University Turbine Systems Research
Project Review Meeting

Nov. 8-10, 2021

Integrated Turbine Component Cooling Designs Facilitated by Additive Manufacturing and Optimization

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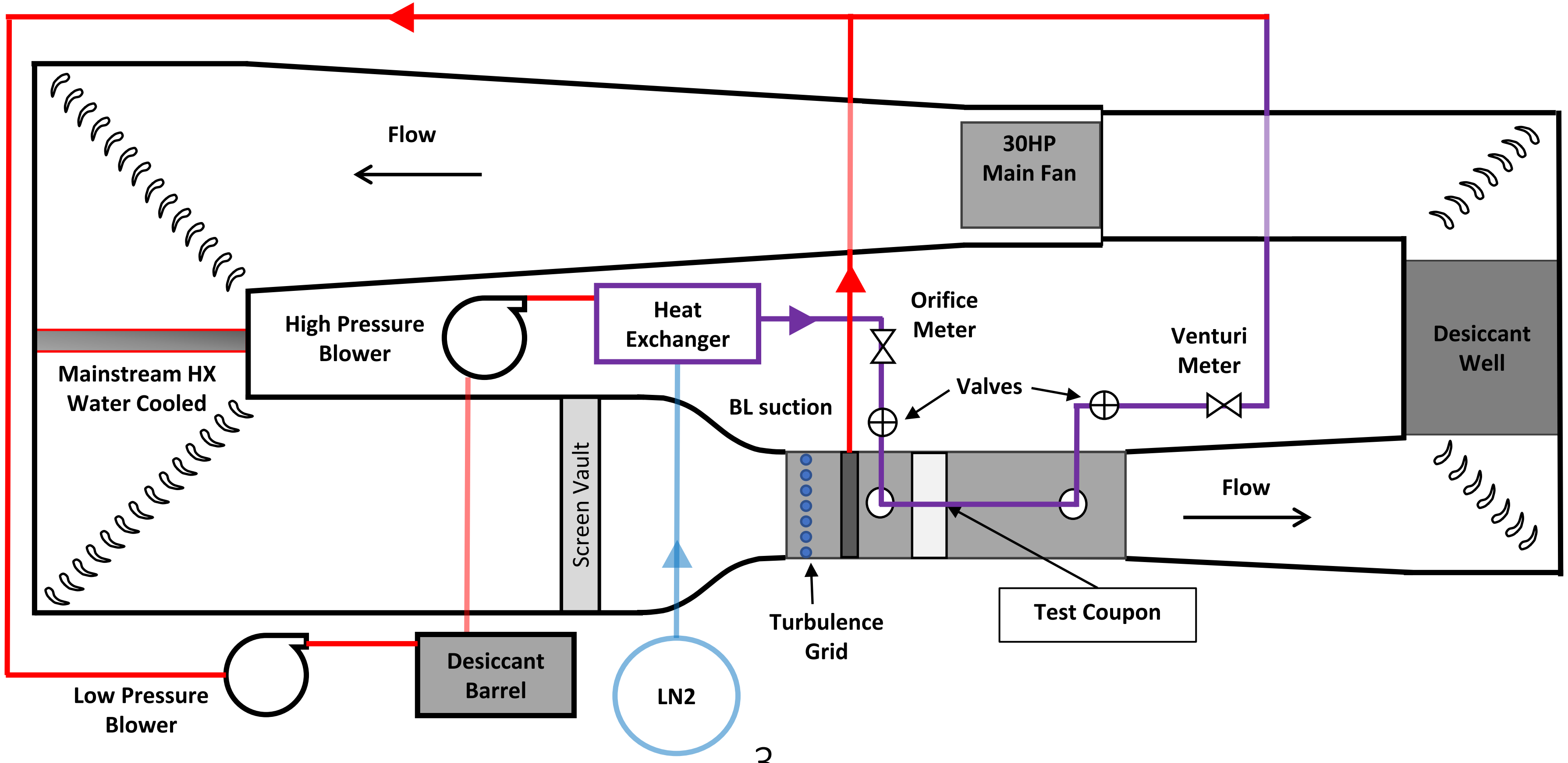
Objectives

- Develop an experimental test facility to determine overall cooling effectiveness and adiabatic effectiveness for a variety of combined film cooling and internal cooling configurations.
- Evaluate the performance of the 15-15-1 RI shaped film cooling hole (previously determined to be optimum for film cooling effectiveness) with:
  - A co-flow internal cooling channel with and without rib turbulators
  - With and without TBC (Thermal barrier coating).
- Evaluate the accuracy of RANS CFD predictions for these cases.
- Compare the performance of "as built" (using engine scale, metal AM builds) shaped holes to the "as designed" holes. The holes tested were designed to mitigate the effects of roughness caused the by the AM builds.

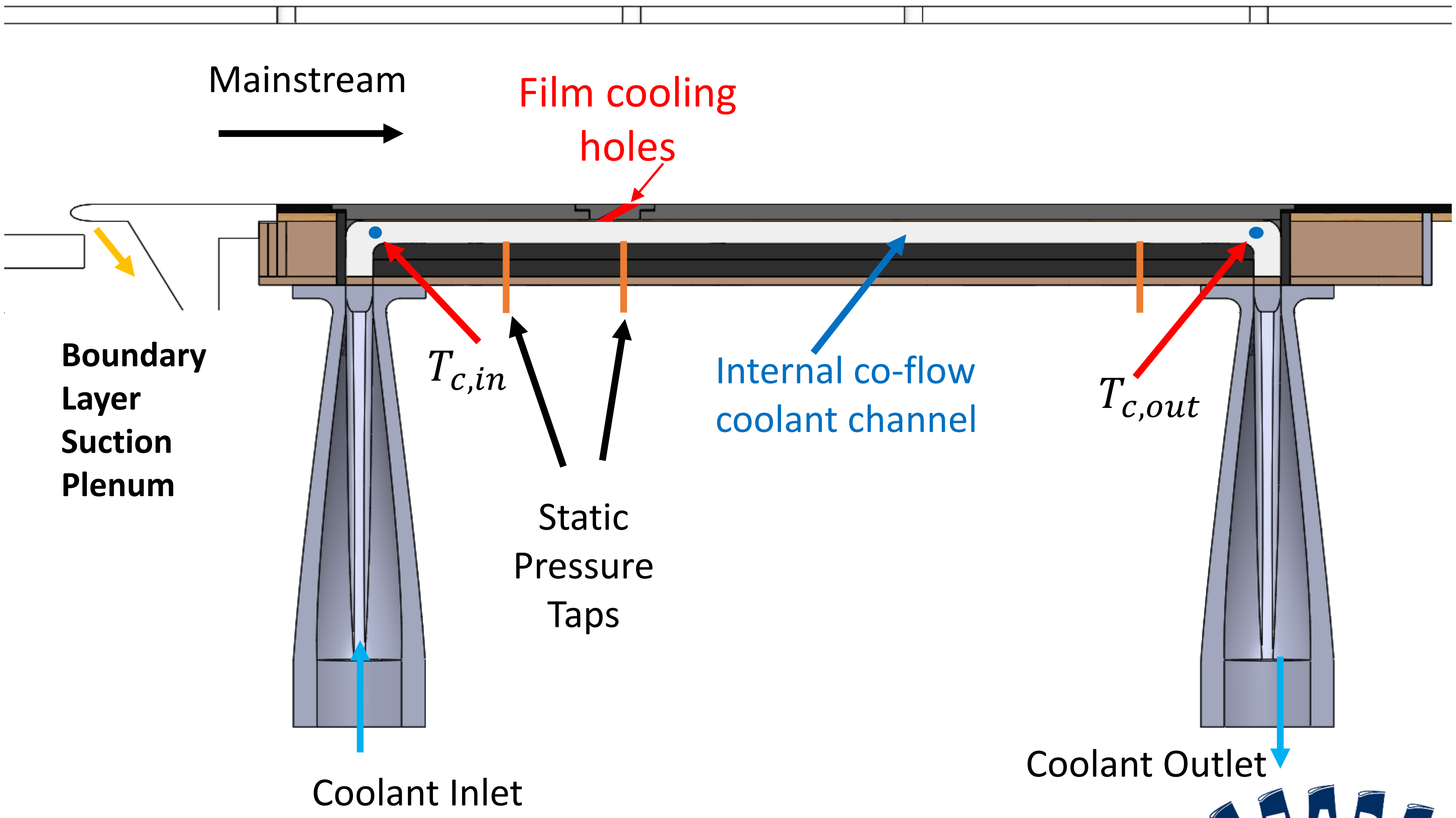
Experiments utilized UT Austin low-speed flat plate wind tunnel facility

- Closed circuit wind tunnel with very low humidity air.
- Coolant flow circuit is cooled with LN_2 to obtain high density ratio coolant flows.

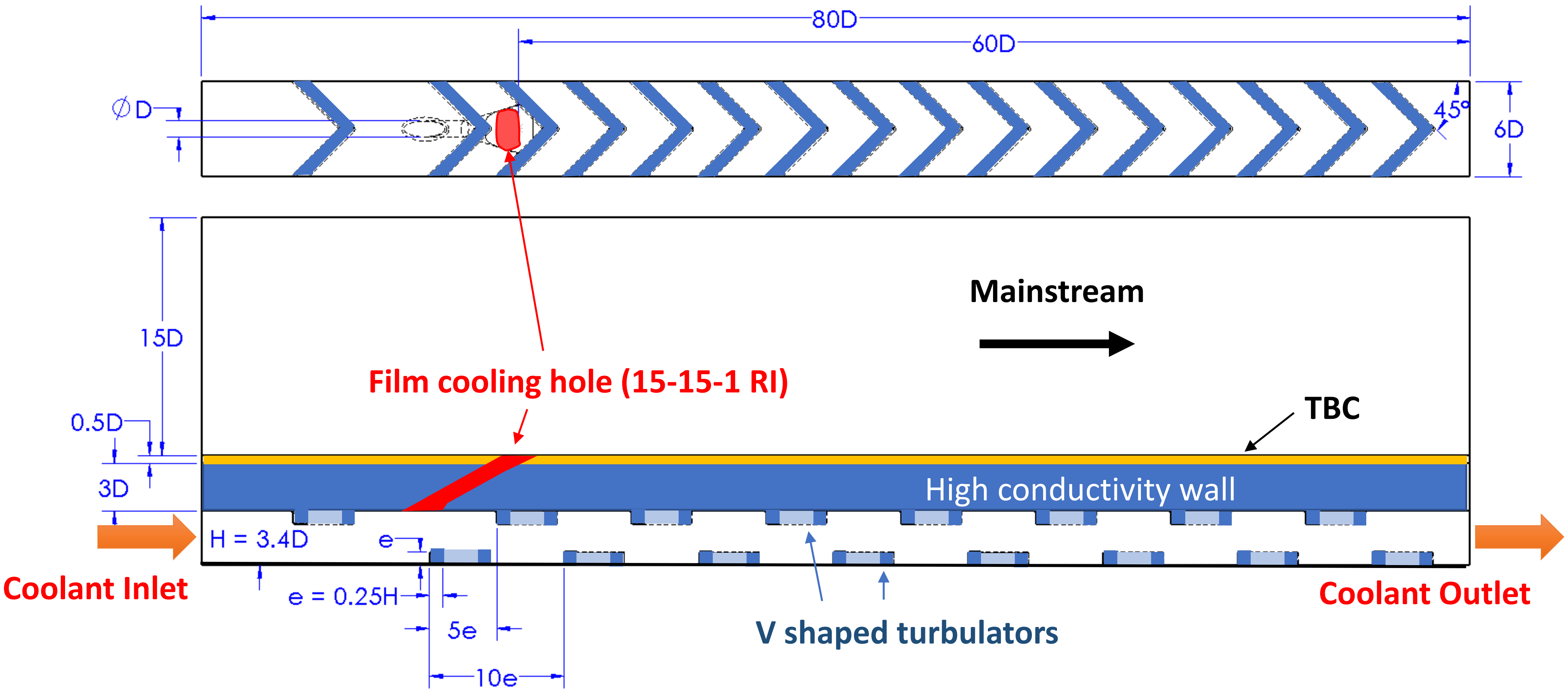


A new test section was installed which enables studies of overall and adiabatic film cooling effectiveness performance for various film cooling hole and internal cooling configurations.

- Turbulence grid upstream (Tu = 5%).
- Density ratio DR = 1.2
- Two test surfaces are used:
  - “Adiabatic” foam
  - Matched-Biot number Corian



Configuration used to evaluate combined internal cooling and film cooling performance.

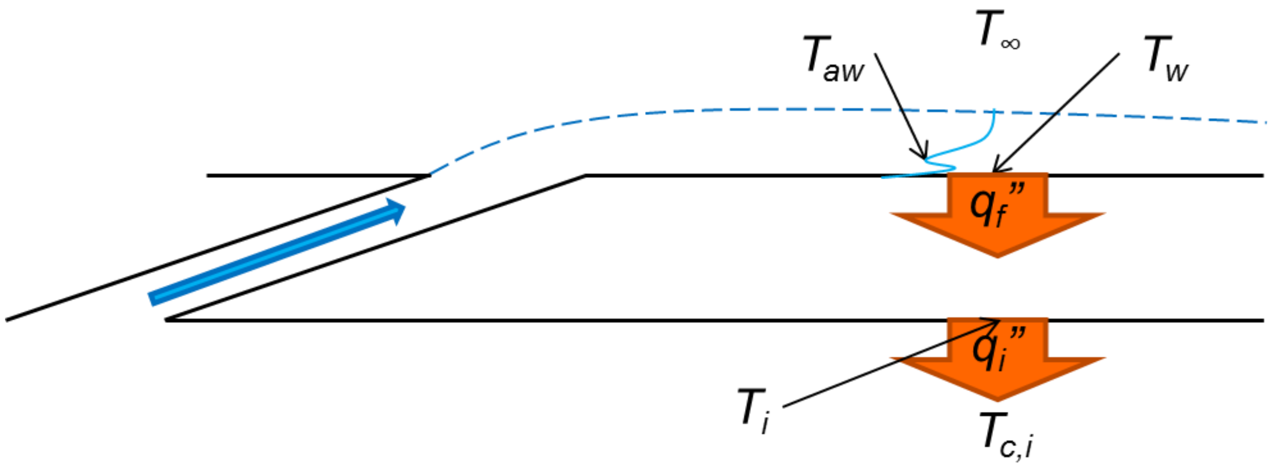


Measurement of ϕ requires a matched Biot number model and matched h_f/h_i

A simplified 1-D analysis using T_{aw} as the driving temperature shows:

$$\phi = \frac{1-\eta}{1+Bi+\frac{h_f}{h_i}} + \eta$$

- At lab scale, it is important to match h_f/h_i, the ratio of internal to external heat transfer coefficients.
- If these two nondimensional parameters are matched to engine conditions, the lab results for ϕ will be comparable to the engine.



$$Bi = \frac{h_f t}{k}$$

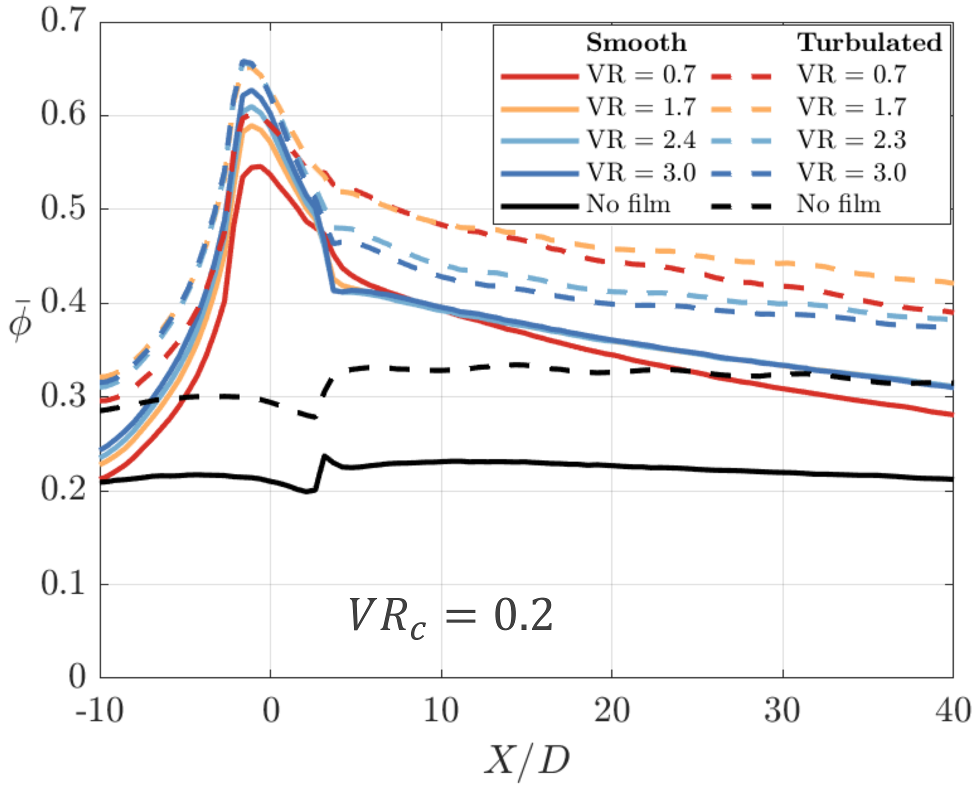
h_f: Heat transfer coefficient with film cooling

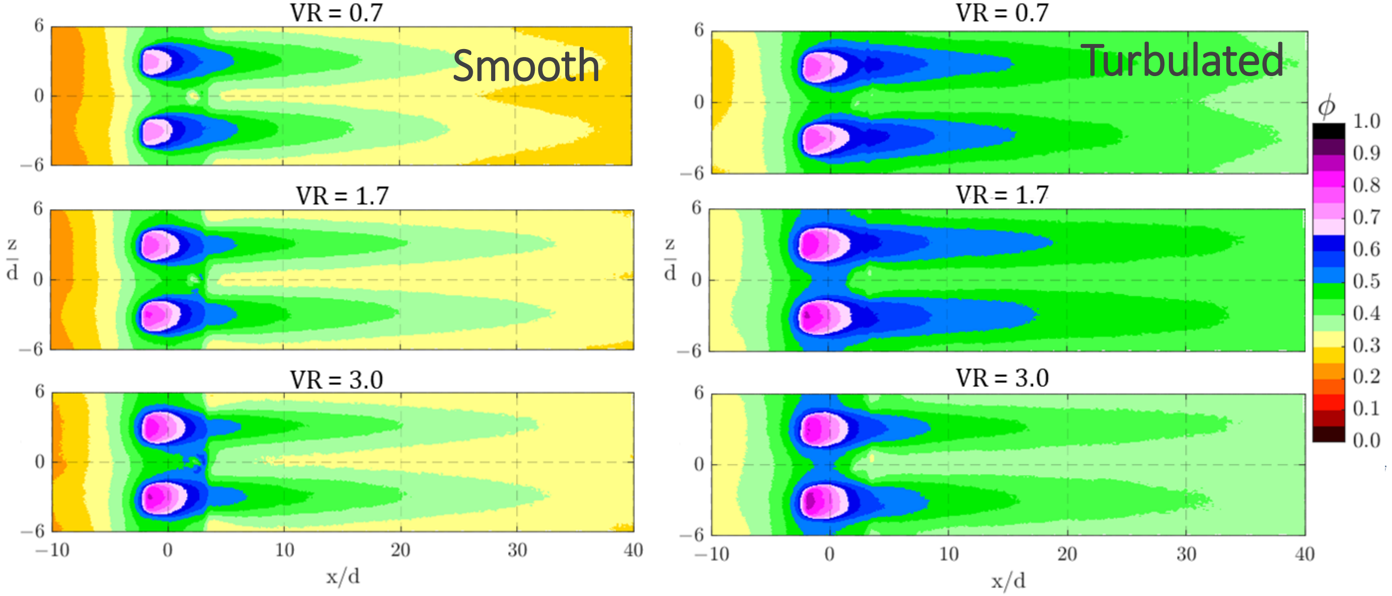
t: Wall thickness

k: Solid thermal conductivity

Turbulators enhance overall cooling effectiveness for integrated cooling designs

- Smooth channel shows little change in $\bar{\phi}$ between VR = 1.7-3.0
- Turbulated channel shows maximum $\bar{\phi}$ at VR = 1.7
- At VR = 1.7, turbulators increase $\bar{\bar{\phi}}$ by 27%
- At VR = 3.0, downstream of holes $VR_c = 0.07$, leading to significantly reduced cooling performance for the turbulated channel case.





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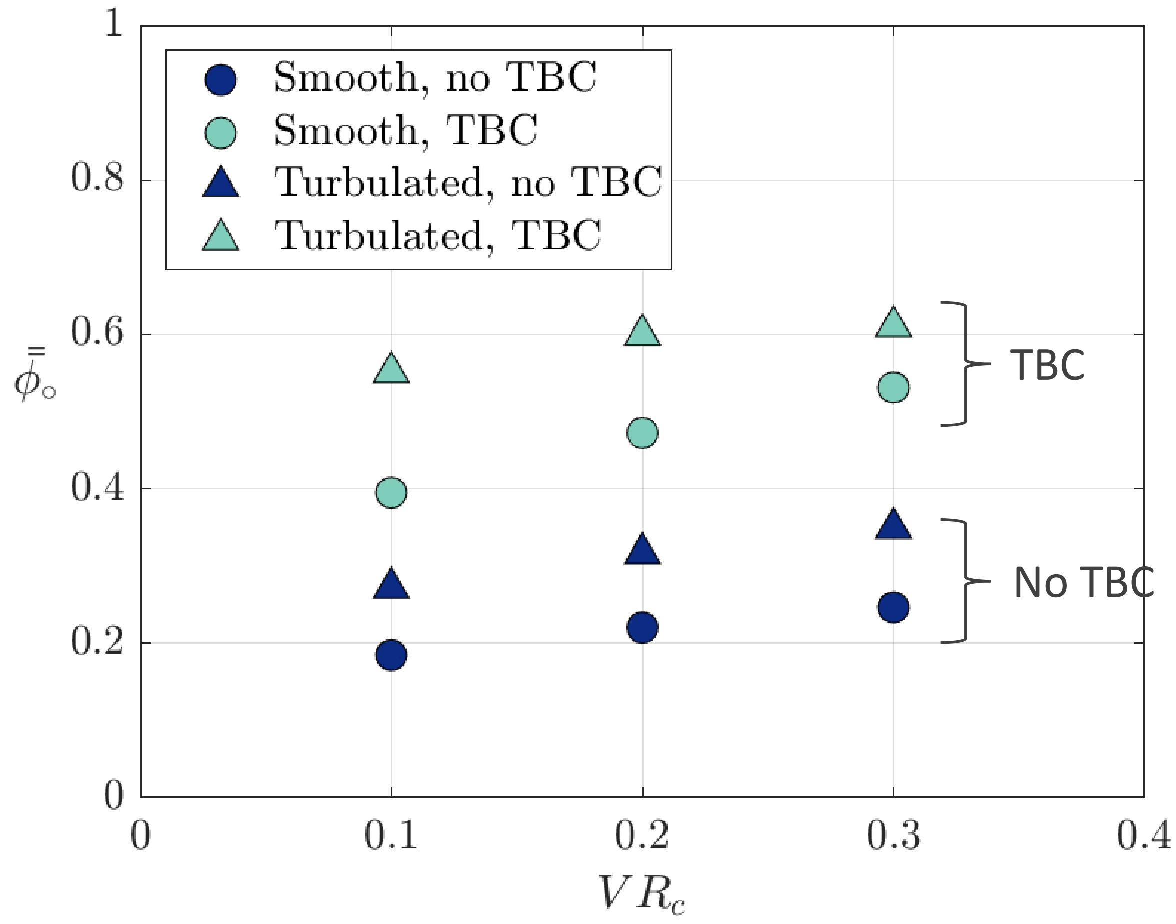
Measurements of overall cooling effectiveness with no film cooling ($\bar{\bar{\phi}}_0$), highlights the improvements with turbulators and with TBC.

- At $VR_c = 0.2$, TBC provides an increase of:
  - Smooth channel: $\Delta\bar{\bar{\phi}}$ = 0.25 (110%)
  - Turbulated channel: $\Delta\bar{\bar{\phi}}$ = 0.28 (90%)



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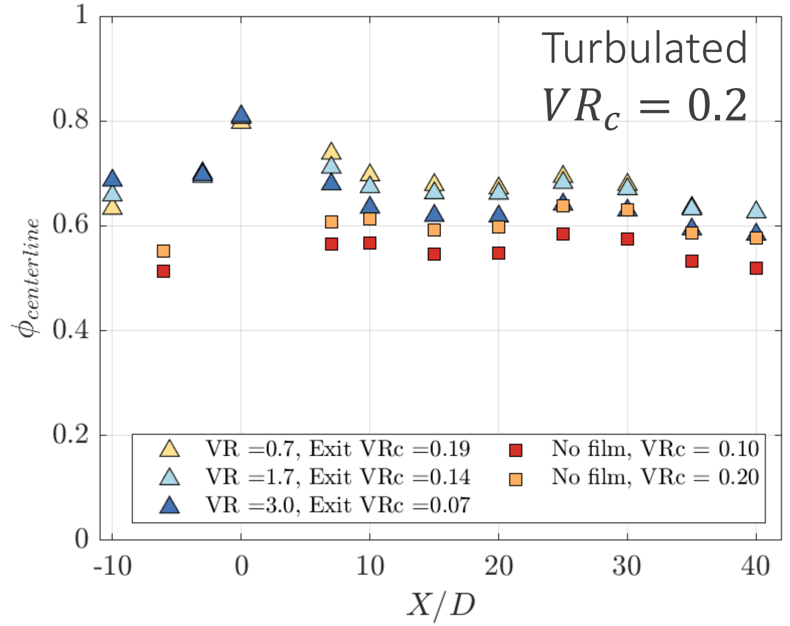
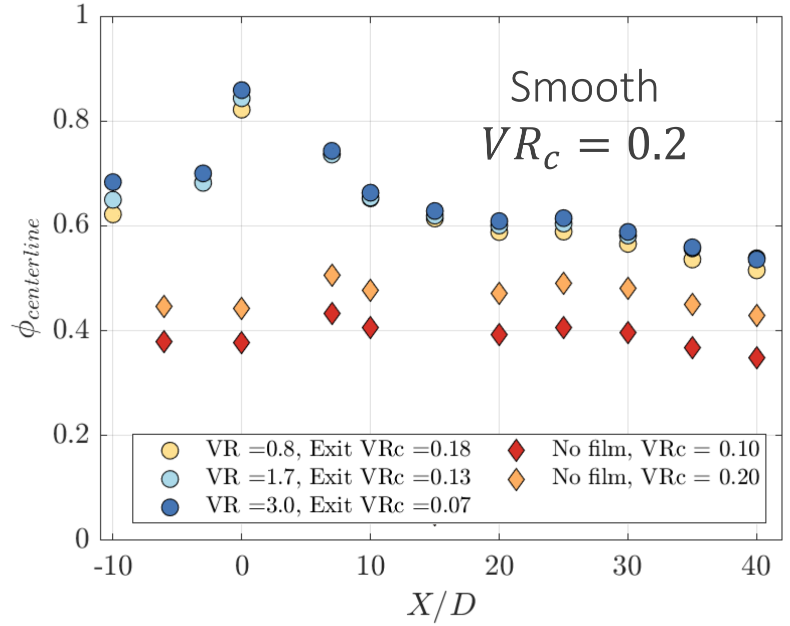
Comparison of performance with TBC and film cooling using smooth and turbulated channels:

- Comparisons of film cooled cases with internal cooling cases show improved overall cooling effectiveness with film cooling
- However, for the case with turbulators, the difference is small.
- For the turbulator case, maximum performance occurred at minimum *VR* = 0.7.





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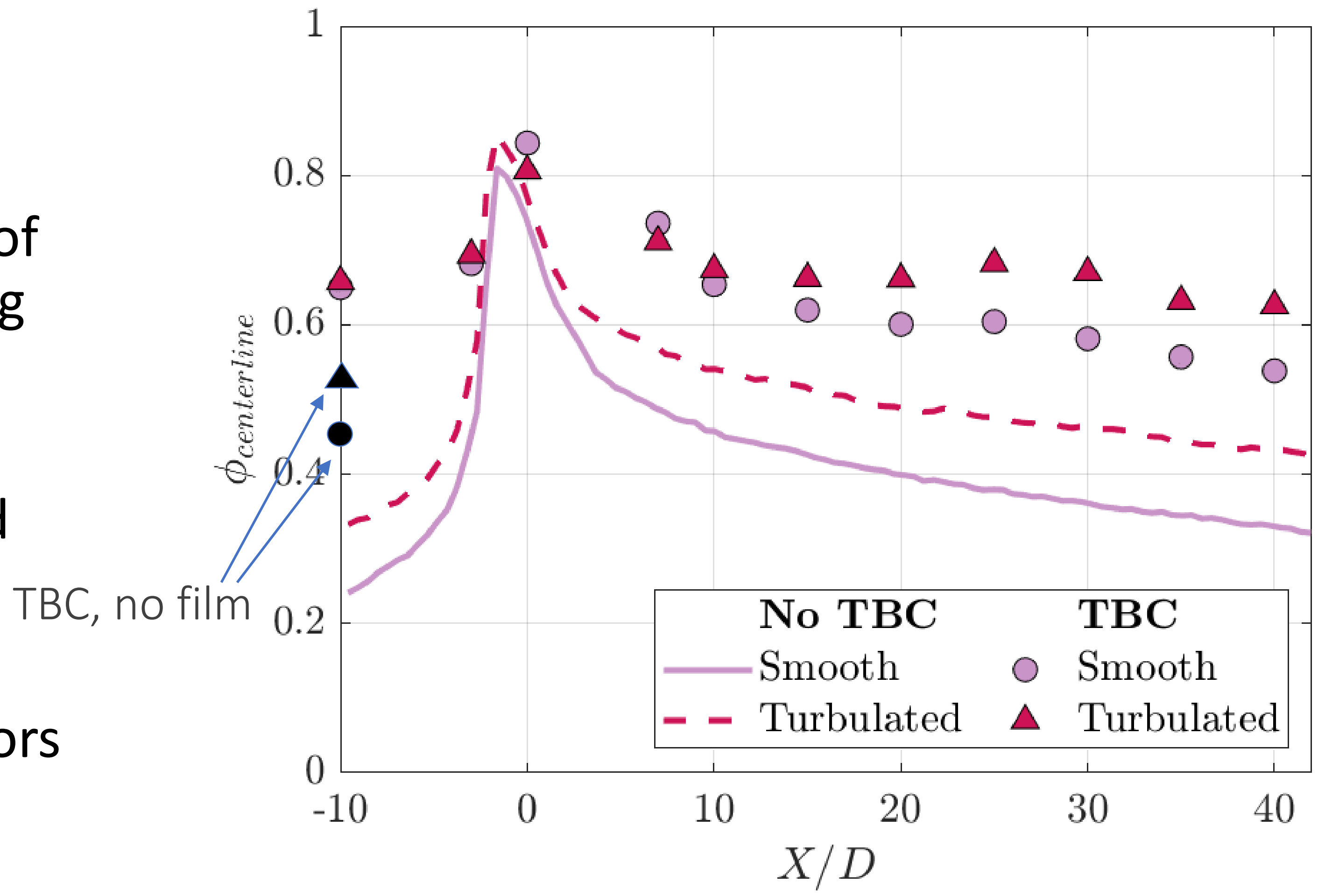
Comparisons of overall cooling effectiveness with and without TBC show the large increases in performance with the addition of TBC.

- Designs with TBC show a noticeably higher ϕ upstream of the film cooling hole, indicating the extended effects of bore cooling when using TBC.
- Thermal gradients are reduced near the hole.
- The TBC increases ϕ by about 50%, where as use of turbulators increases ϕ an additional 10%.



$VR_c = 0.20, VR = 1.7$

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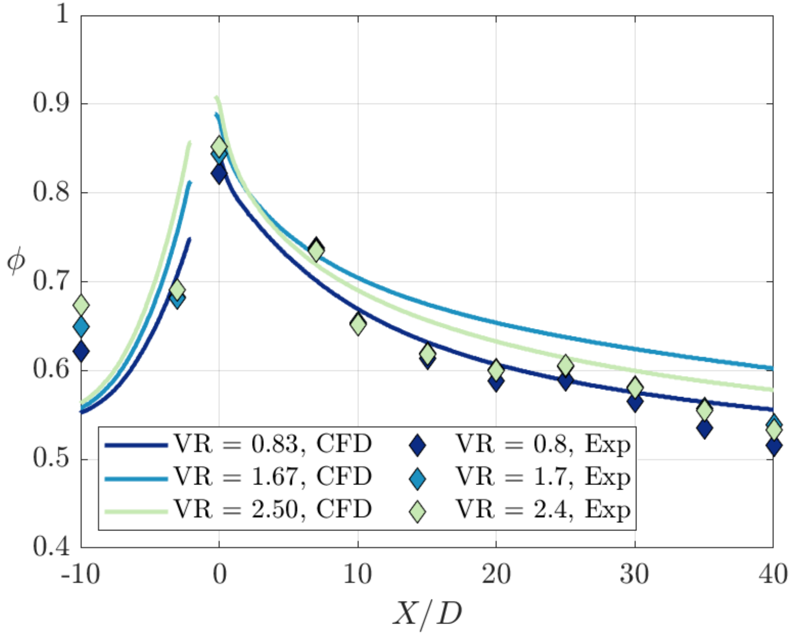
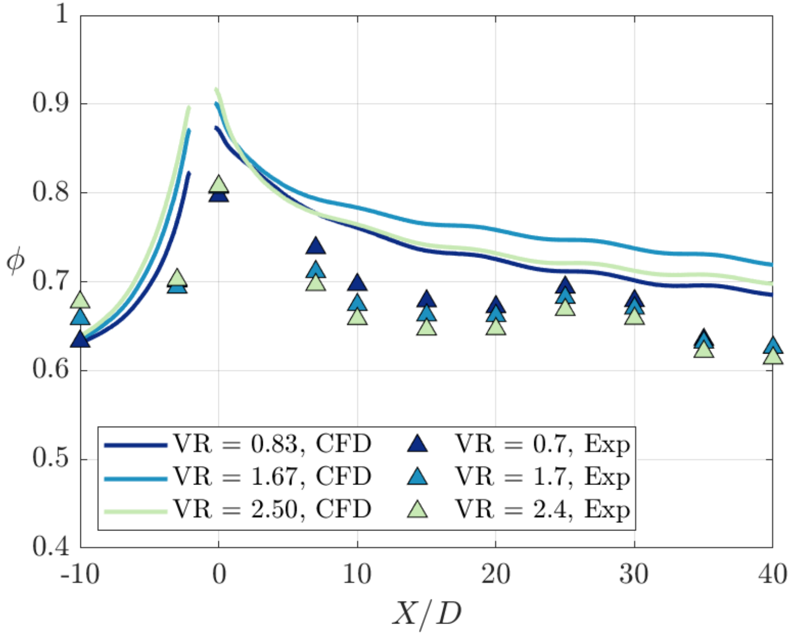
Comparisons of CFD predictions with measurements when using TBC show that overall cooling effectiveness performance is slightly overpredicted for smooth channels and significantly overpredicted with turbulators.

TBC cases, *VR_c* = 0.2

Smooth internal channel



Internal channel with turbulators



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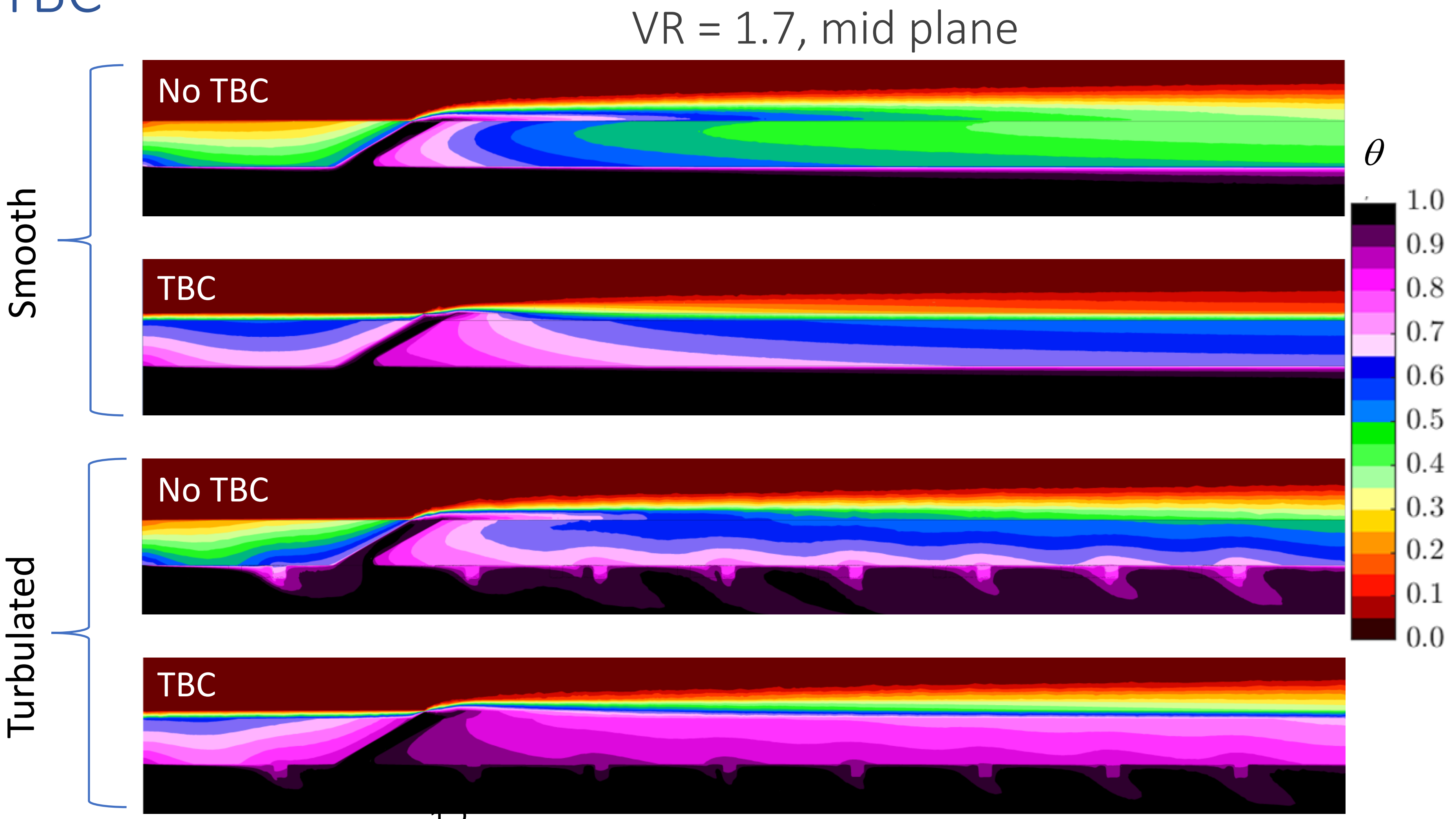
CFD simulations show temperature distributions in the “metal” due to combined internal and film cooling with and without turbulators and TBC

- These thermal fields show the significant additional cooling due to turbulators and TBC
- Thermal gradient are significantly reduced with TBC.
- Cooling effects upstream of the coolant hole are noticeably enhanced when using TBC



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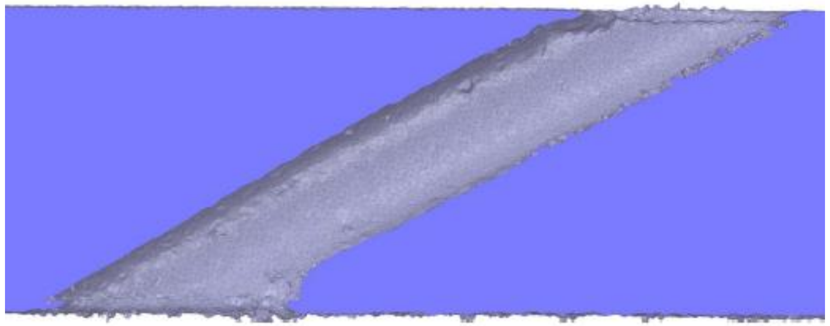
Experimental models used to evaluate the "as built" engine scale metal AM models by comparing with a large scale "as designed" models.

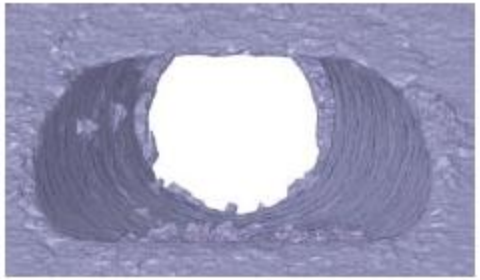
All models are for the 9-9-3 RI shaped hole.

1x scale metal AM build

Cross-section along hole centerline

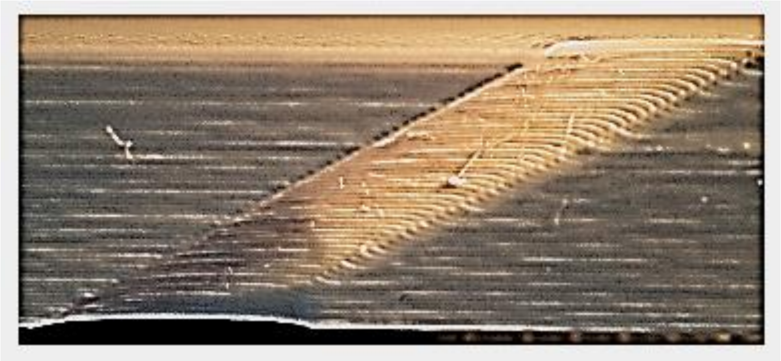


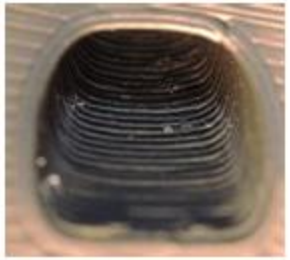
Hole outlet



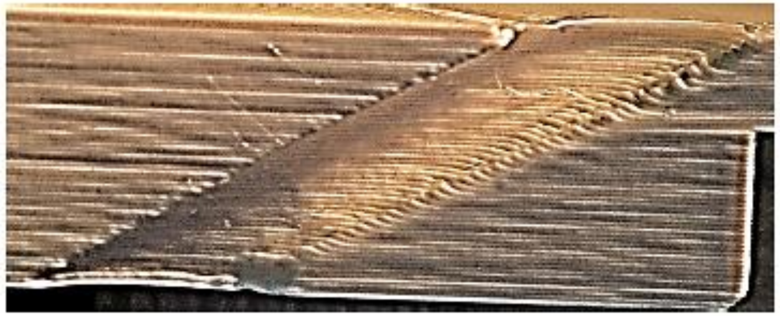
5x scale PLA AM builds

Cross-section and hole outlet for the "As Designed" hole





Cross-section and hole outlet for the "As Built" hole



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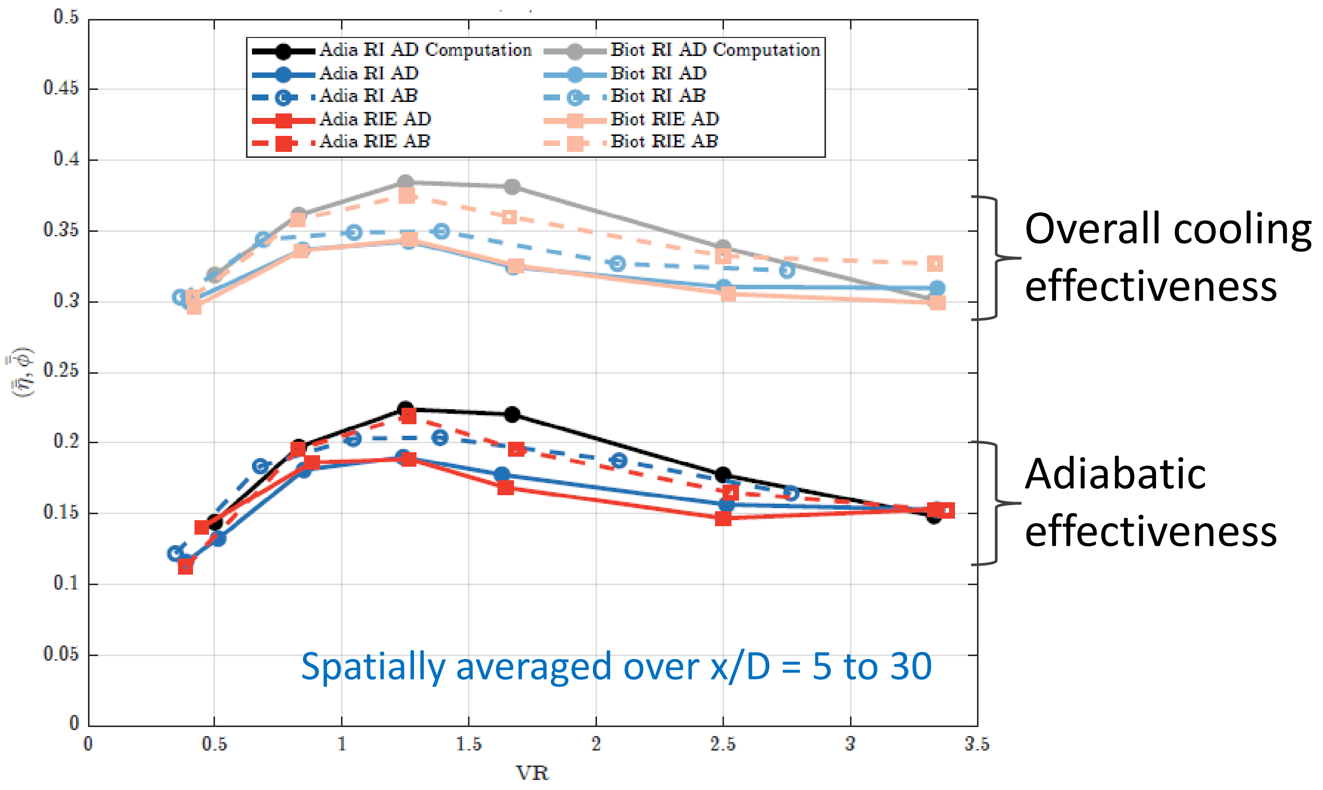
Spatially averaged overall and adiabatic cooling effectiveness for varying “as built” and “as designed” hole geometries.

- The RI (rounded inlet) and RIE (rounded inlet and exit) 9-9-3 holes were designed to mitigate the effects of the AM build roughness
- Generally there was negligible difference between the “as designed” and the “as built” models tested.
- Computational predictions followed the same trends as the experimental results, though predicted noticeably higher performances at the intermediate *VRs*

9-9-3 shape holes



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Conclusions

- The new test facility at UT allows efficient testing of overall cooling effectiveness and adiabatic effectiveness for a wide variety of combined internal and film cooling configurations.
- For all cases tested, film cooling provided an improvement in cooling effectiveness compared to internal cooling alone, although for the case with internal turbulators and external TBC, the internal cooling alone was close to the combined film and internal cooling.
- RANS computations generally provided reasonable predictions of performance, but overpredicted overall effectiveness when TBC was added.
- The RI and RIE film cooling hole designs effectively mitigated the effects of roughness due to engine scale, metal AM builds.

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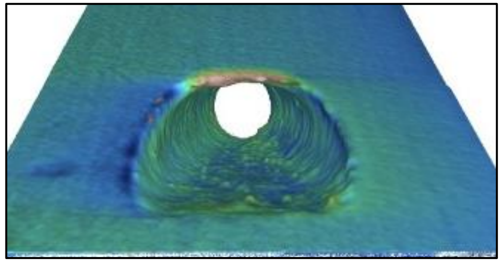
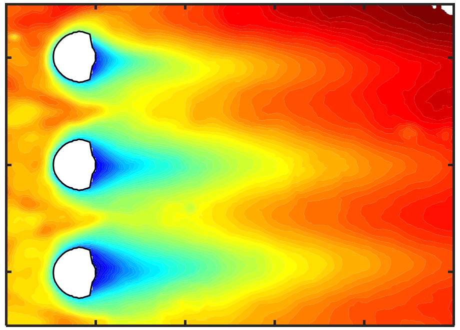
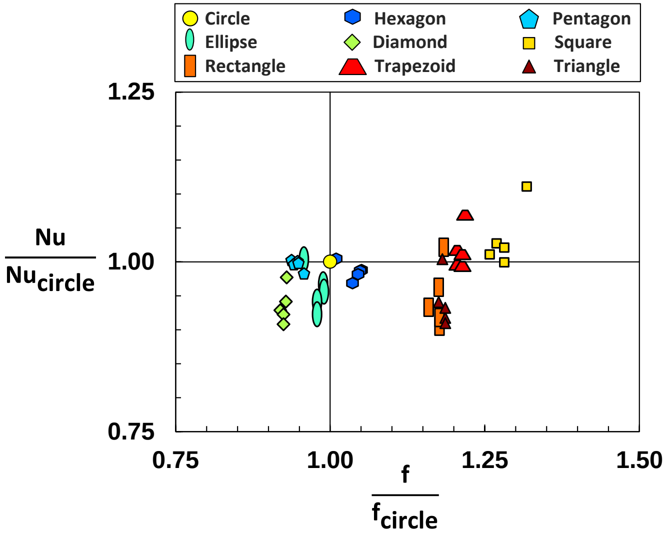
Penn State's START Lab will cover results of both film cooling, shaped microchannel cooling, and build effects on surface roughness



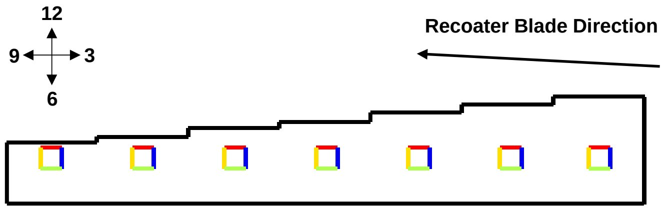
Cooling Hole Printability

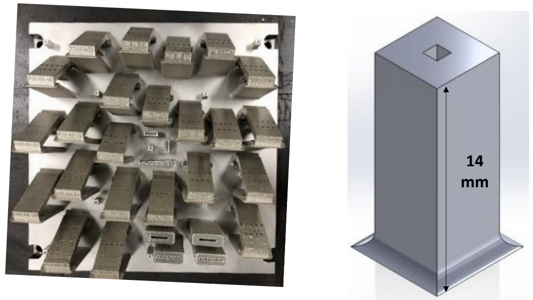


Film Cooling Results



Shaped Microchannel Results





Effect of Build on Channel Roughness

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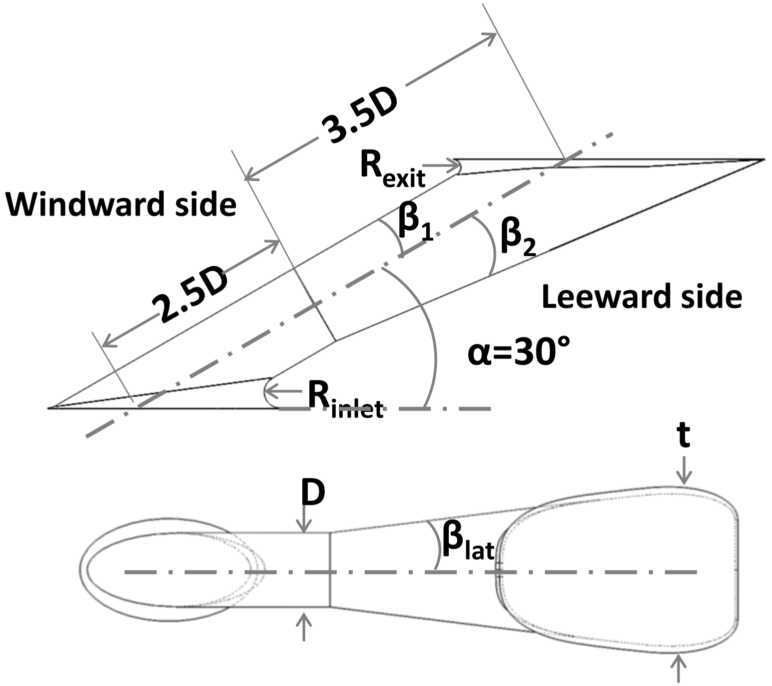
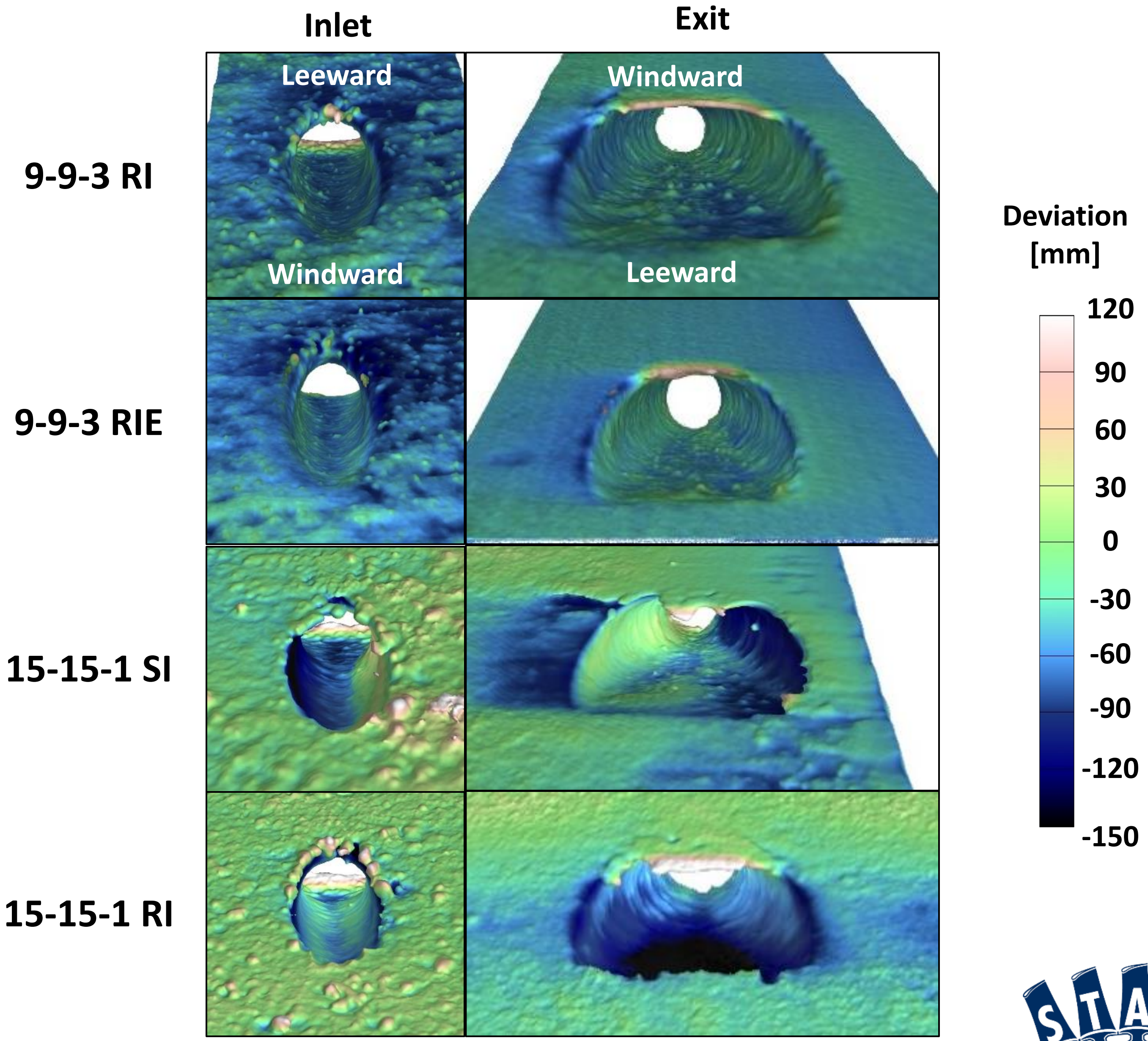
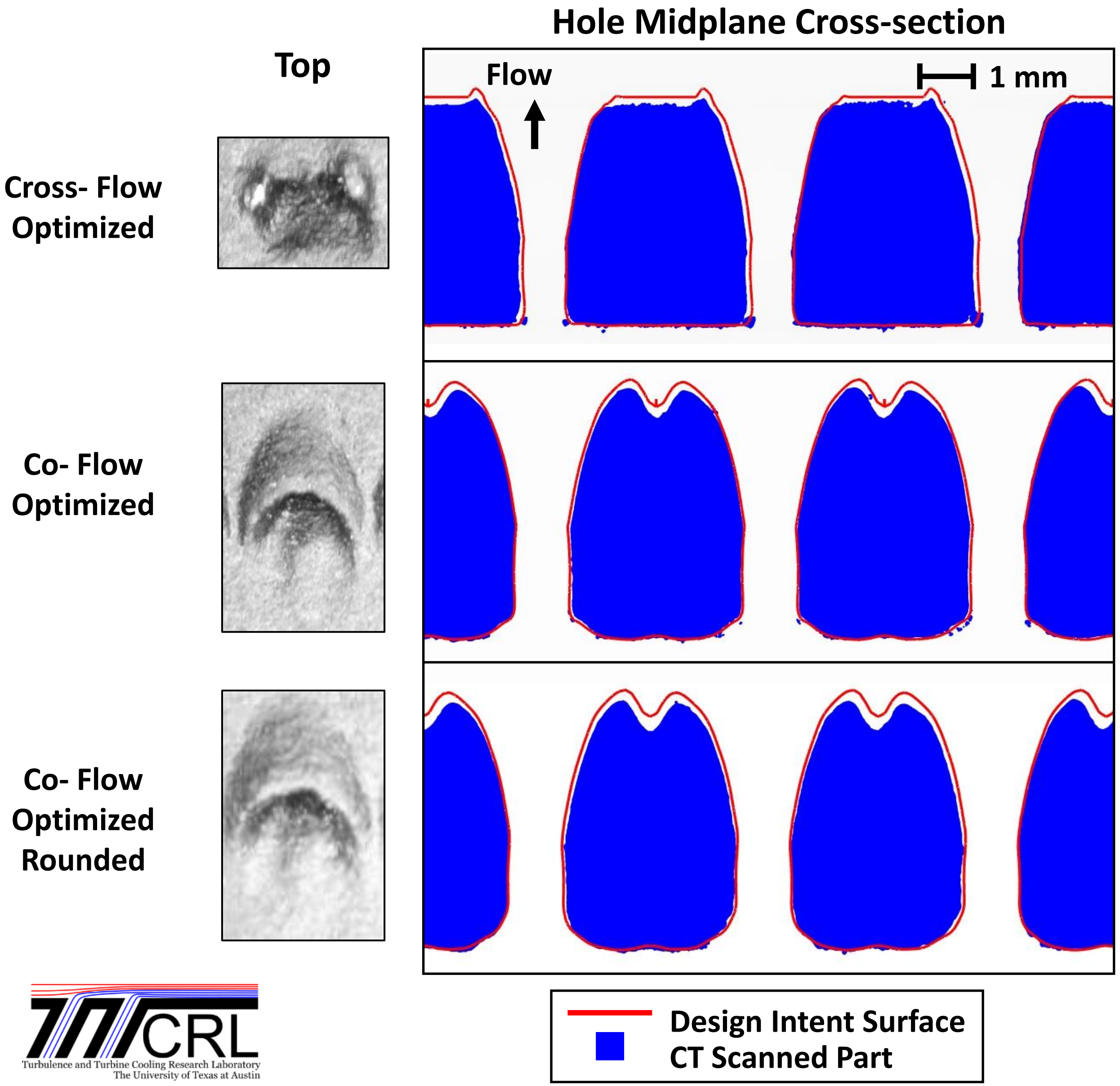
The holes printed close to the design intent, but with noticeable roughness features at the inlet of the hole

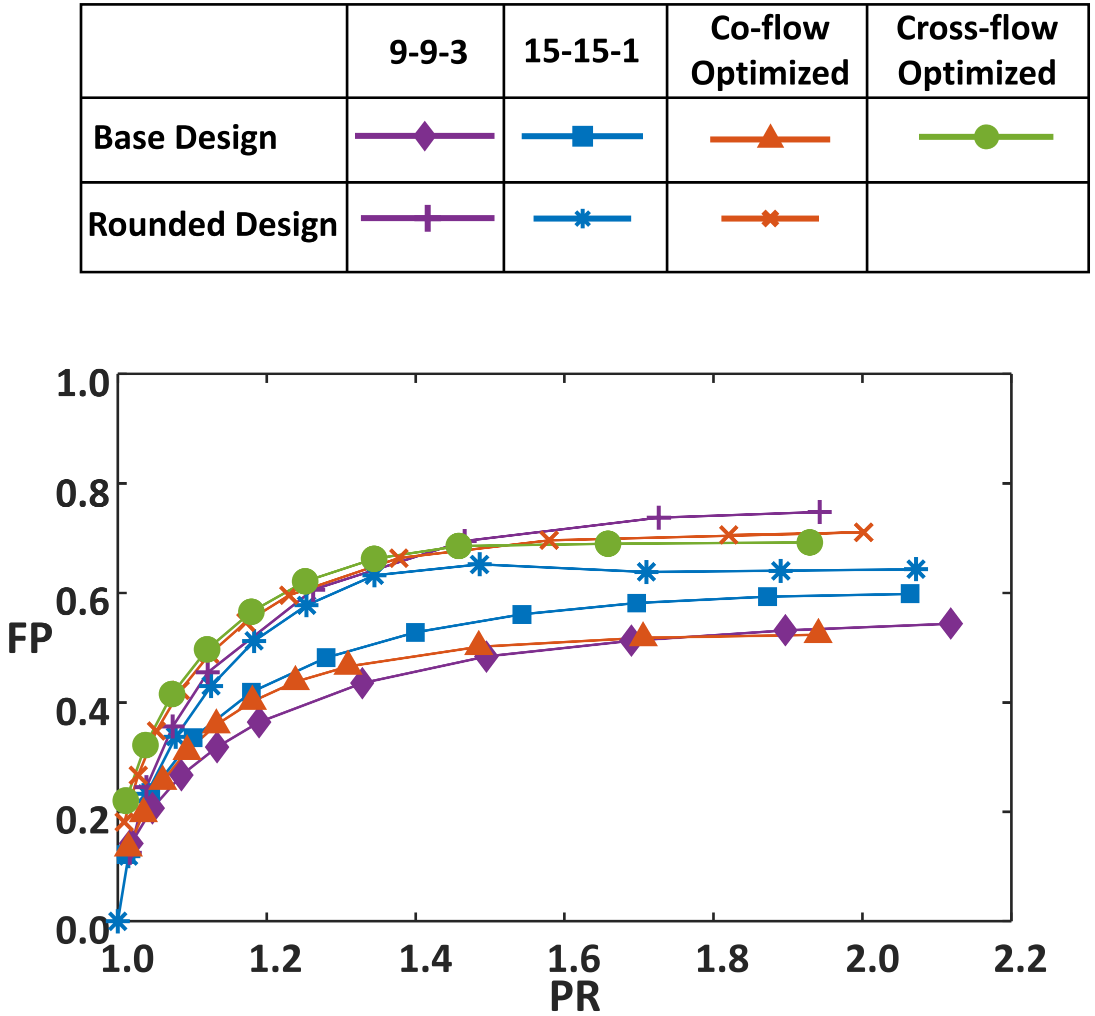


Hole Shape	β_{lat}	β_1	β_2	R_{inlet}	R_{exit}
15-15-1 SI	15°	0°	1°	-	-
15-15-1 RI	15°	0°	1°	0.25D	-
9-9-3 RI	8.6°	-2.2°	0.6°	0.25D	-
9-9-3 RIE	8.6°	-2.2°	0.6°	0.4D	0.2D



Rounding features in the metering section of the hole increases the amount of coolant that will pass through for a given pressure ratio





$$PR = \frac{P_c}{P_\infty} \qquad FP = \frac{\dot{m}_f \sqrt{R_c T_c}}{P_c A_{c,m}}$$

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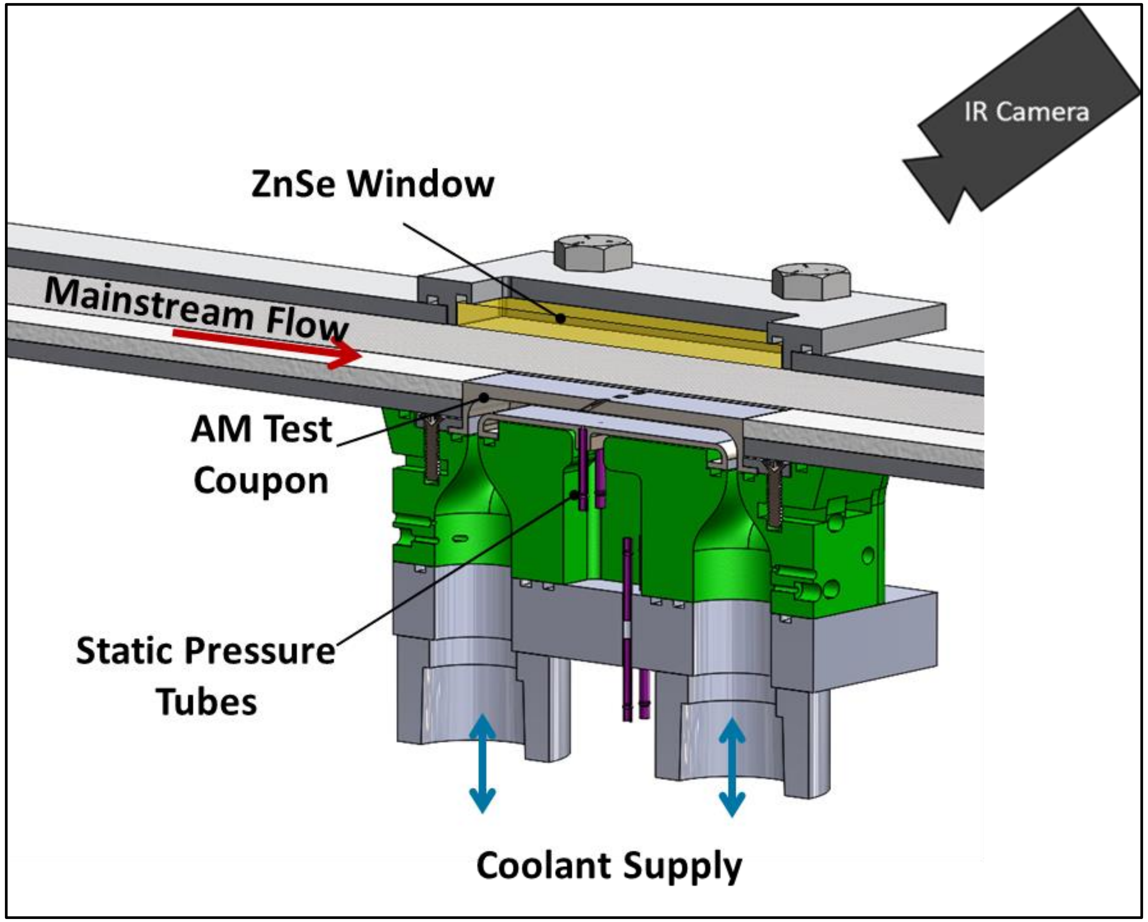
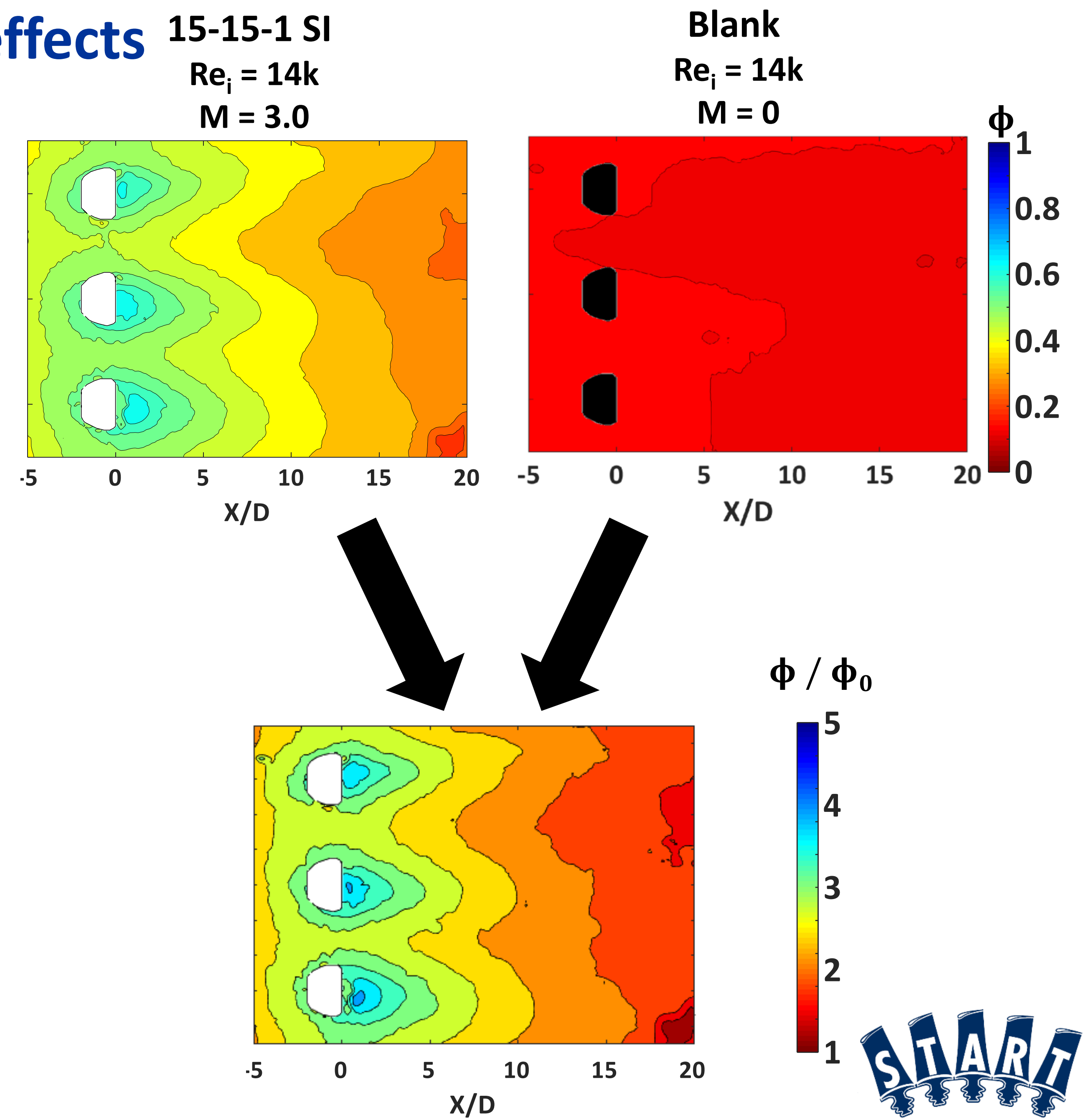
A coupon with no film-cooling hole was used to normalized the effectiveness, thereby focusing in on the film-cooling effects





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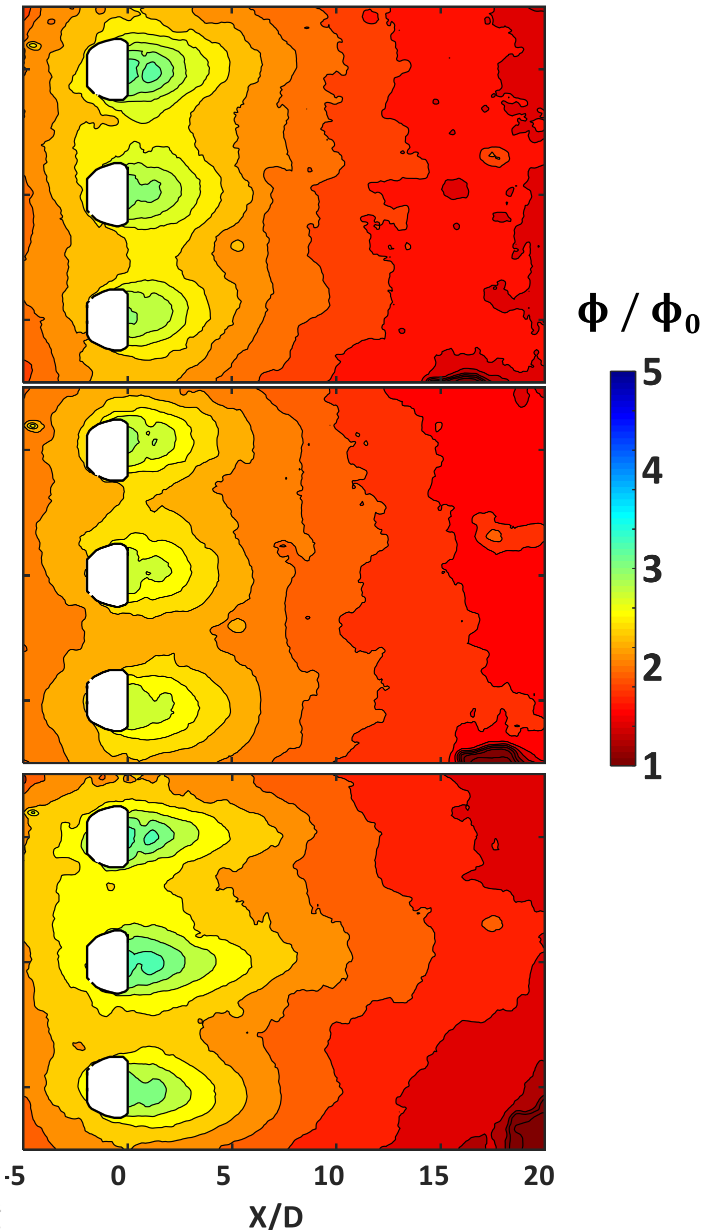
Compressibility does not have a significant effect on the cooling performance

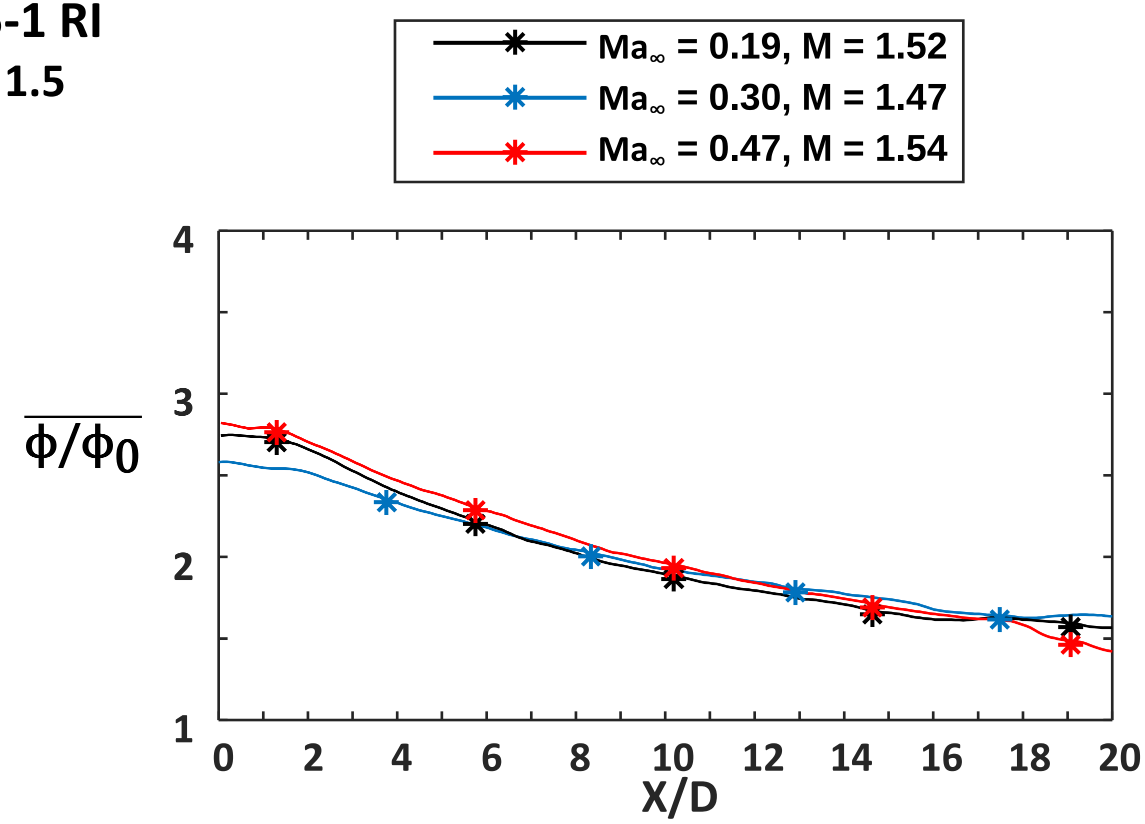
Ma$_\infty$ = 0.19

Ma$_\infty$ = 0.30

Ma$_\infty$ = 0.47



15-15-1 RI
M = 1.5



Ma$_\infty$	Re$_\infty$	Ma$_c$	Re$_c$	Re$_f$
0.19	216575	0.022	14322	29434
0.30	221043	0.034	14188	28767
0.47	211837	0.052	14113	28732

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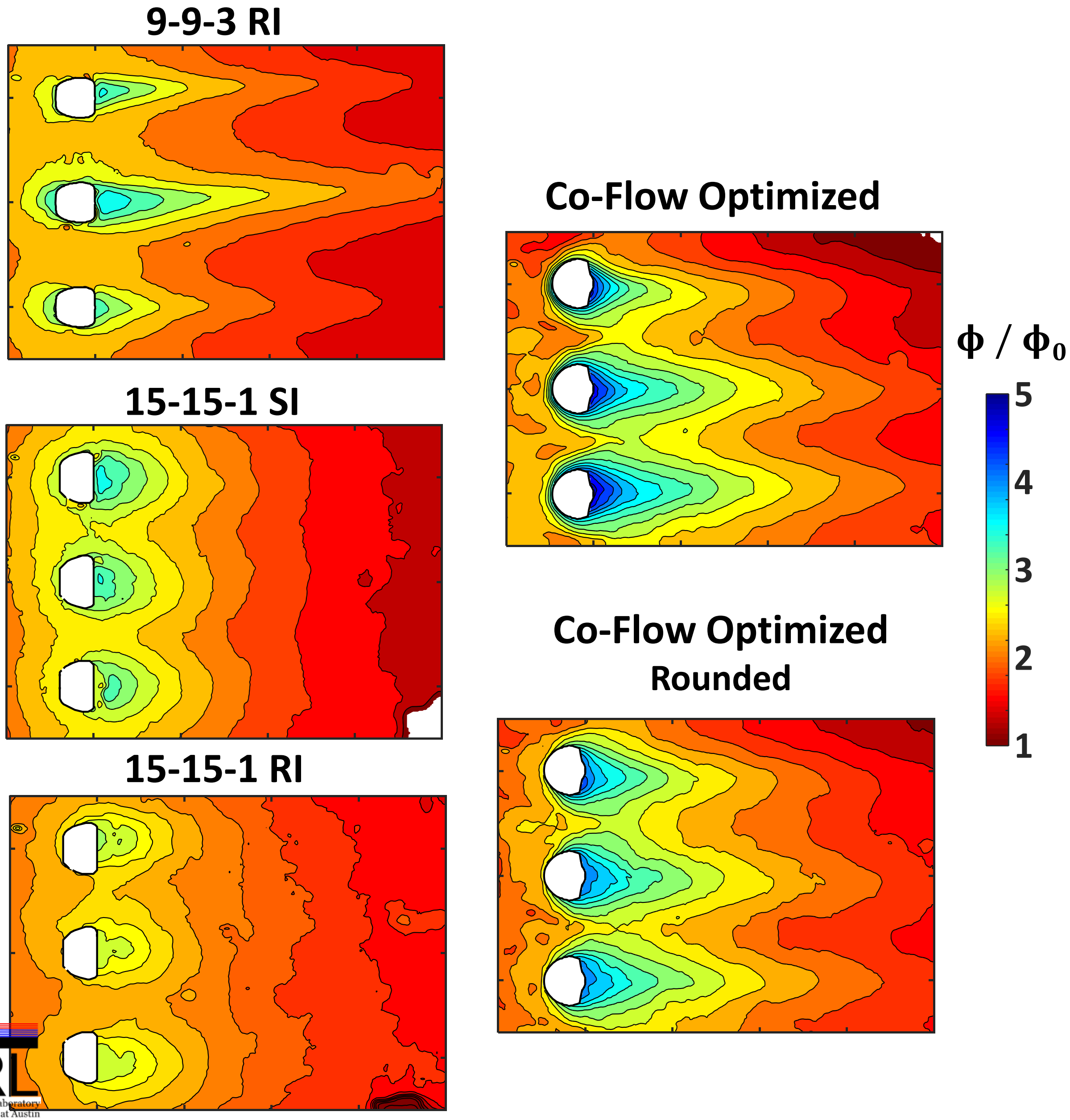
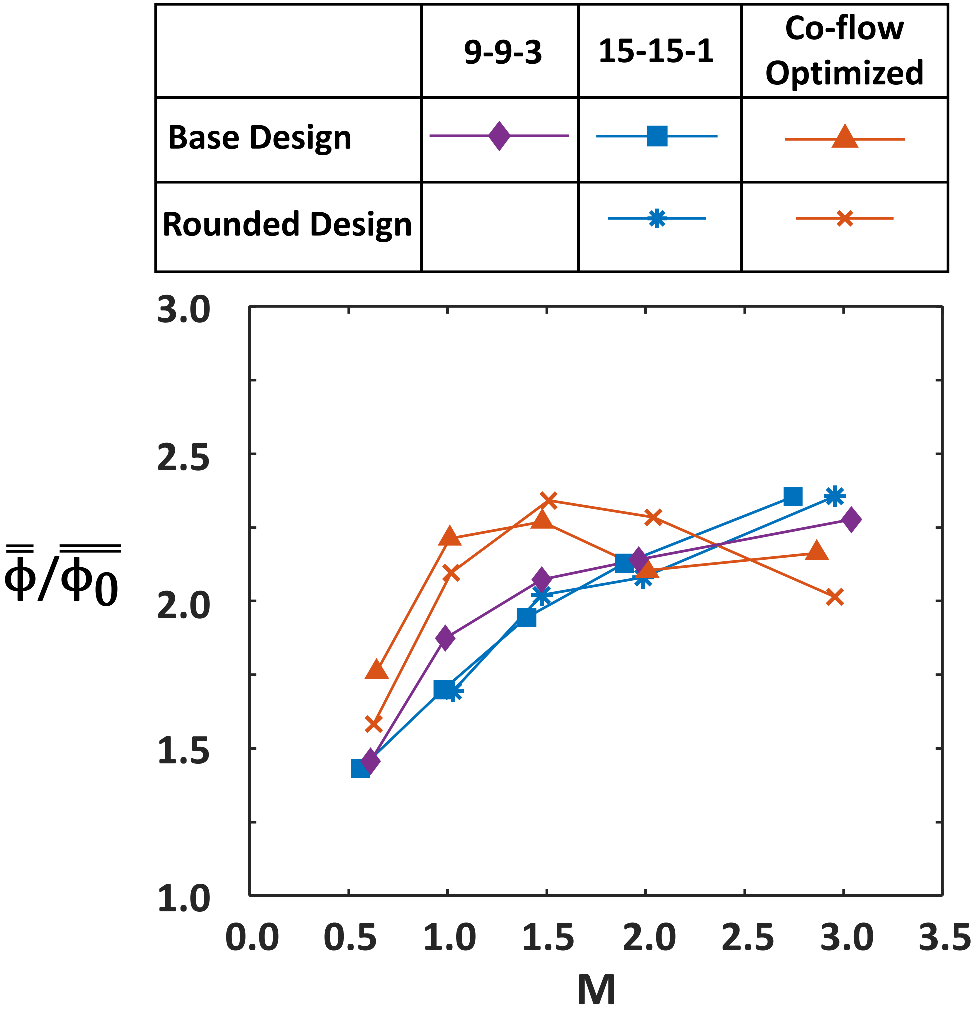
The co-flow optimized holes have higher effectiveness augmentation than the base shaped holes at the lower blowing ratios

M = 1.5





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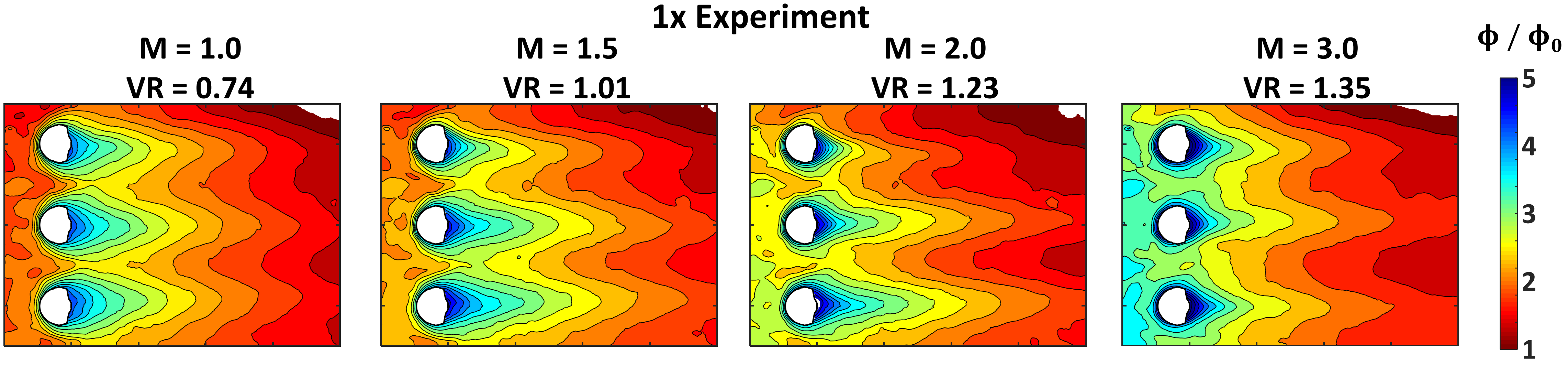
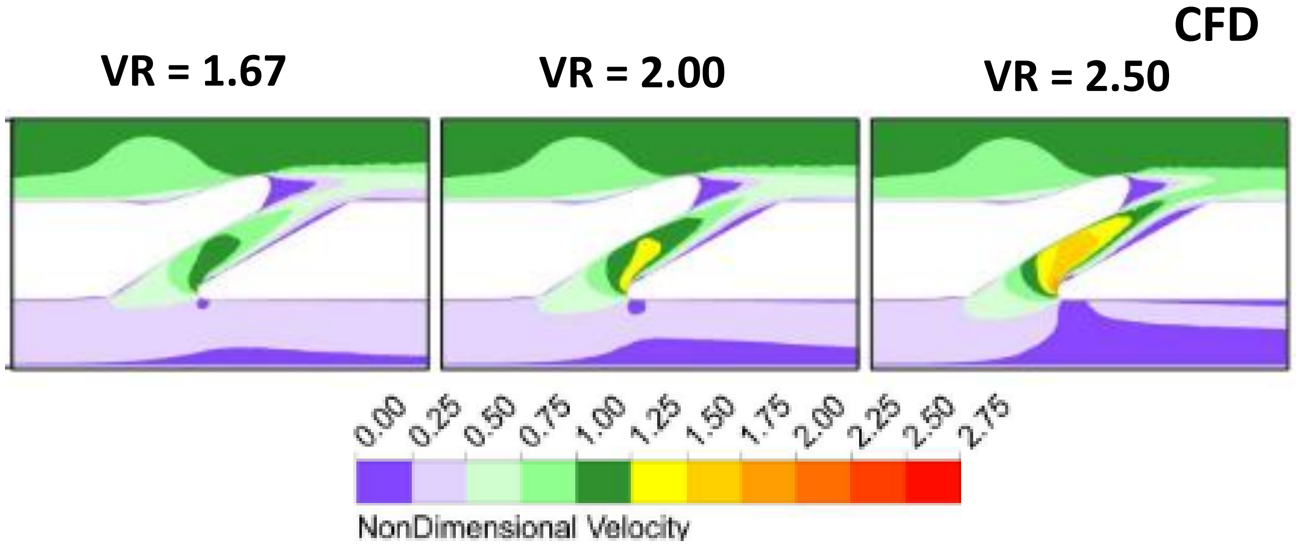
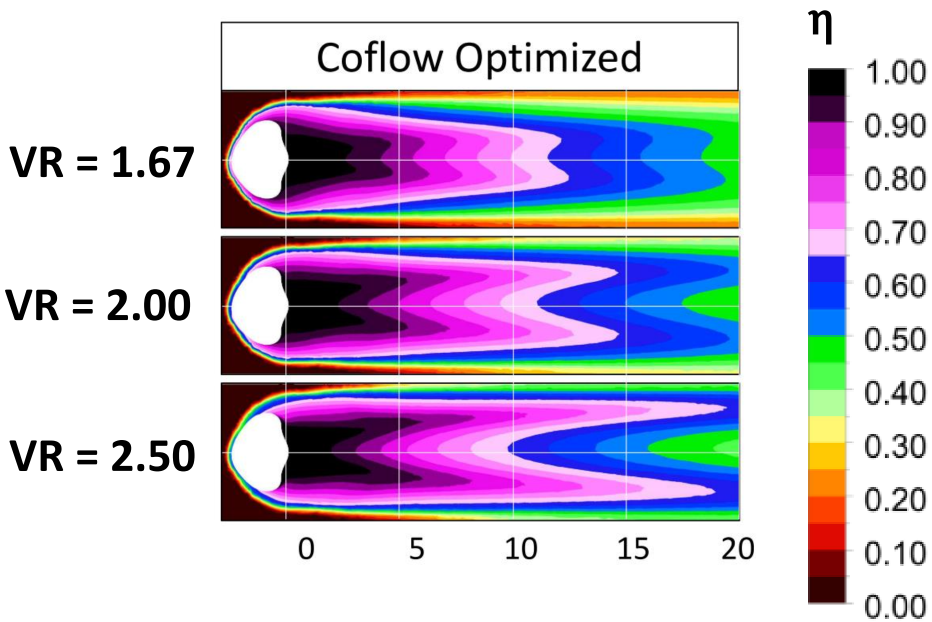
Unlike CFD, experiments do not show a separation in the hole causing bifurcation of the coolant jet







Jones, F. B., Oliver, T., and Bogard, D. G., 2021, "Adjoint Optimization of Film Cooling Hole Geometry," Proceedings of ASME 2021 Turbo Expo. Virtual, Online, June 7-11, GT2021-59332.

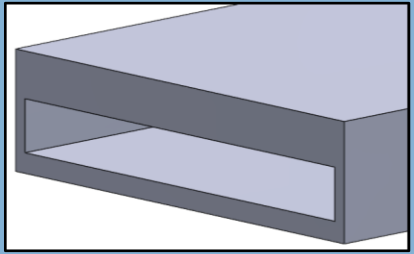
Further studies will look focus more towards the effect of the internal channels

Rib Study

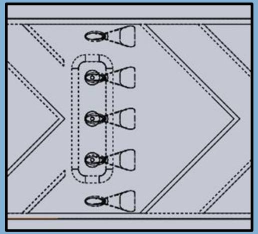
Single Channel, H = 3.4D

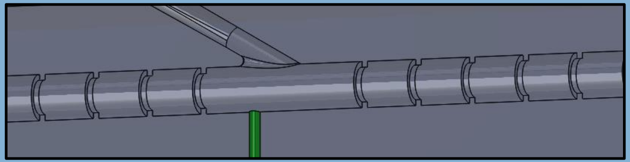
Nine Microchannels

No Ribs



Ribs





Channel Shape Study

Circle

Ellipse

Square

Rectangle

Pentagon

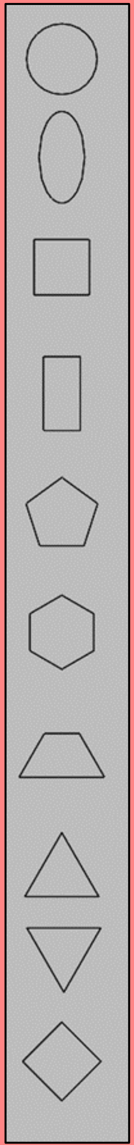
Hexagon

Trapezoid

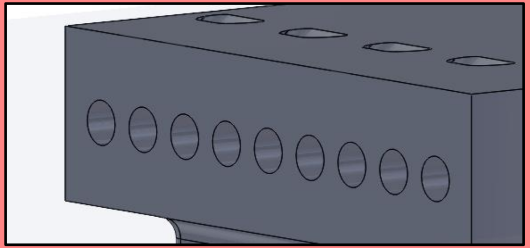
Triangle - up

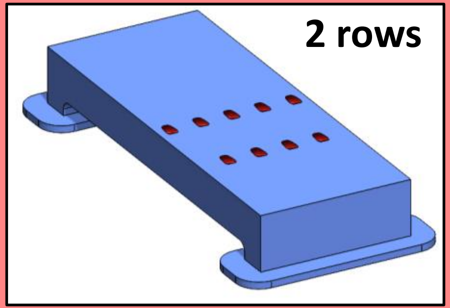
Triangle - down

Diamond



Nine Microchannels
No Ribs





Multiple channels were fabricated with different channel shapes at the 90° build direction to investigate the impact shape has on cooling performance

Circle

Ellipse

Square

Rectangle

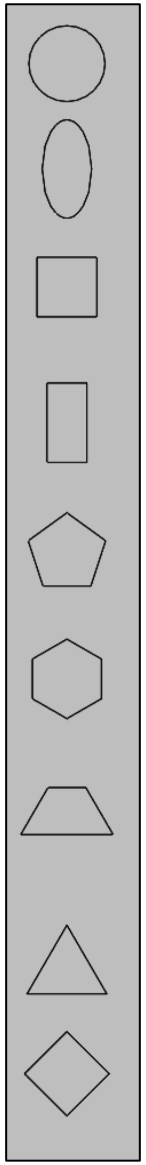
Pentagon

Hexagon

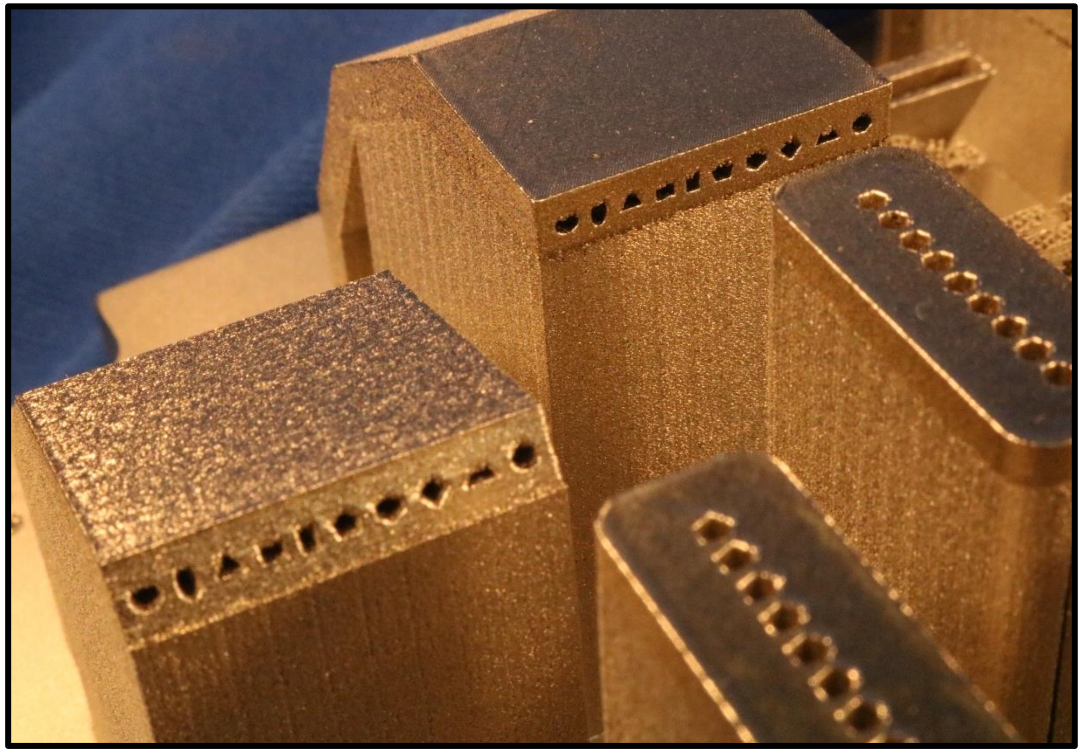
Trapezoid

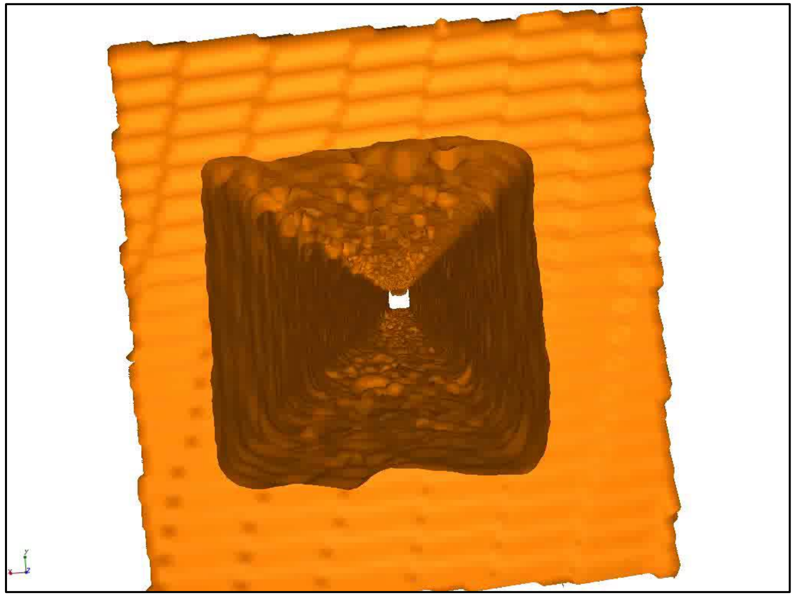
Triangle

Diamond

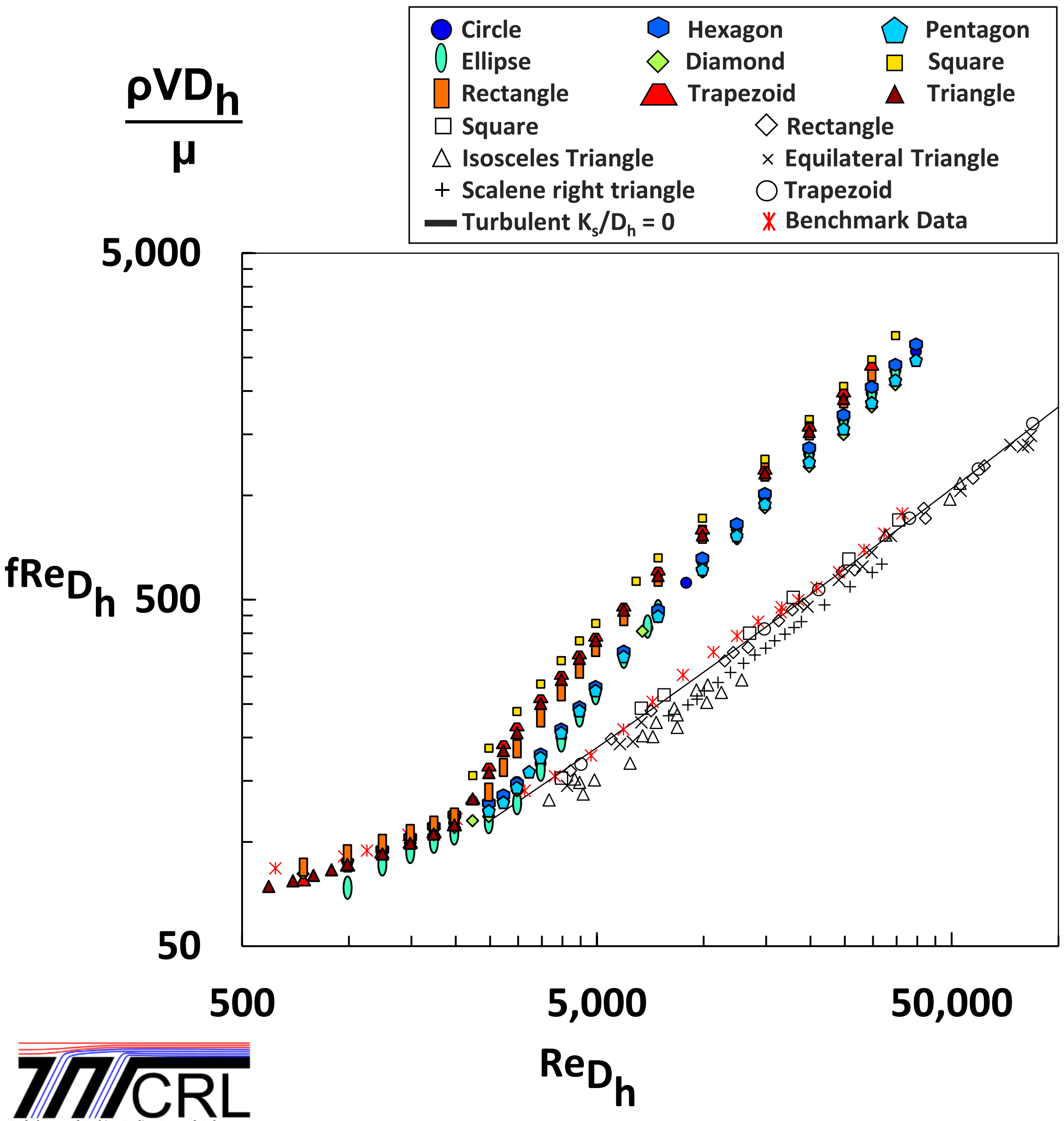


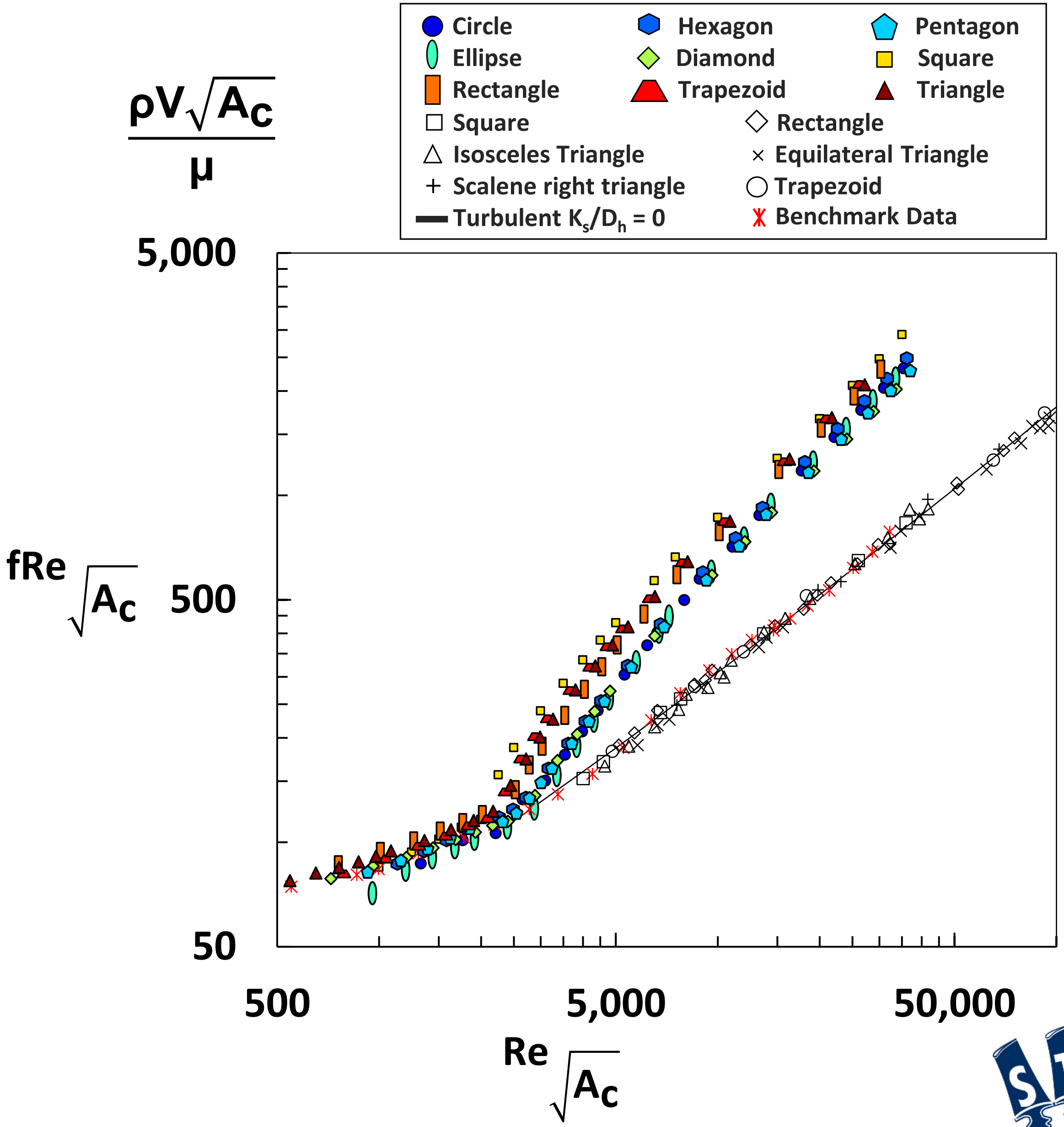
Constant Perimeter





Scaling friction factors were compared with that proposed by Duan et al. 2012 using $\sqrt{A_c}$





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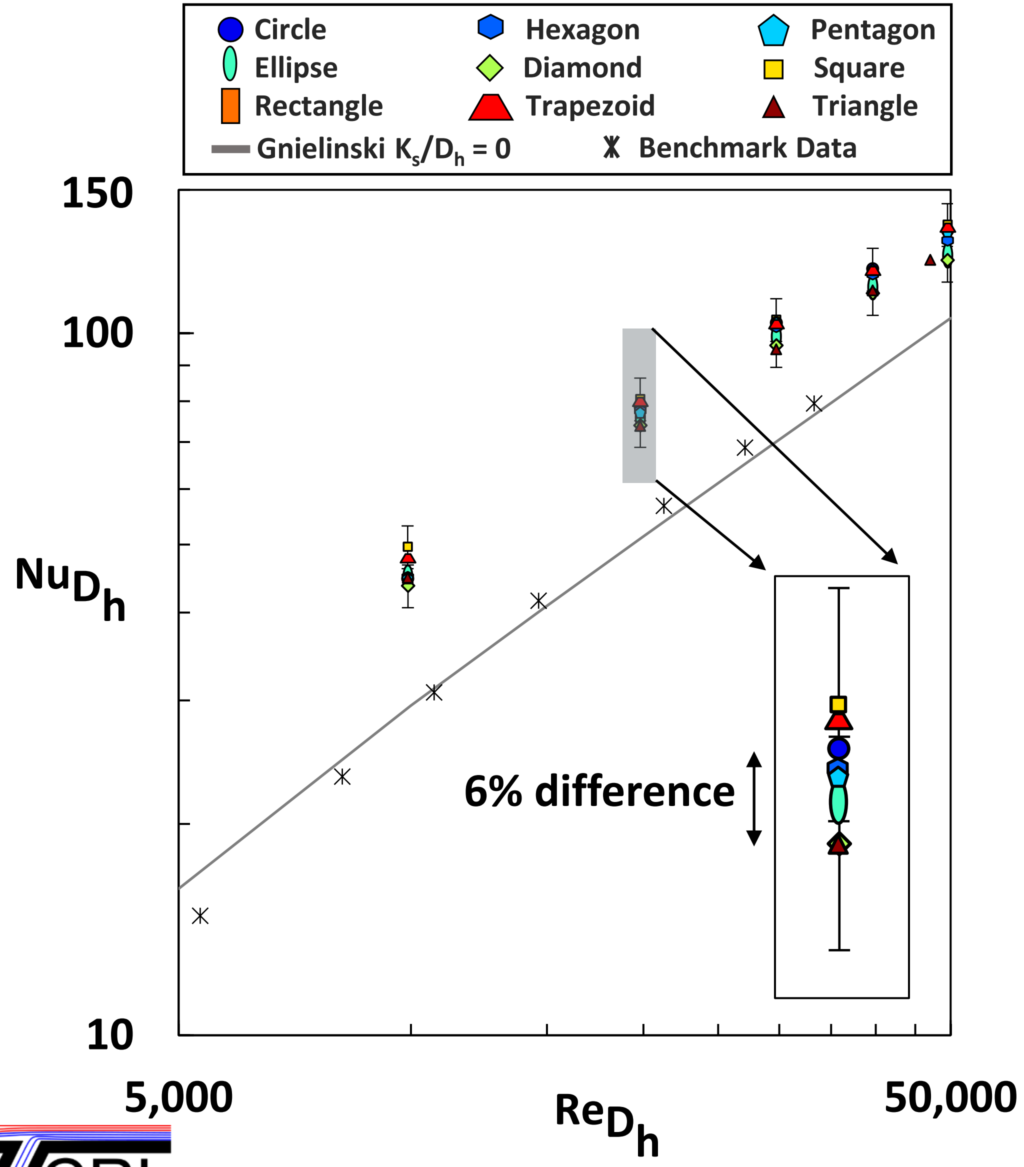
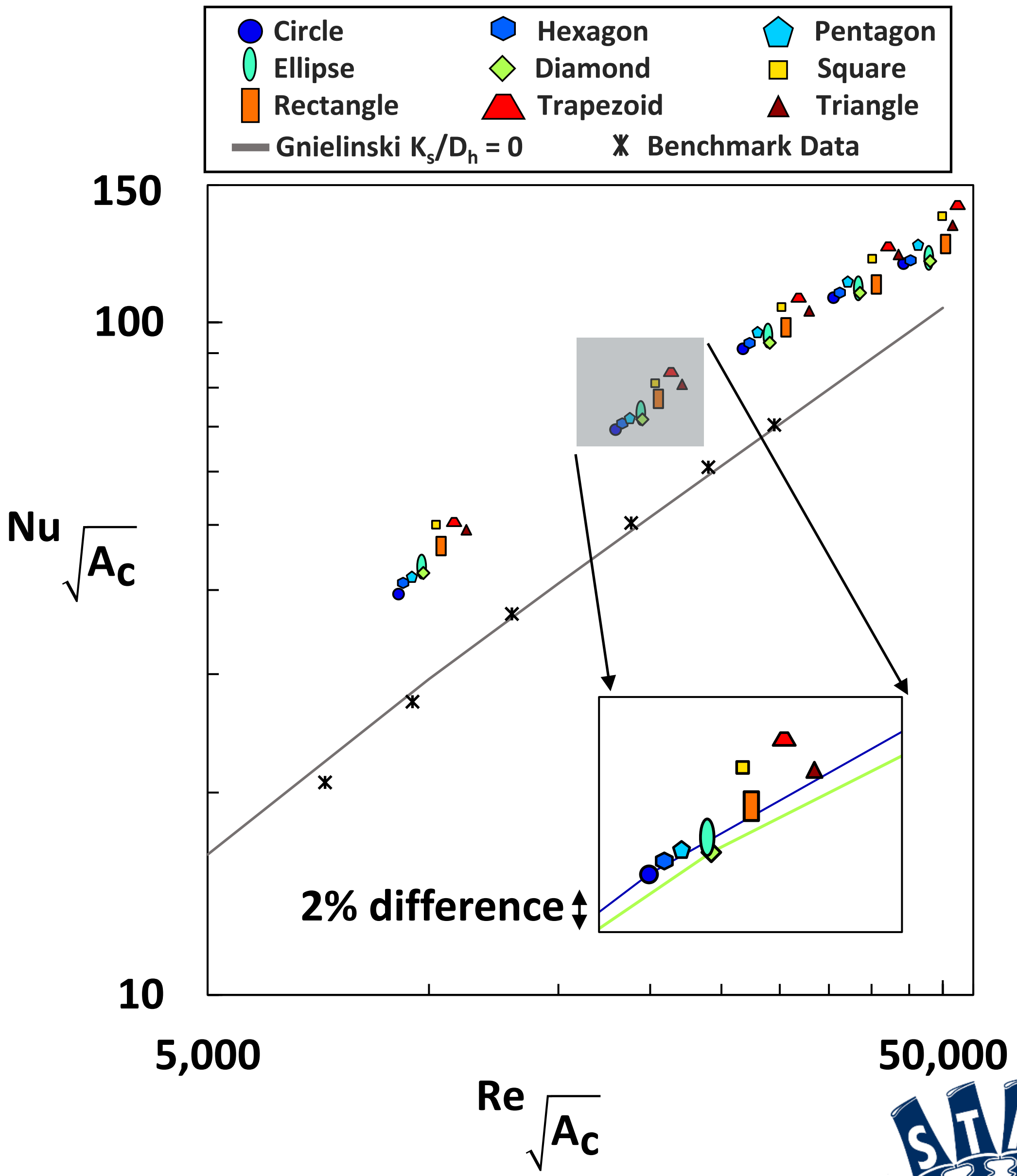
Nusselt number using $\sqrt{A_c}$ reduces scatter compared to using D_h for different channel shapes





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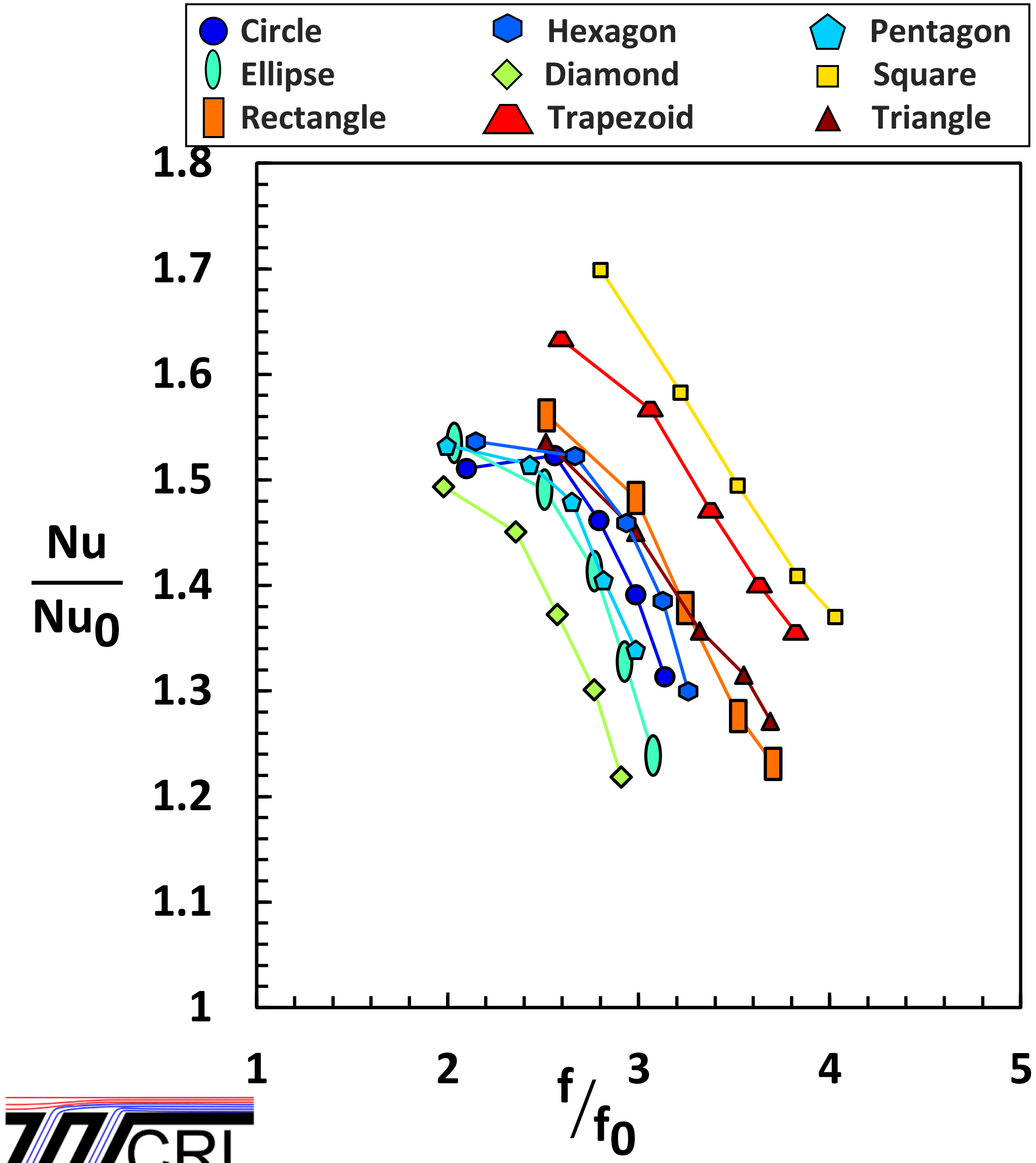
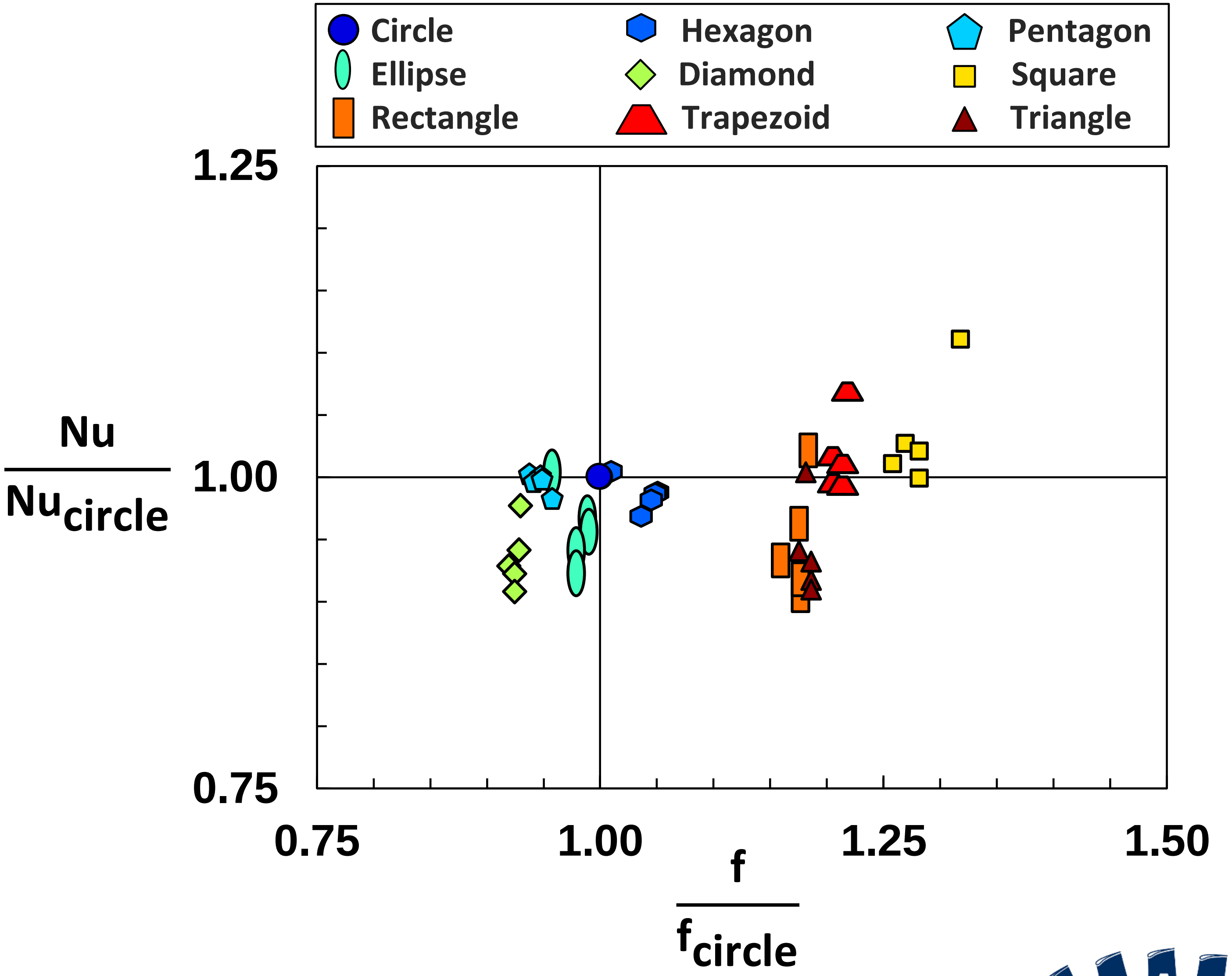
The diamond exhibits the lowest friction factor and Nusselt augmentation, while the square and trapezoid showed the highest friction factor and Nusselt augmentations





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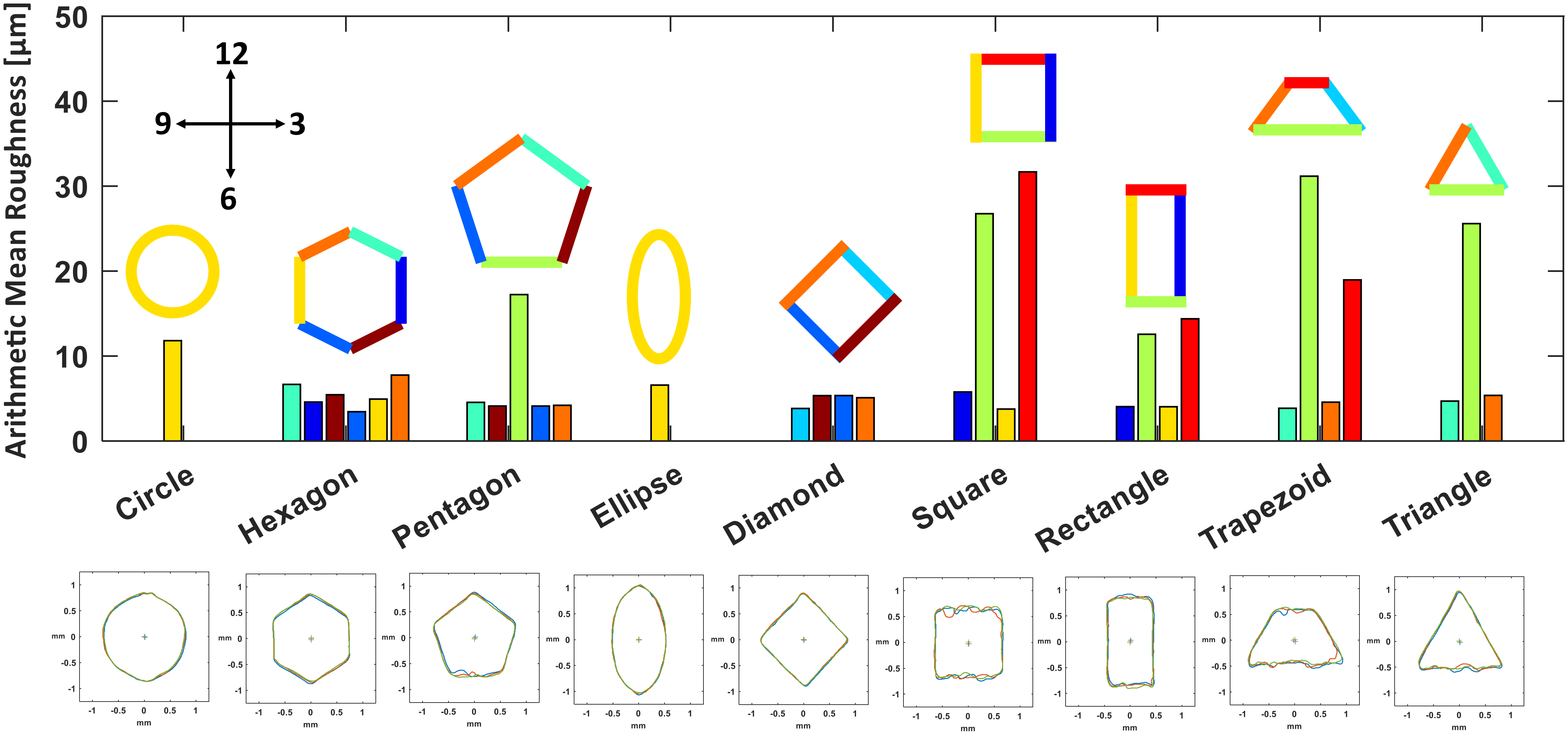
A higher surface roughness is observed on the 6 and 12 o'clock surfaces relative to all other internal surfaces, despite all channels being fabricated at the 90° build direction



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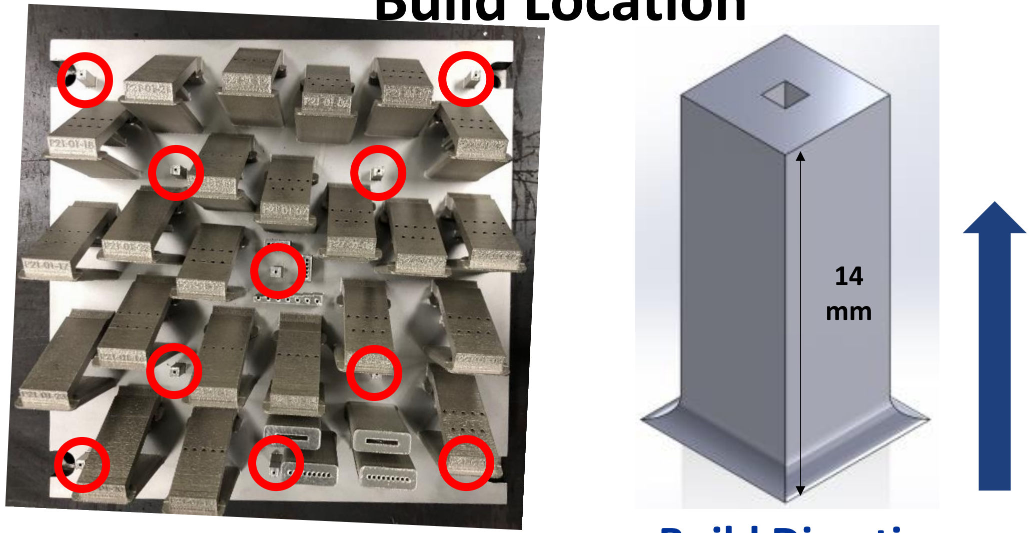
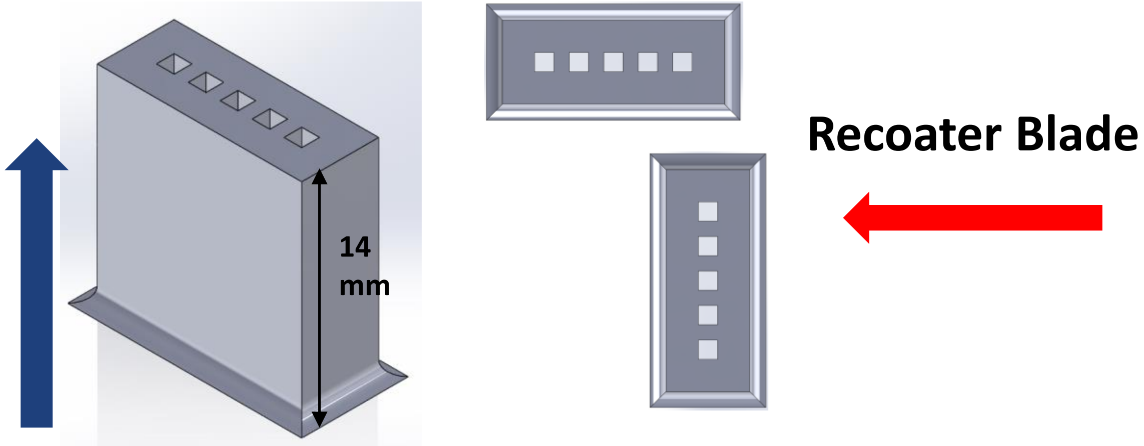
START

Multiple samples were designed in order to investigate the cause for the high surface roughness seen in the 90° internal channels

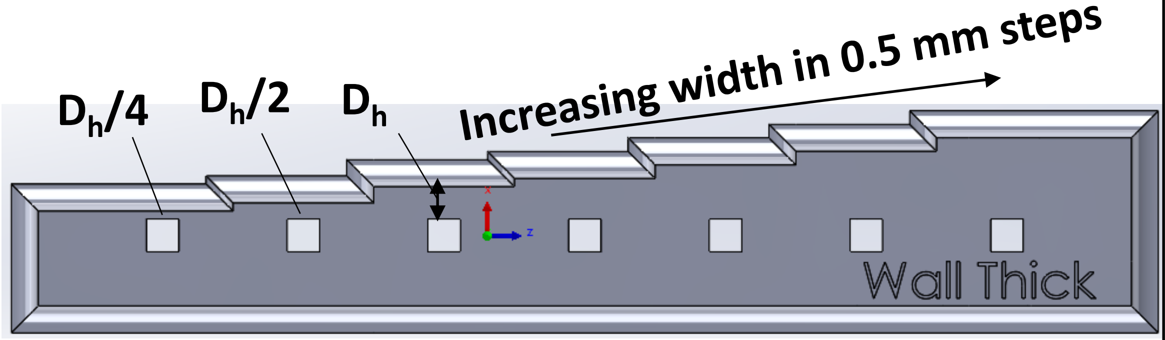
Build Location



Recoater Blade Direction

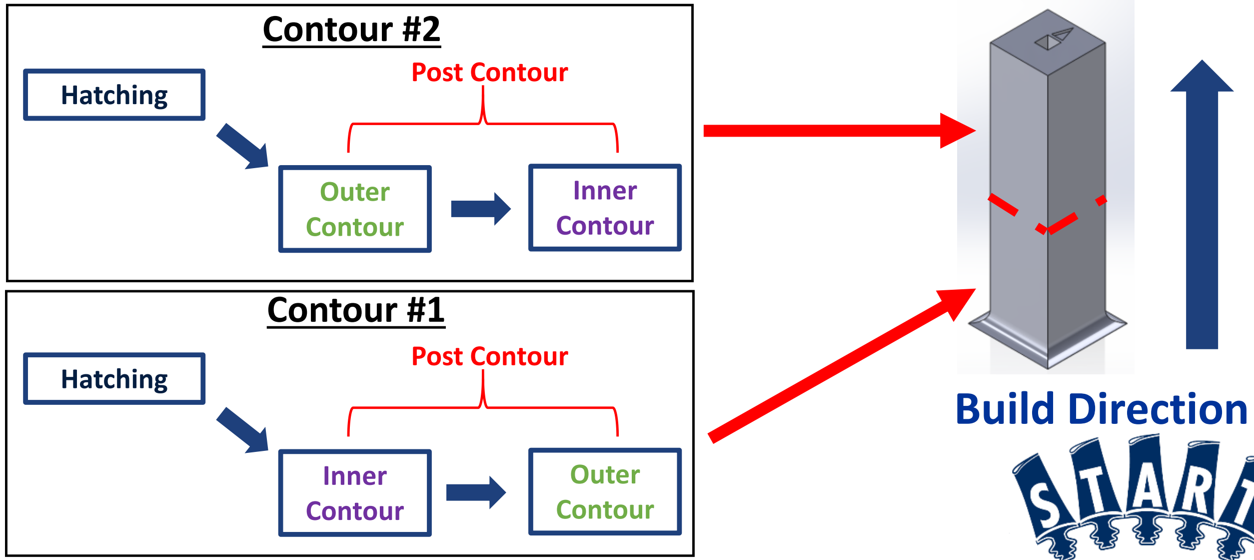


Wall Thickness



$D_h = D_{h,\text{ square internal channel}}$

Contour Priority



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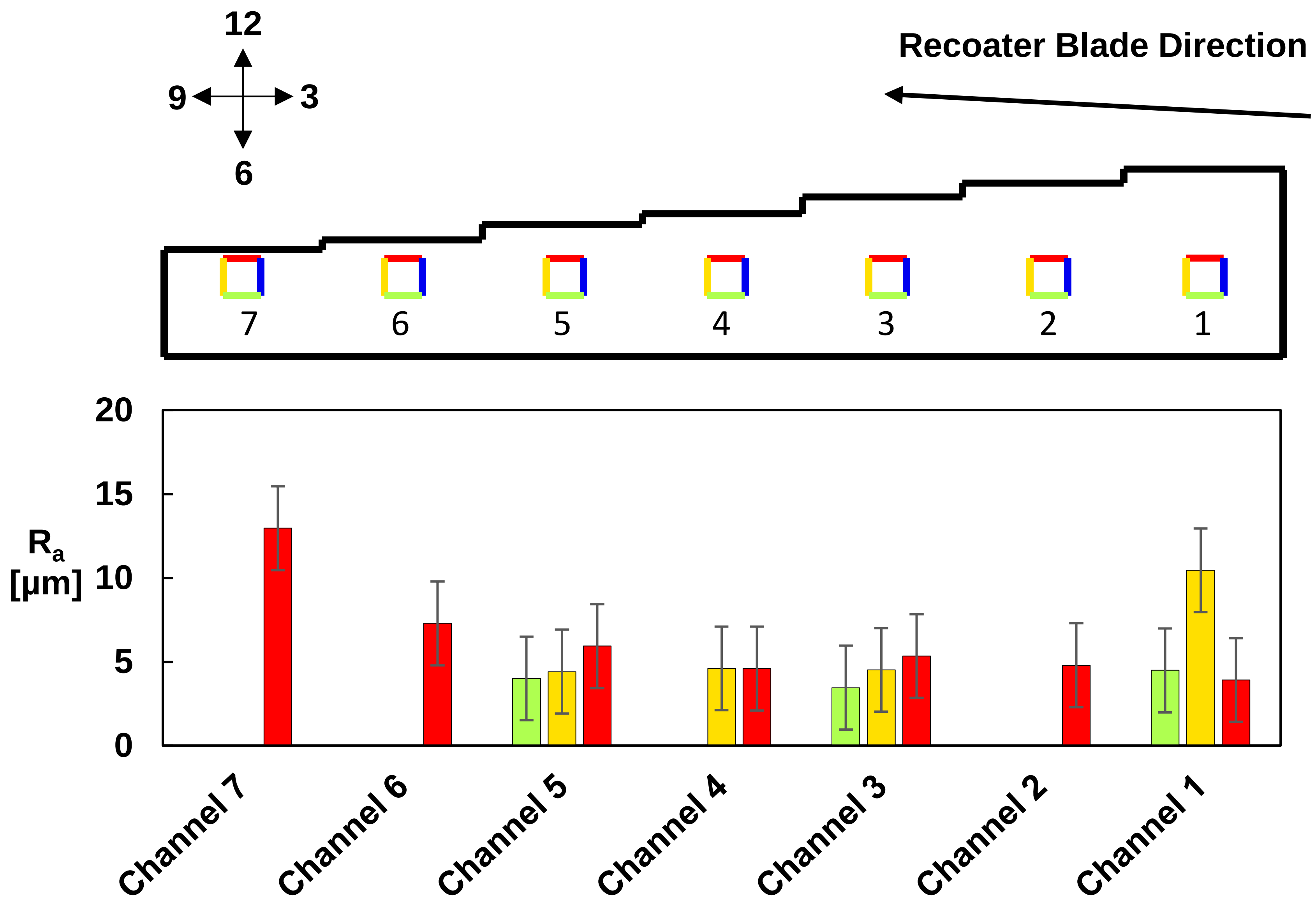
CT scan measurements show that arithmetic mean roughness increases as wall thickness decreases

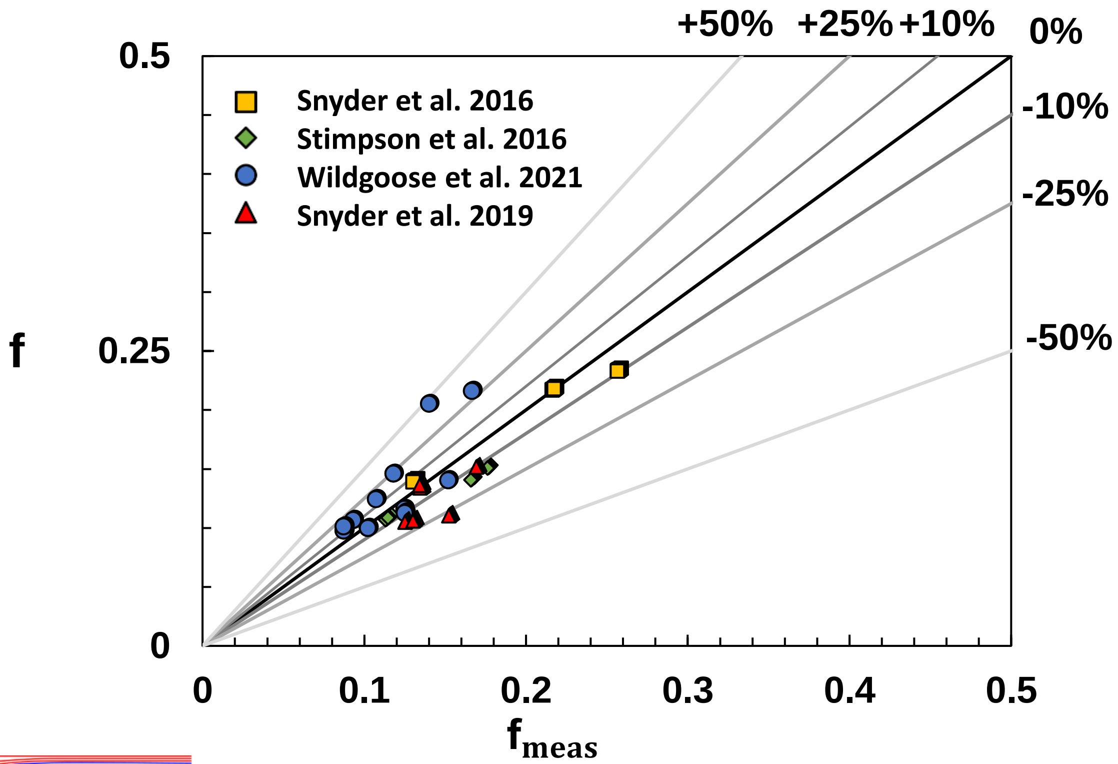


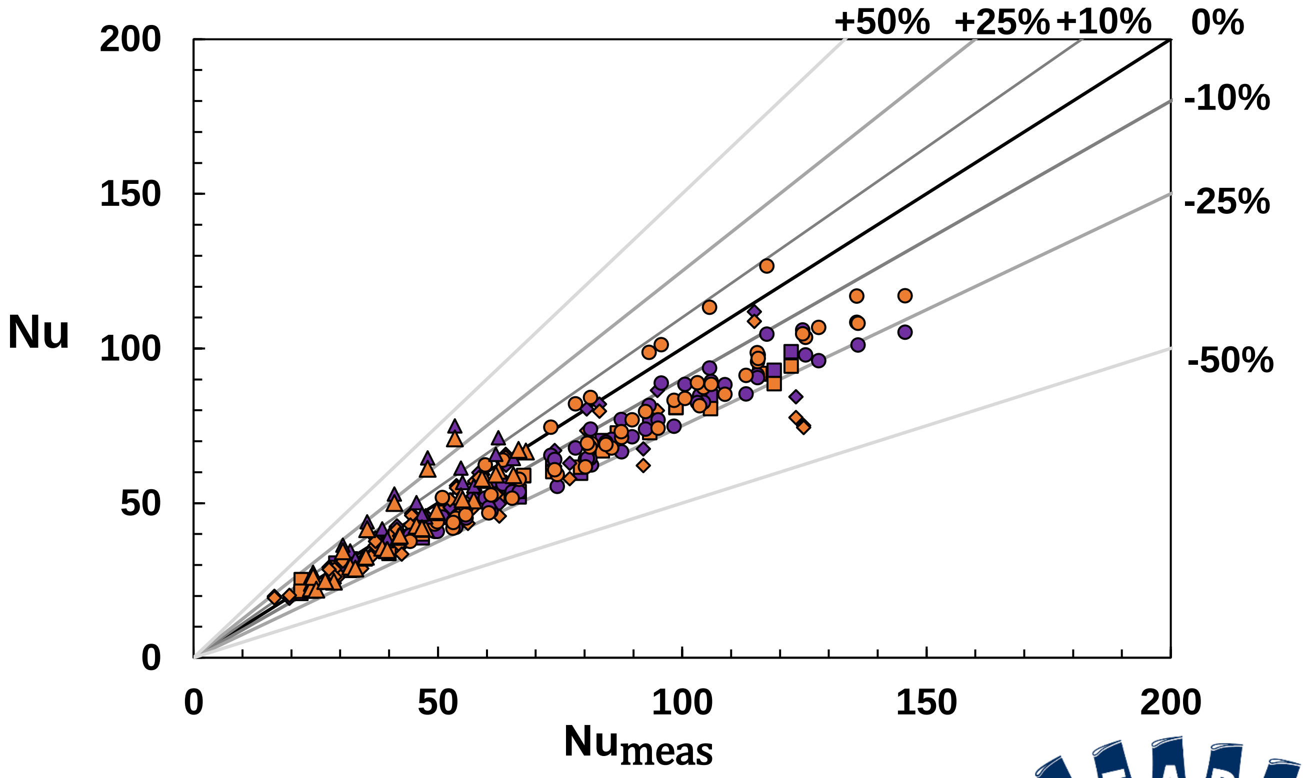
A correlation was created to predict the pressure loss and convective heat transfer of additively made cooling passages with different channel sizes, materials, and build directions

$$\frac{K_s}{D_h}=11\,\frac{R_a}{D_h}$$

$$\frac{1}{\sqrt{f}}=-2.0\log\left[\frac{K_s/D_h}{3.7}+\frac{2.51}{Re\sqrt{f}}\right]$$

$$Nu=\frac{\left(Re^{0.5}-29\right)Pr\left(\sqrt{f/8}\right)}{0.6\left(1-Pr^{2/3}\right)}$$





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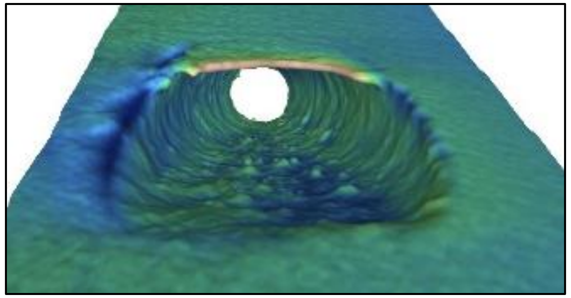
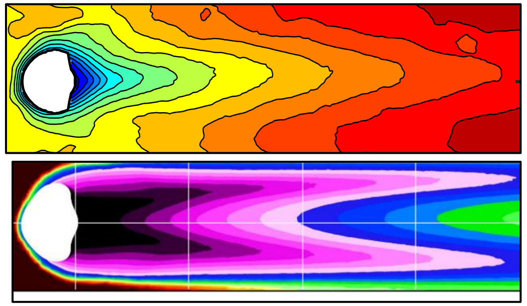
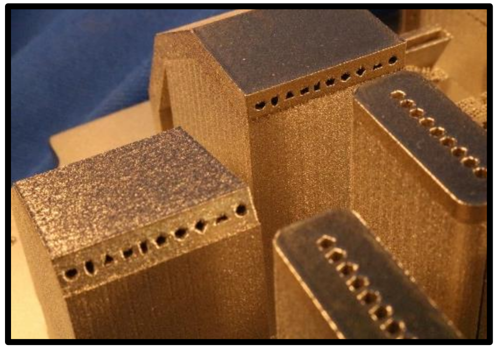
K. A. Thole, S.P. Lynch., A.J. Wildgoose, Review of Advances in Convective Heat Transfer Developed Through Additive Manufacturing, Advances in Heat Transfer, 2021



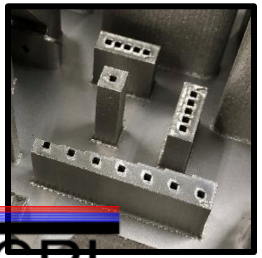
Overall, the AM process captures the features of the cooling holes, with some variations due to surface roughness



The surface roughness within the cooling holes can significantly change the type of cooling pattern from the computational prediction



The combined effects of channel shape and roughness results in impacts to pressure loss and heat transfer augmentation



The influence of build parameters are being investigated to explain the cause for high surface roughness in vertical channels