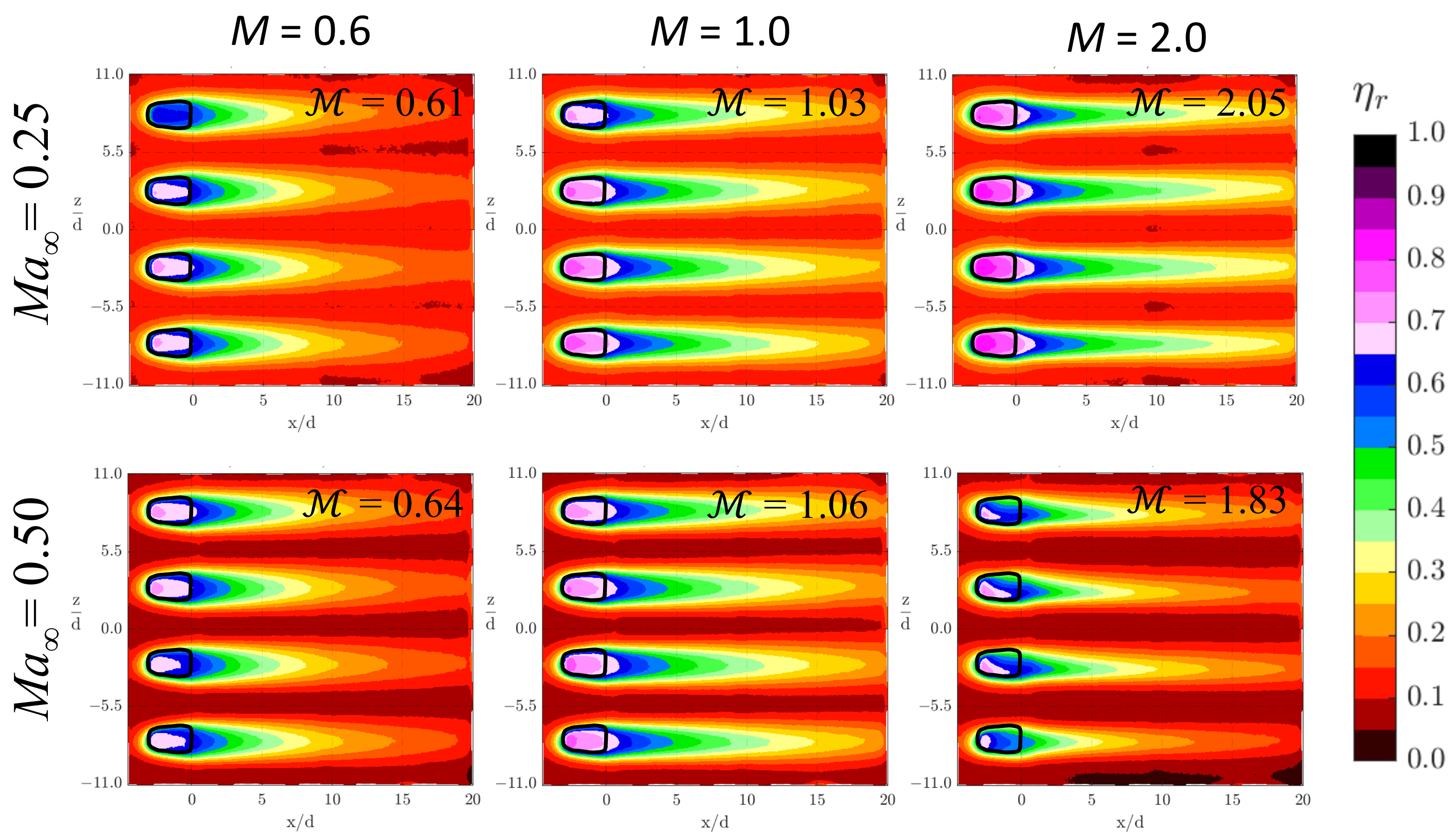
Contours of adiabatic effectiveness, η_r, for the 7-7-7 holes with mainstream Mach numbers of 0.25 and 0.50.

- Similar η_r distributions at $\mathcal{M} < 1$ at both Ma_∞
- For $\mathcal{M} = 2$, $Ma_\infty = 0.25$: Uniform coolant coverage.
- For $\mathcal{M} = 2$, $Ma_\infty = 0.50$: Jet profile narrows and biases toward bottom of hole. The results in significantly reduced laterally average film effectiveness. This skewness of the coolant jets at higher Mach number was also seen in the LES computational predictions



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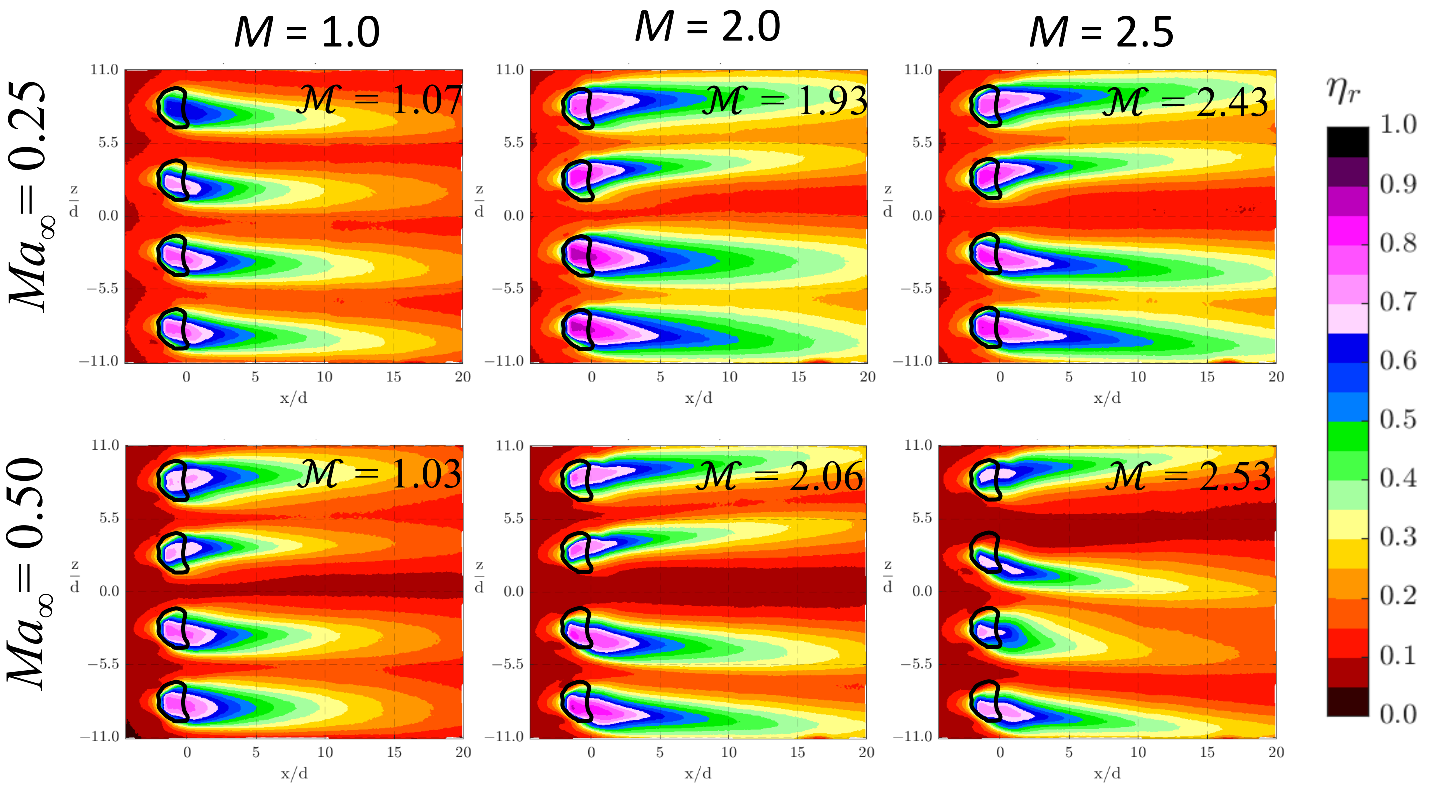
Contours of adiabatic effectiveness, η_r, for the AOpt holes with mainstream Mach numbers of 0.25 and 0.50.

- $Ma_\infty = 0.25$ features a broader distribution of coolant.
    - Likely results from the apparent broader coolant distribution at hole exit.
    - The reduced coolant spread at hole exit for $Ma_\infty = 0.50$ causes the significant decline in performance.
- Severity of jet biasing increases with Ma_∞ at constant $\mathcal{M}$
- Observed unsteadiness of jet biasing over large time scale.



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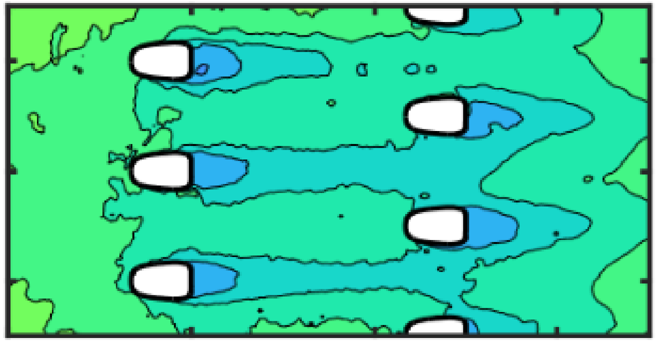
Conclusions

- There is a significant decrease in the maximum $\bar{\bar{\eta}}_r$ as Ma_∞ increases for shaped film cooling holes at $\mathcal{M} > 1$.
- Findings show that compressible effects are an important consideration in shaped hole film cooling studies.
- The AOpt geometry consistently outperforms the baseline 7-7-7 hole at $\mathcal{M} > 1$ when comparing data at the same Ma_∞.
- Future work will evaluate a broader scope of flow conditions and higher Ma_∞.

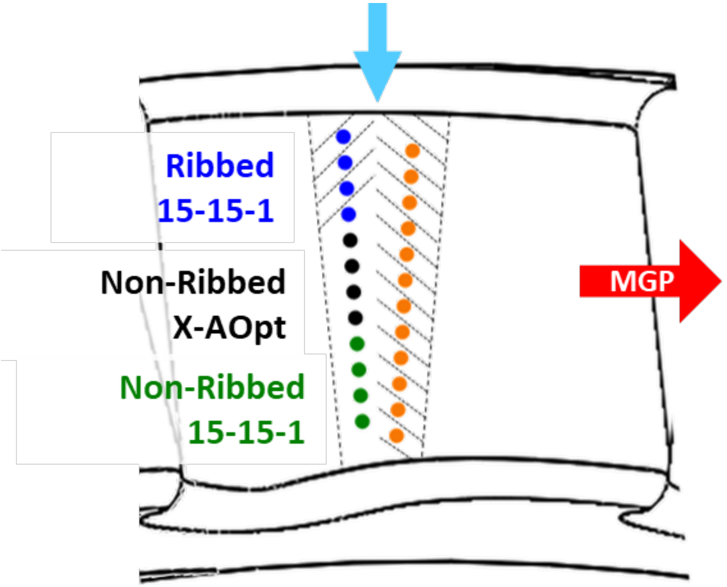
Integrated Turbine Component Cooling Designs Facilitated by Additive Manufacturing and Optimization

Nicholas Gailey, Emma Veley Karen A. Thole

This presentation will cover the impact of the feed channel shape and provide results from three holes integrated into the NExT vane

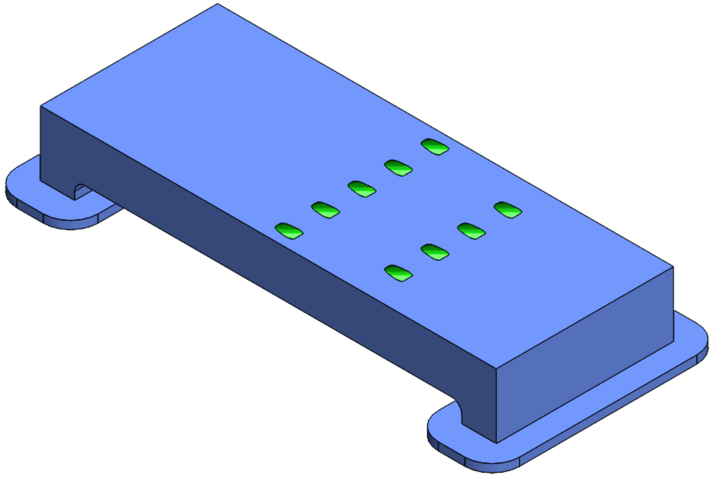


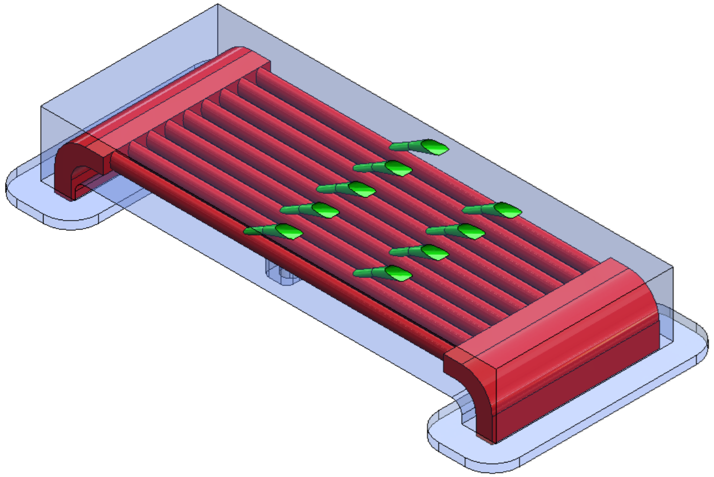
Coolant Supply Channel Shapes Effects on Film Cooling



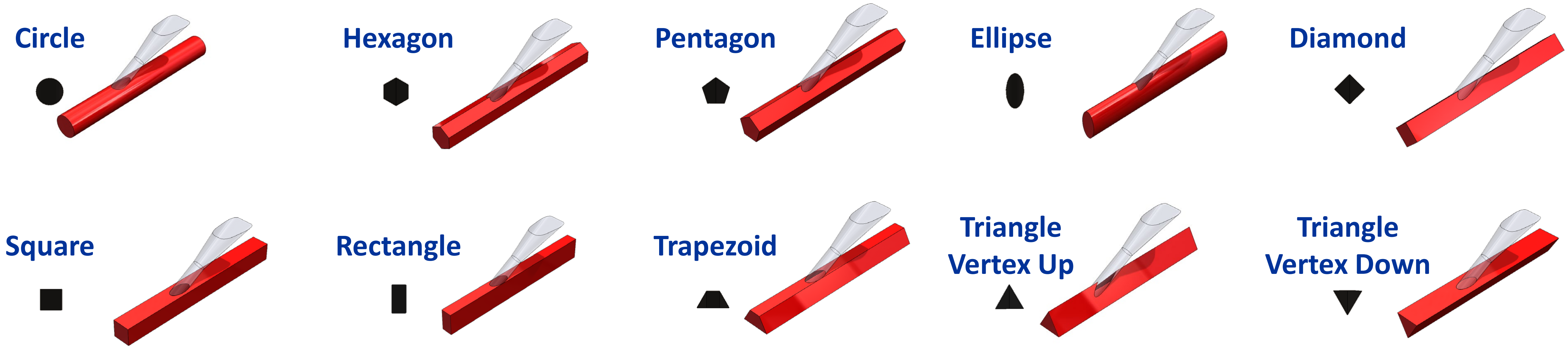
Comparison of Different Hole Shapes in the NExT Vane

Ten different channel shapes with a constant perimeter were used to feed individual 7-7-7 holes





D_{777} = 0.762 mm (0.03")



The perimeter was maintained between different channel shapes (p = 4.79 mm)

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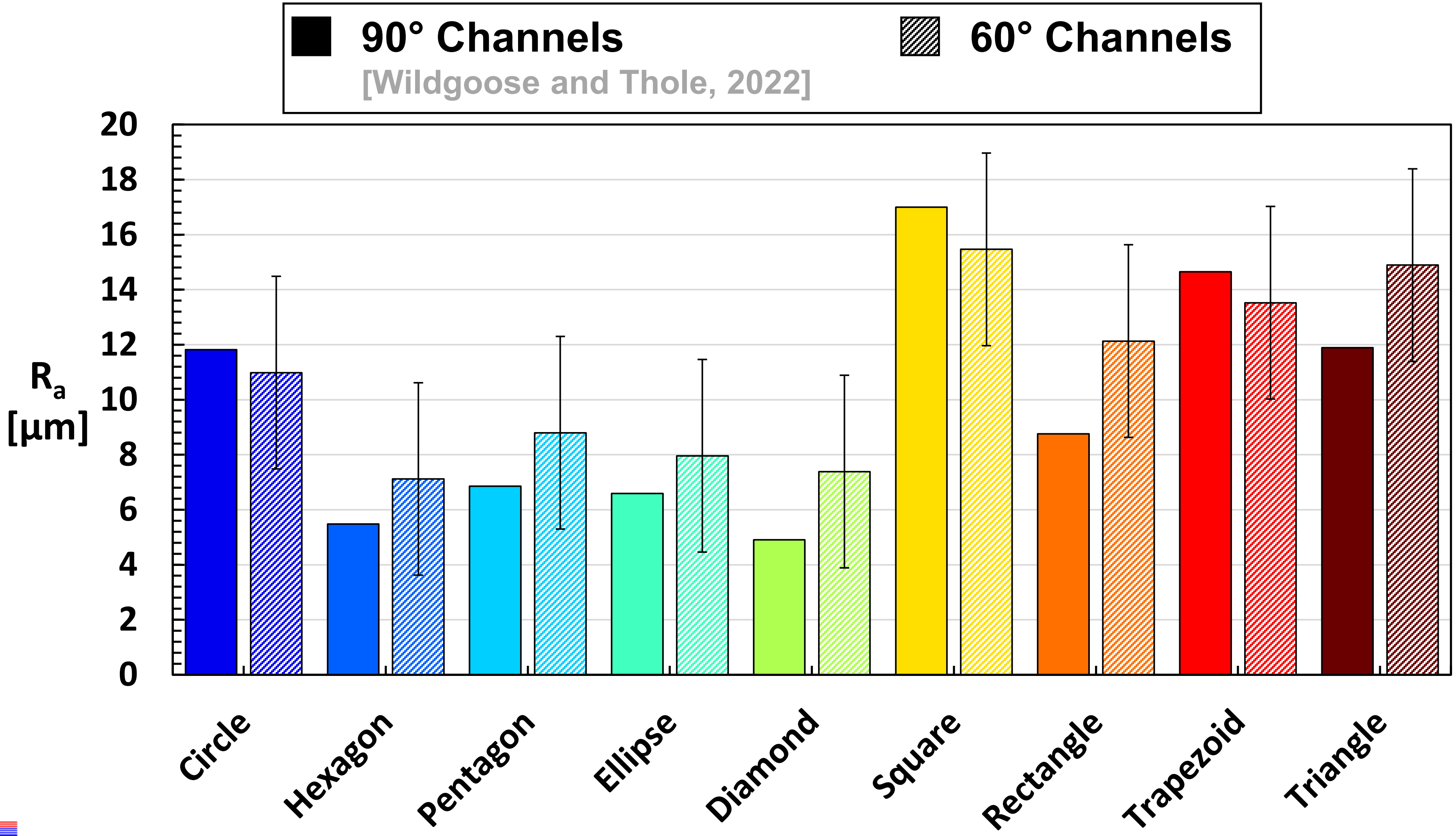
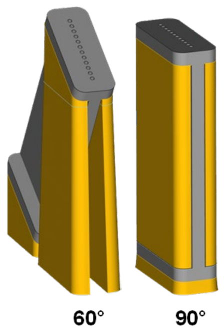
The area-weighted average roughness for these shaped channels built at 60° within the measurement uncertainty of those built at 90°





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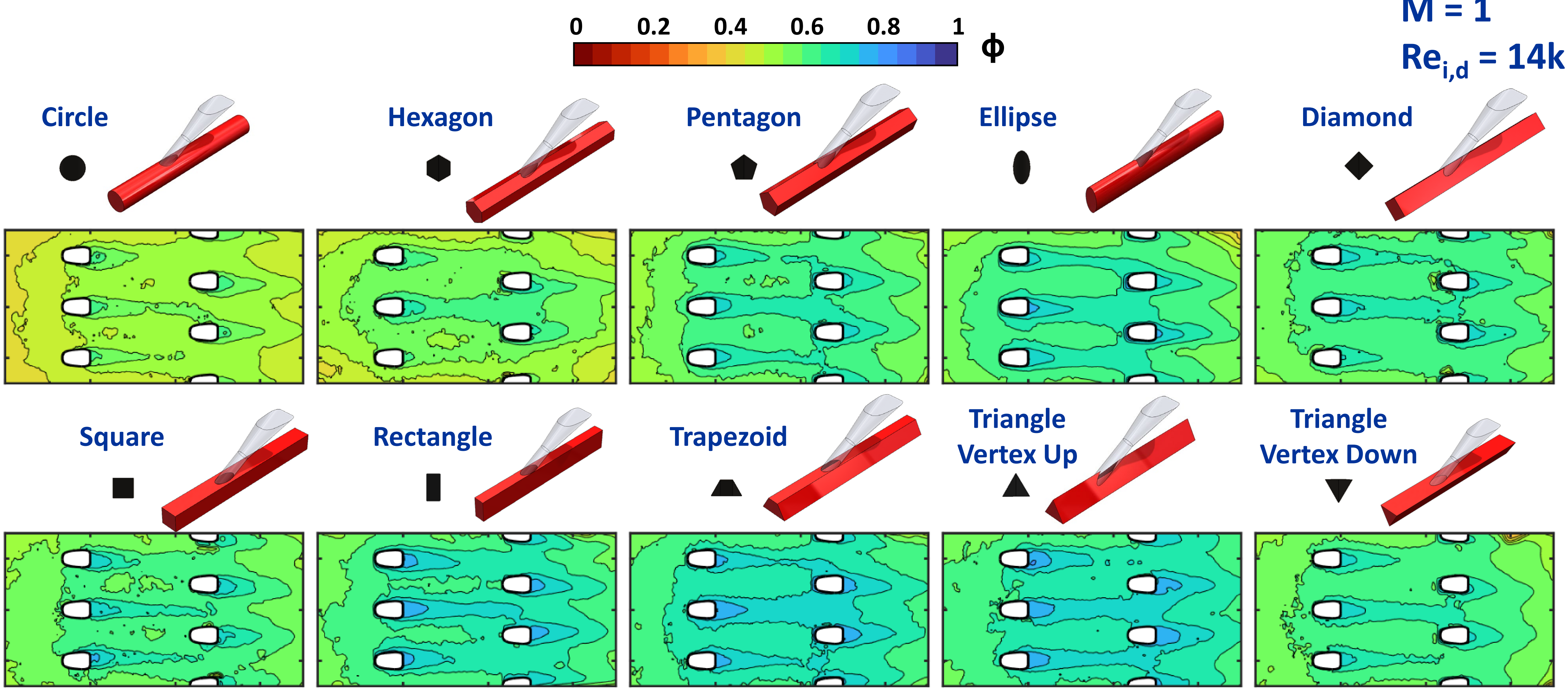
Of the designs tested the Circle had the lowest ϕ and the Trapezoid and Triangle – Vertex Up had the highest ϕ



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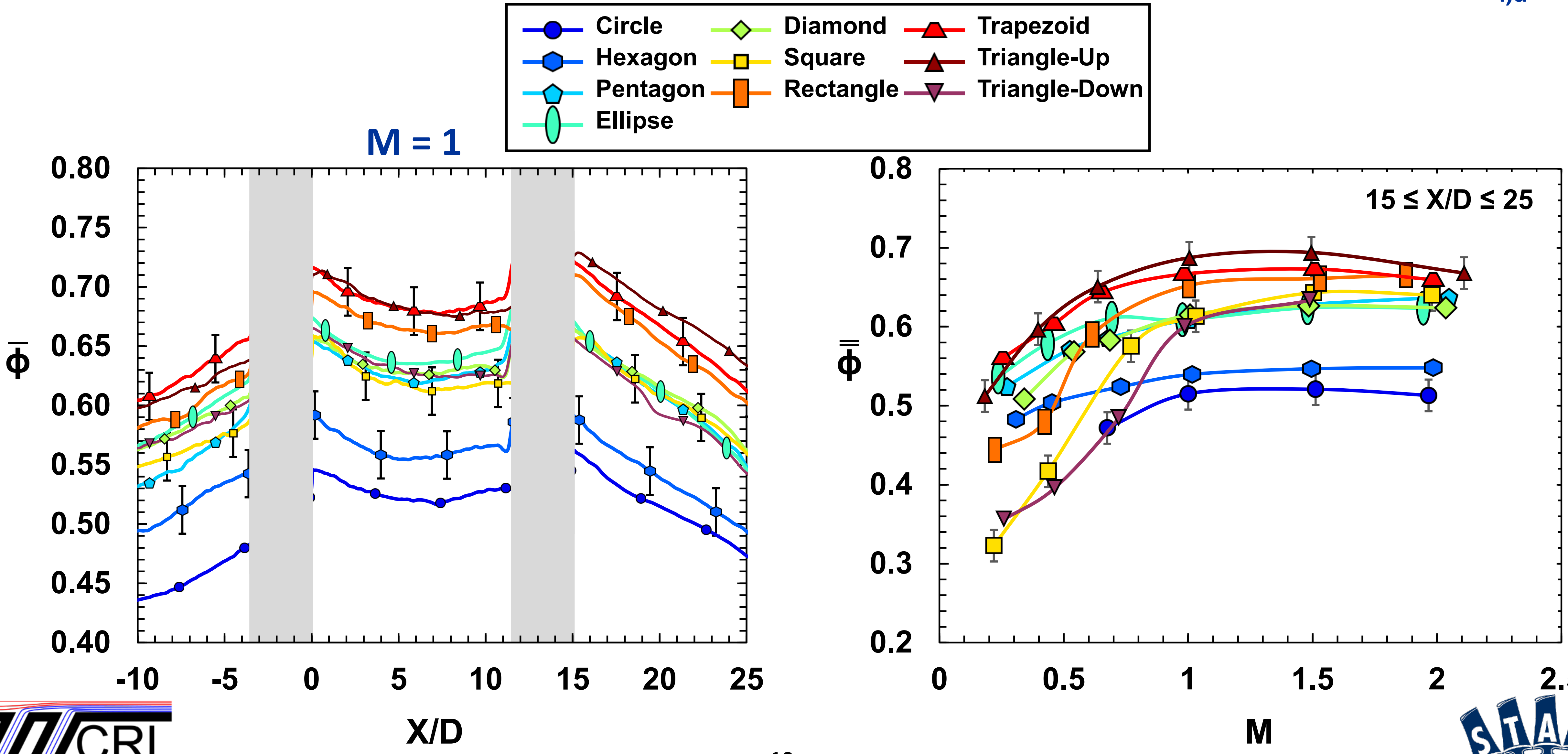
The Trapezoid and Triangle – Up have the highest overall effectiveness of all the channel shapes across the tested range of blowing ratios

$Re_{i,d} = 14k$



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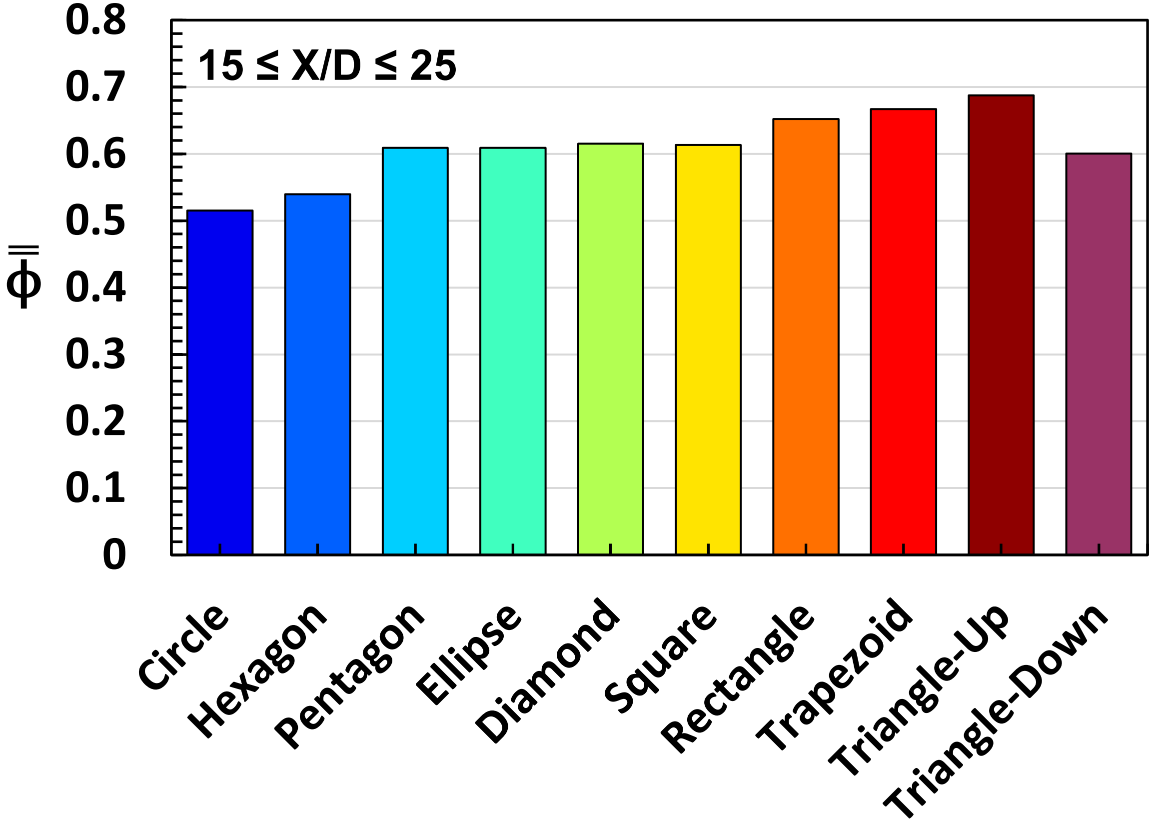
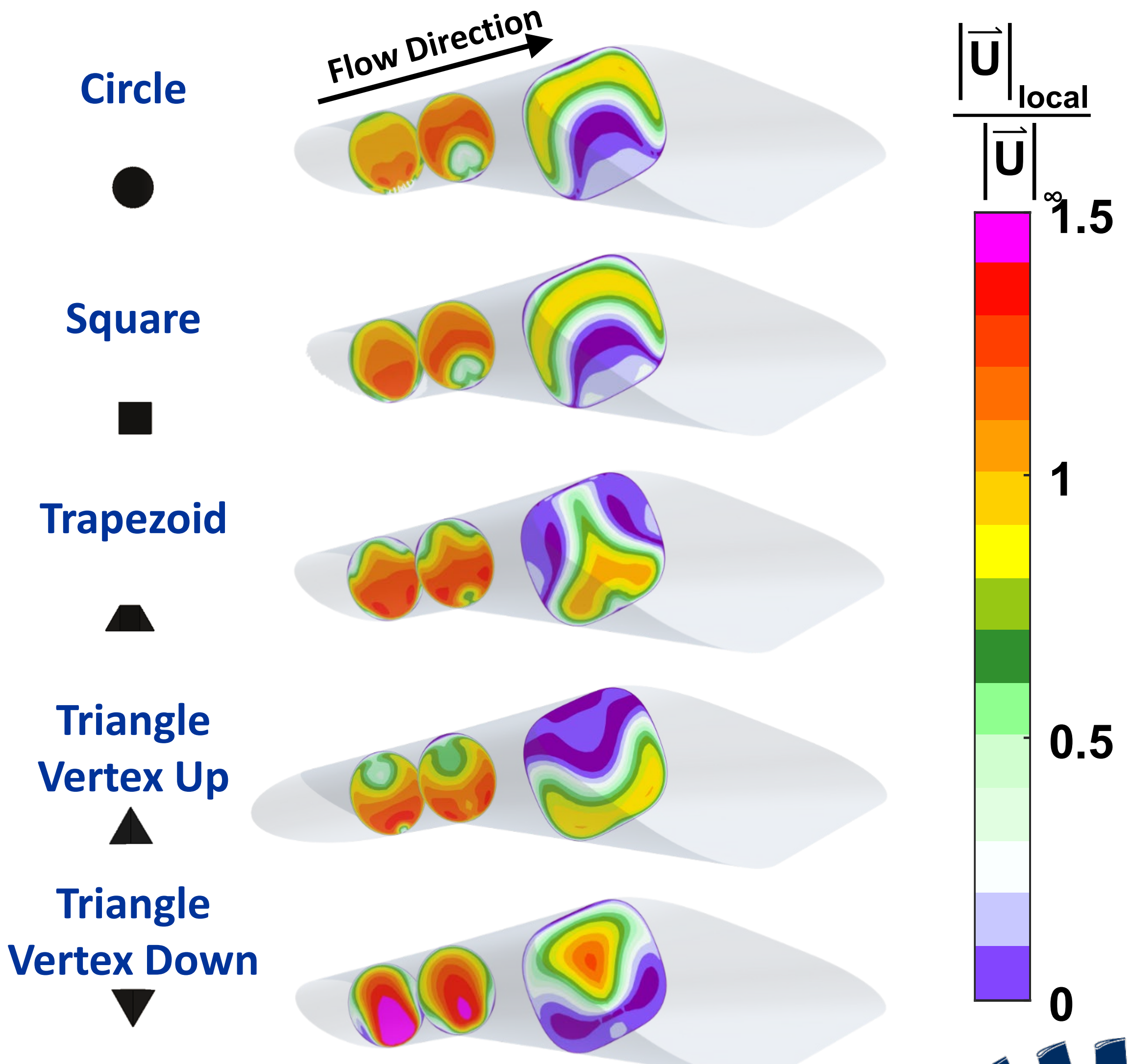
Shapes that result in higher velocities near the bottom of the hole have relatively higher overall effectiveness

Experimental

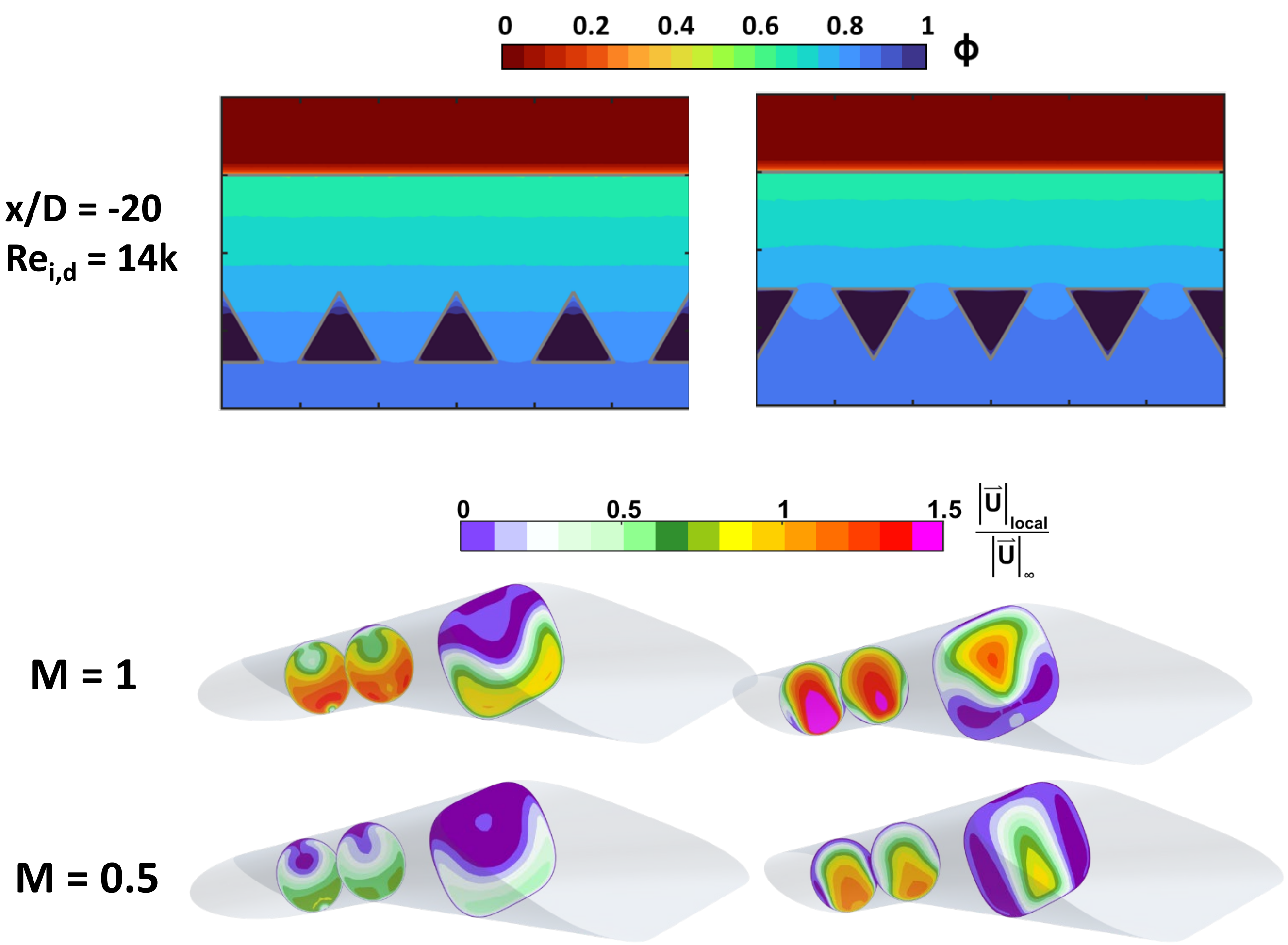


Computational

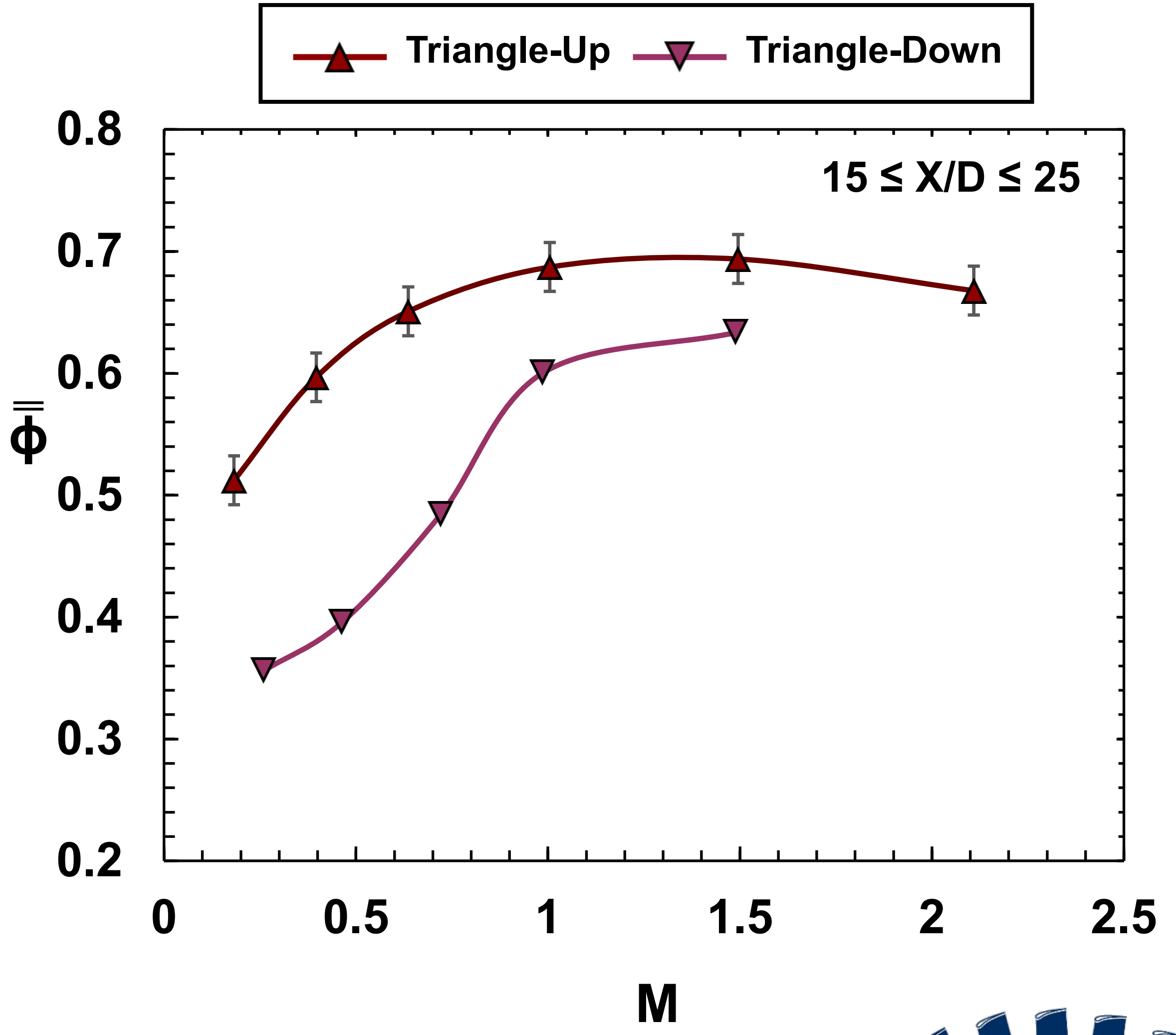


Triangle – Up has a surface exposed to cooler fluid in the supply with film-cooling flows that favor the bottom wall of the hole both leading to better overall effectiveness

Computational



Experimental



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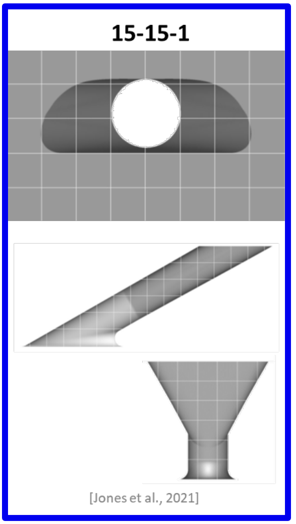
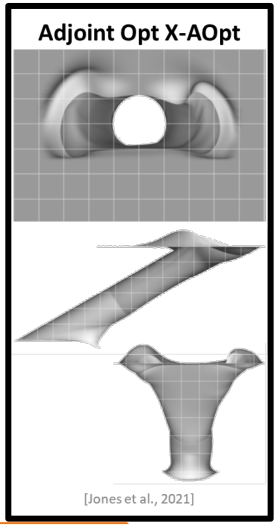
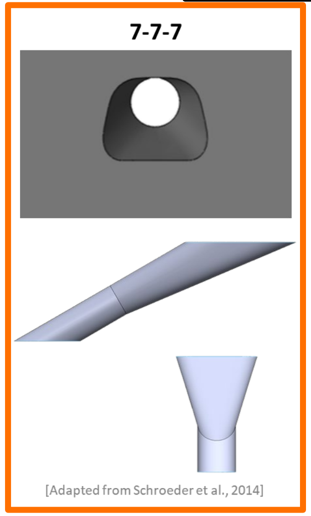
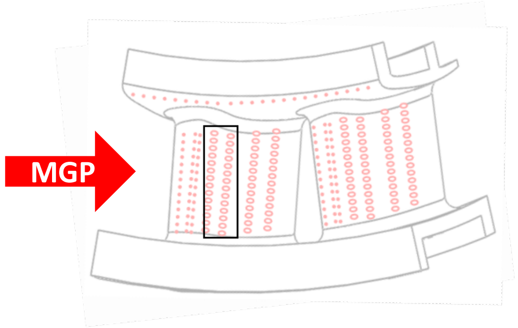
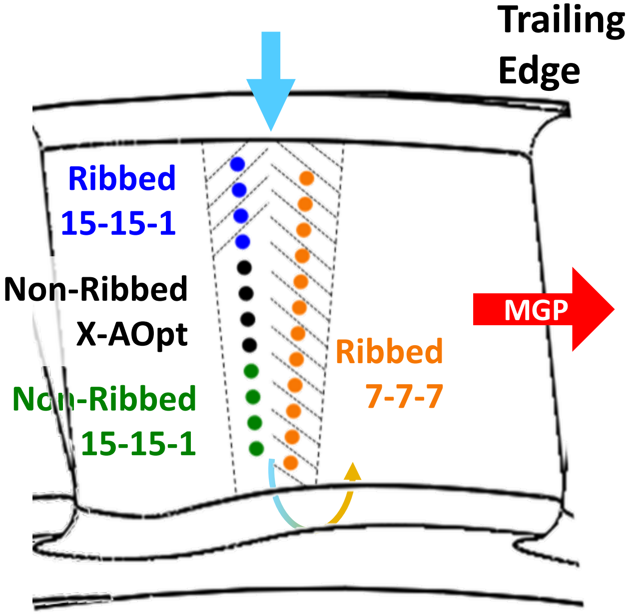
The NExT vane was used to compare four different cooling hole designs

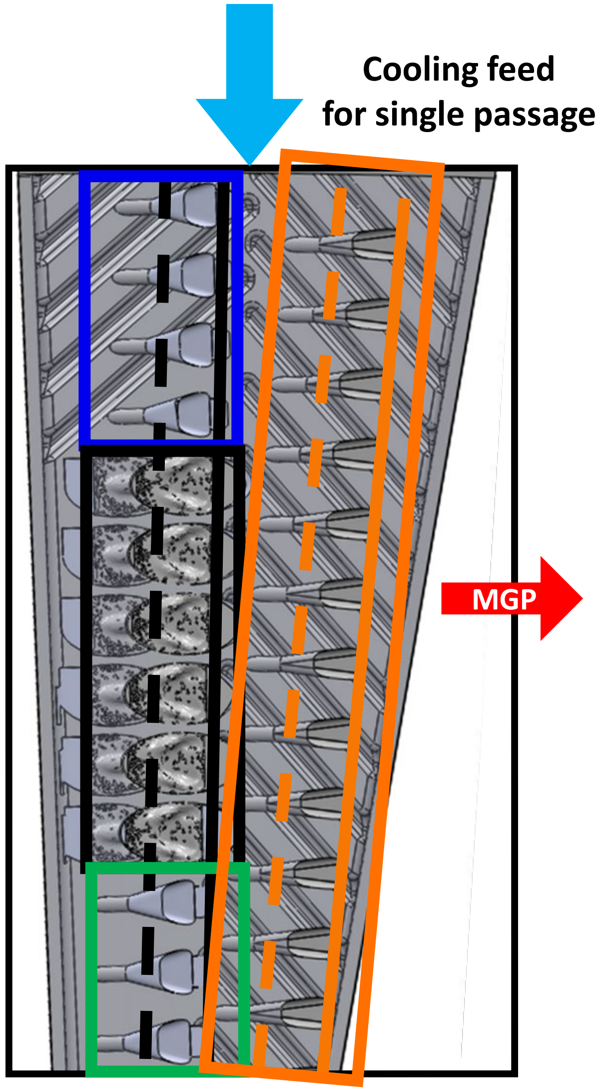


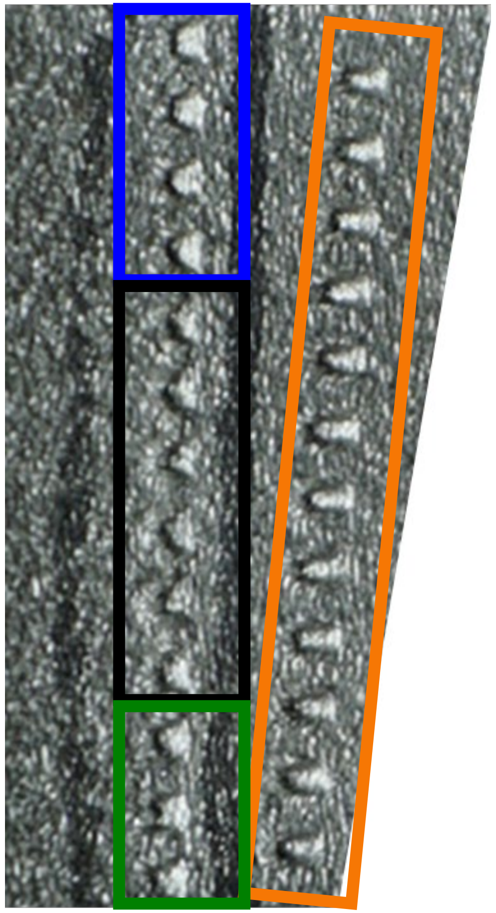












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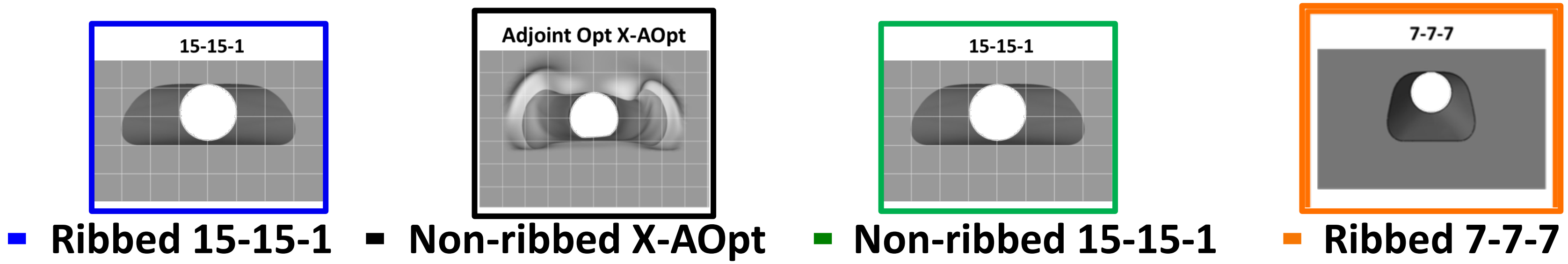
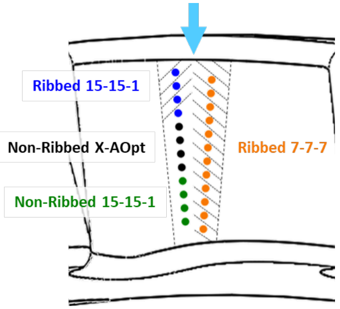
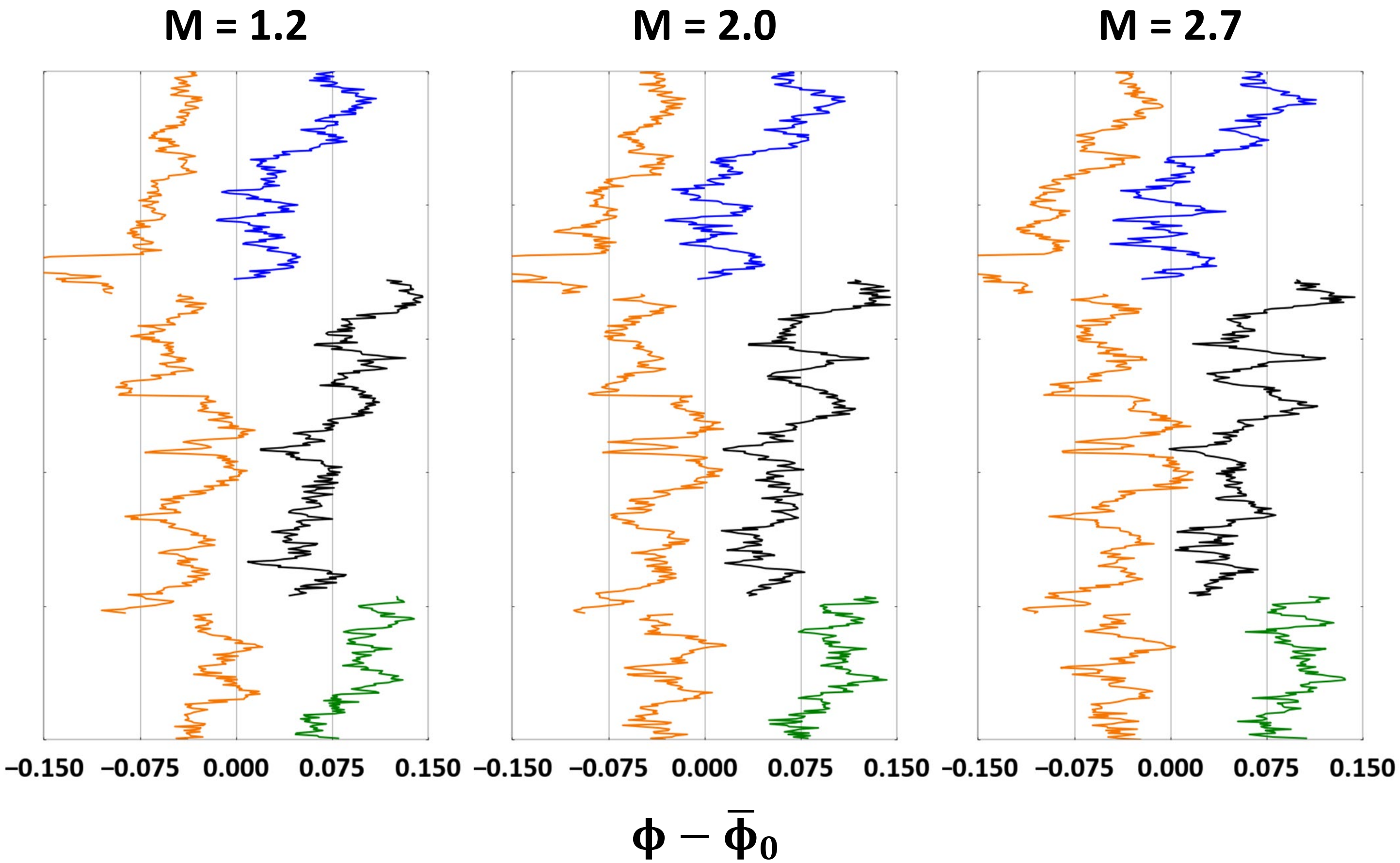
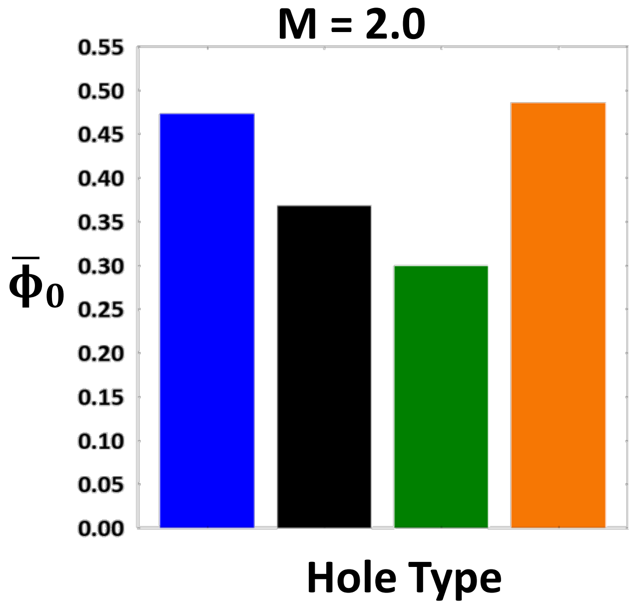
The non-ribbed 15-15-1 cooling hole showed the highest increase in overall cooling effectiveness with respect to upstream conditions

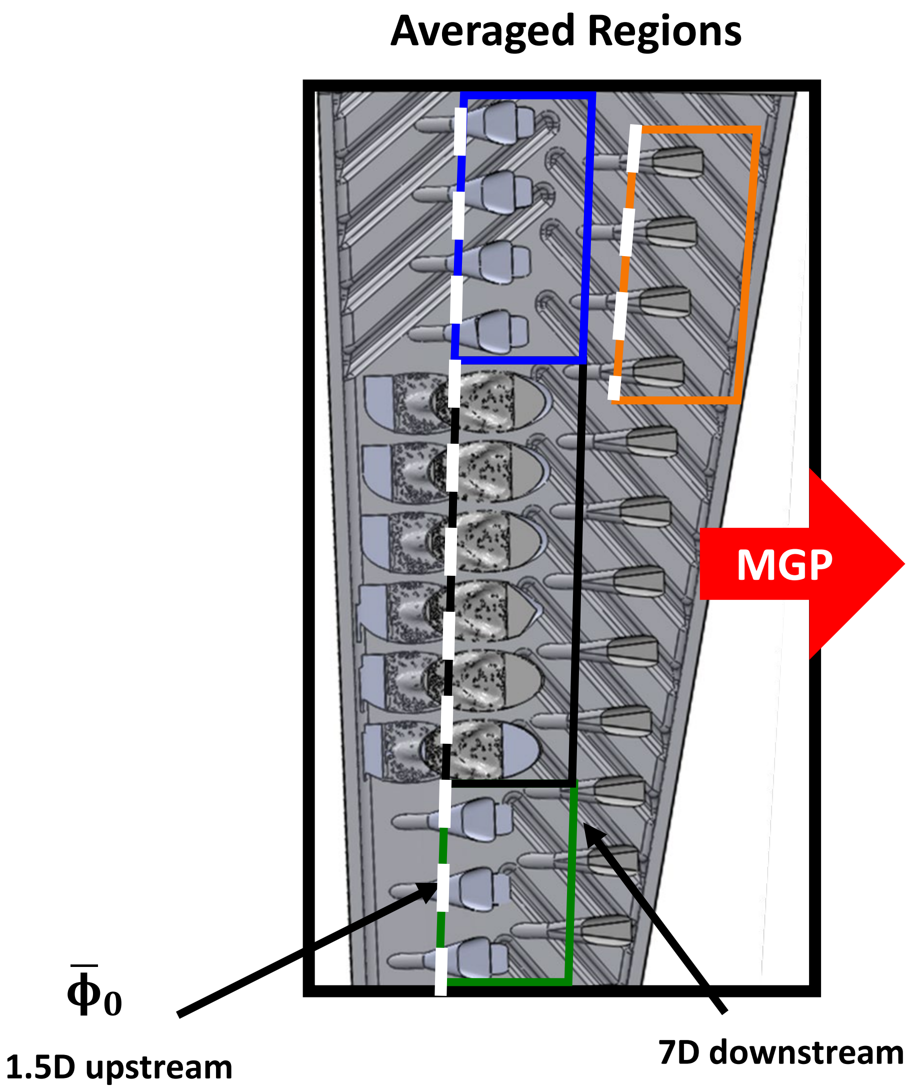


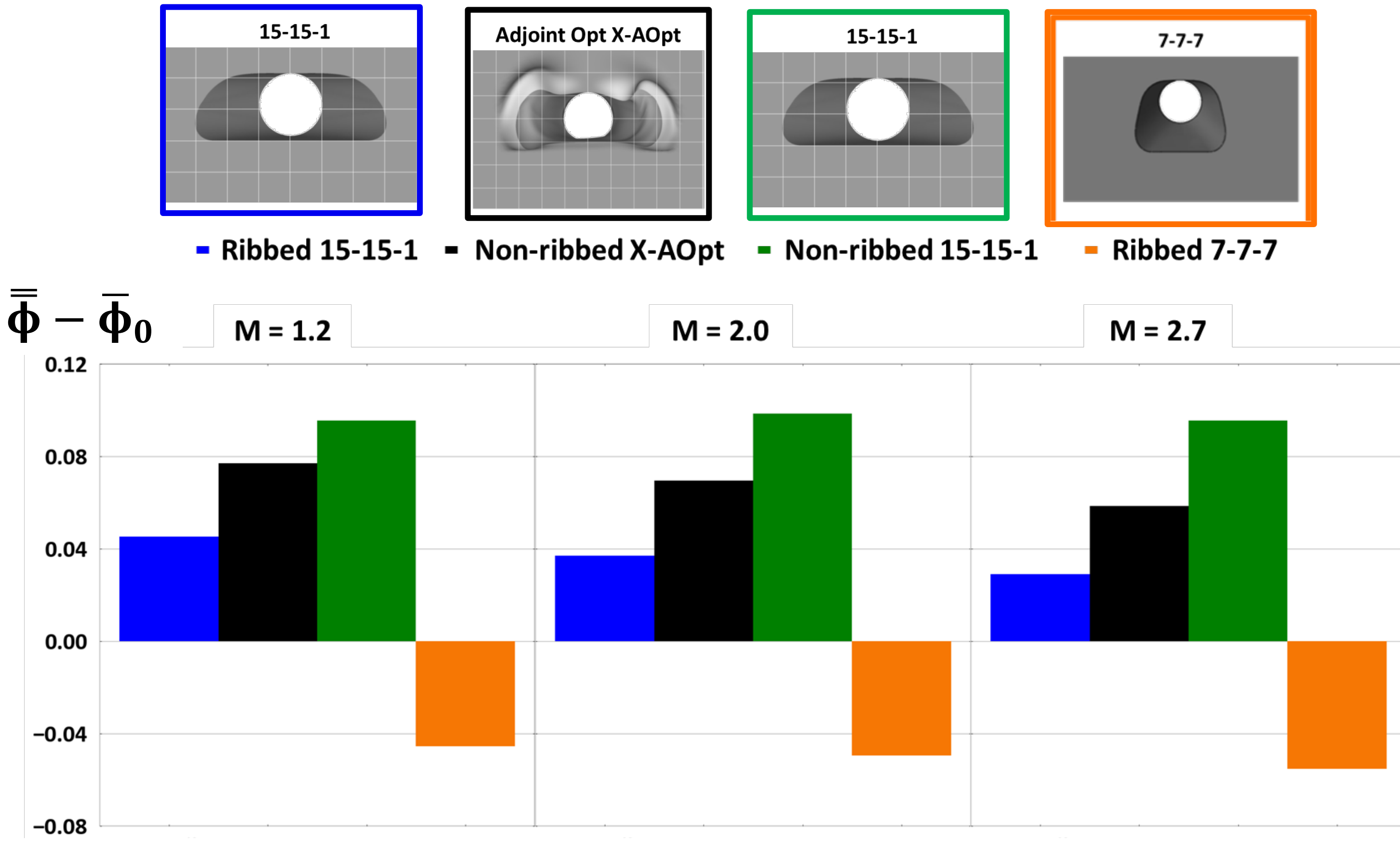






Except for the 777 hole, all cooling holes showed an area-averaged improvement to overall effectiveness with the 15-15-1 having the highest





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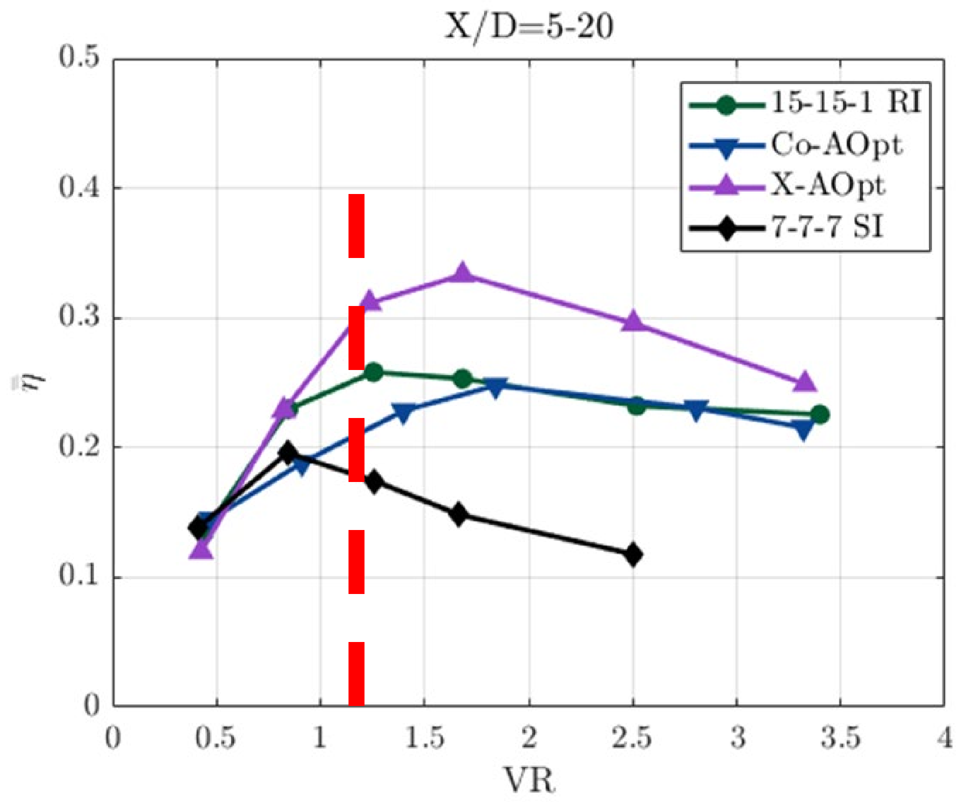
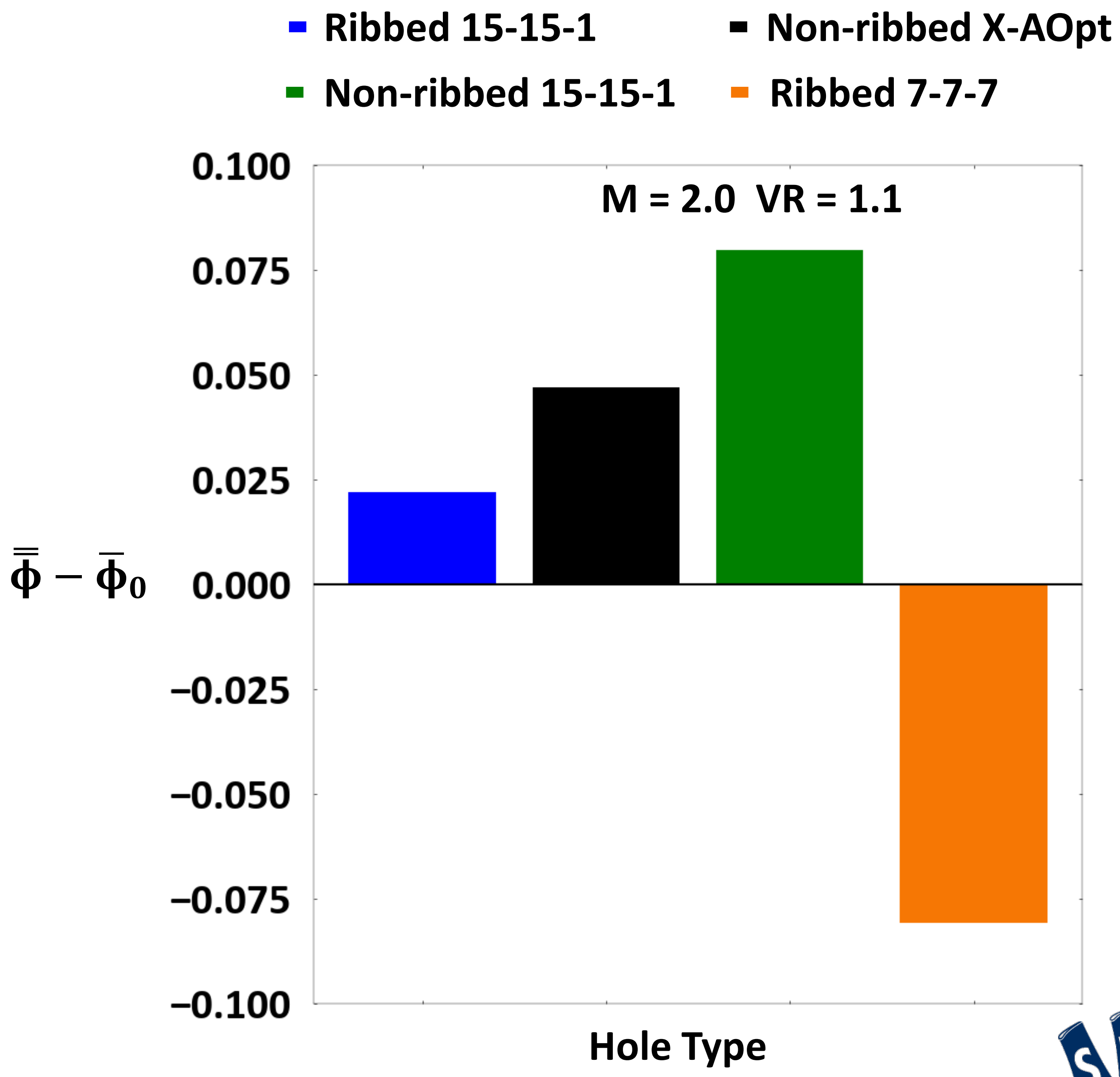
Area averaged effectiveness values show the group of 7-7-7 holes underperform when compared to the upstream 15-15-1 holes at similar spans



Daniel Gutierrez, Christopher Yoon, Michael T. Furgeson, David G. Bogard
GT2022-83436



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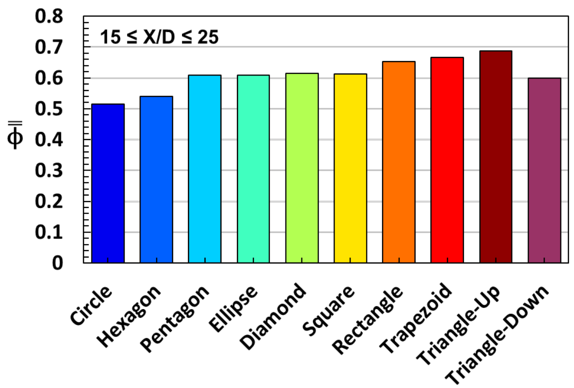
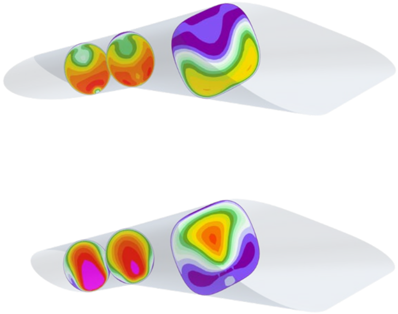
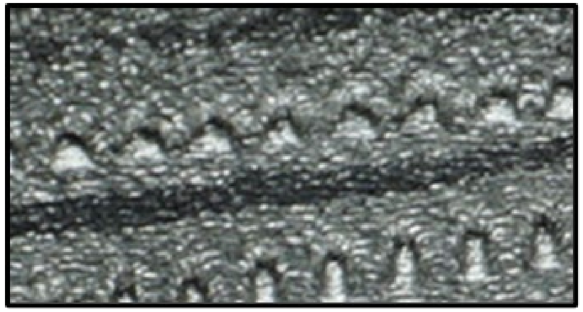
The shape of the feed channel affects the flow through the cooling holes and consequently the film cooling performance



The experimental results showed that the overall cooling effectiveness was dependent upon the feed channel geometry



The secondary flow structures through the channel can cause the flow through the holes to attach to different sides of the diffuser



Film-cooling holes were integrated into the NExT vane to compare performance showing good cooling from the 15-15-1 hole

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