University Turbine Systems Research
Project Review Meeting

Sept. 27-29, 2022

Integrated Turbine Component Cooling Designs Facilitated by Additive Manufacturing and Optimization

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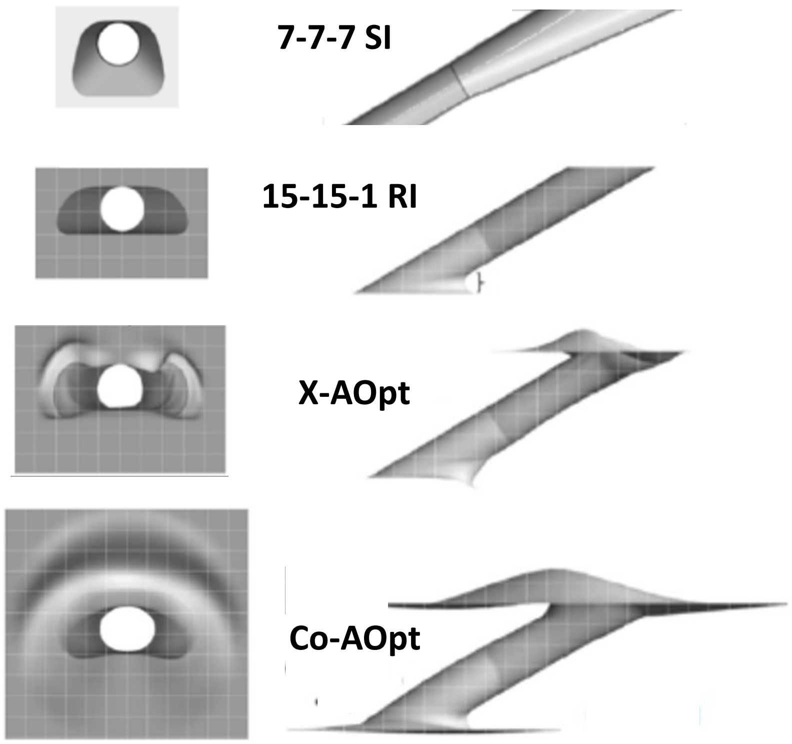
Objectives of this research program

- Experimental verification of the performance for the adjoint optimized film cooling holes.
- Compare performance of AM built 1X (engine scale) models and 5X models.
- Determine appropriate scaling of film cooling performance with varying coolant density ratios.
- Evaluate the effect of coolant feed channel velocity ratio and flow direction.
- Use off-wall thermal field measurements to determine how the adjoint optimized film cooling holes improve cooling performance.

Hole geometries tested



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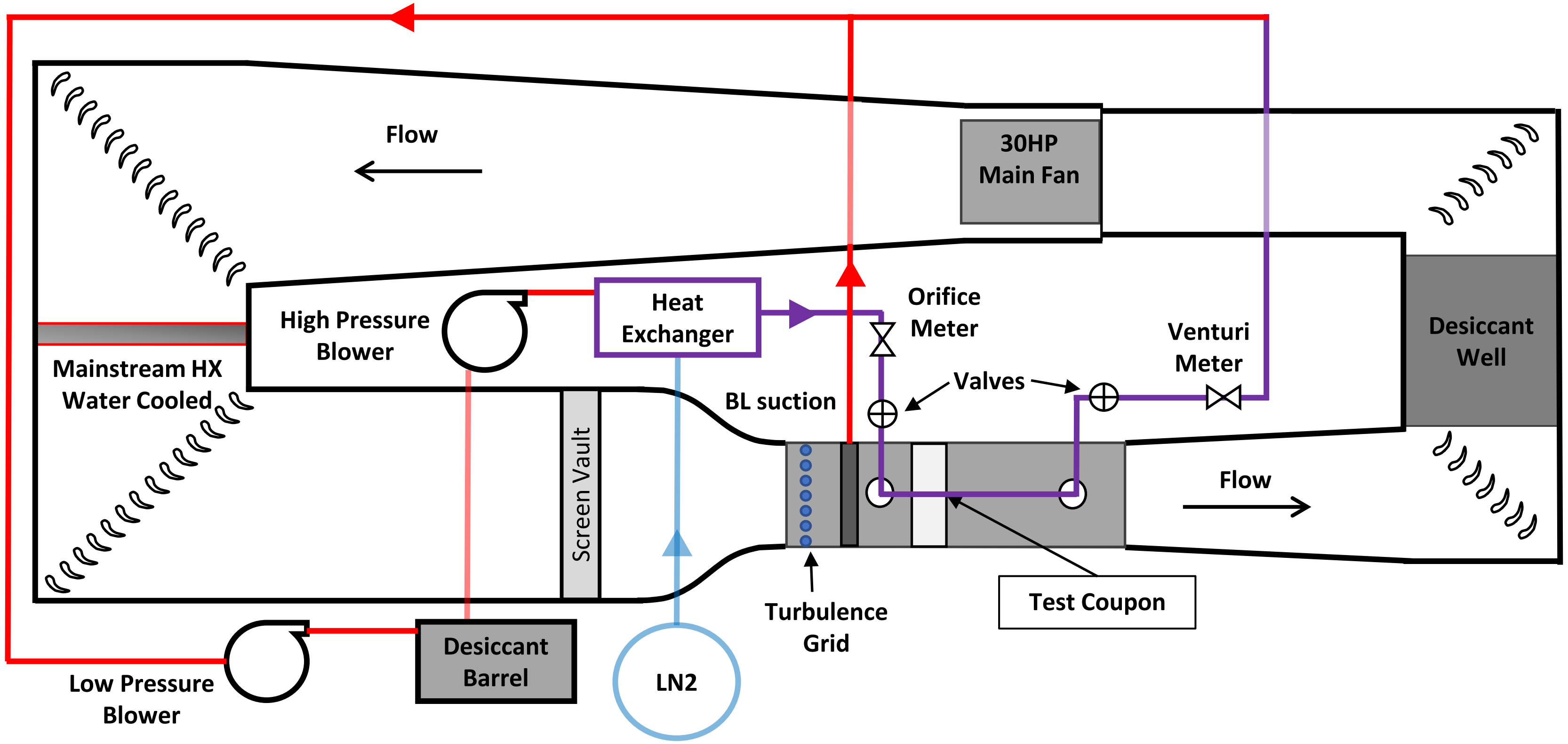
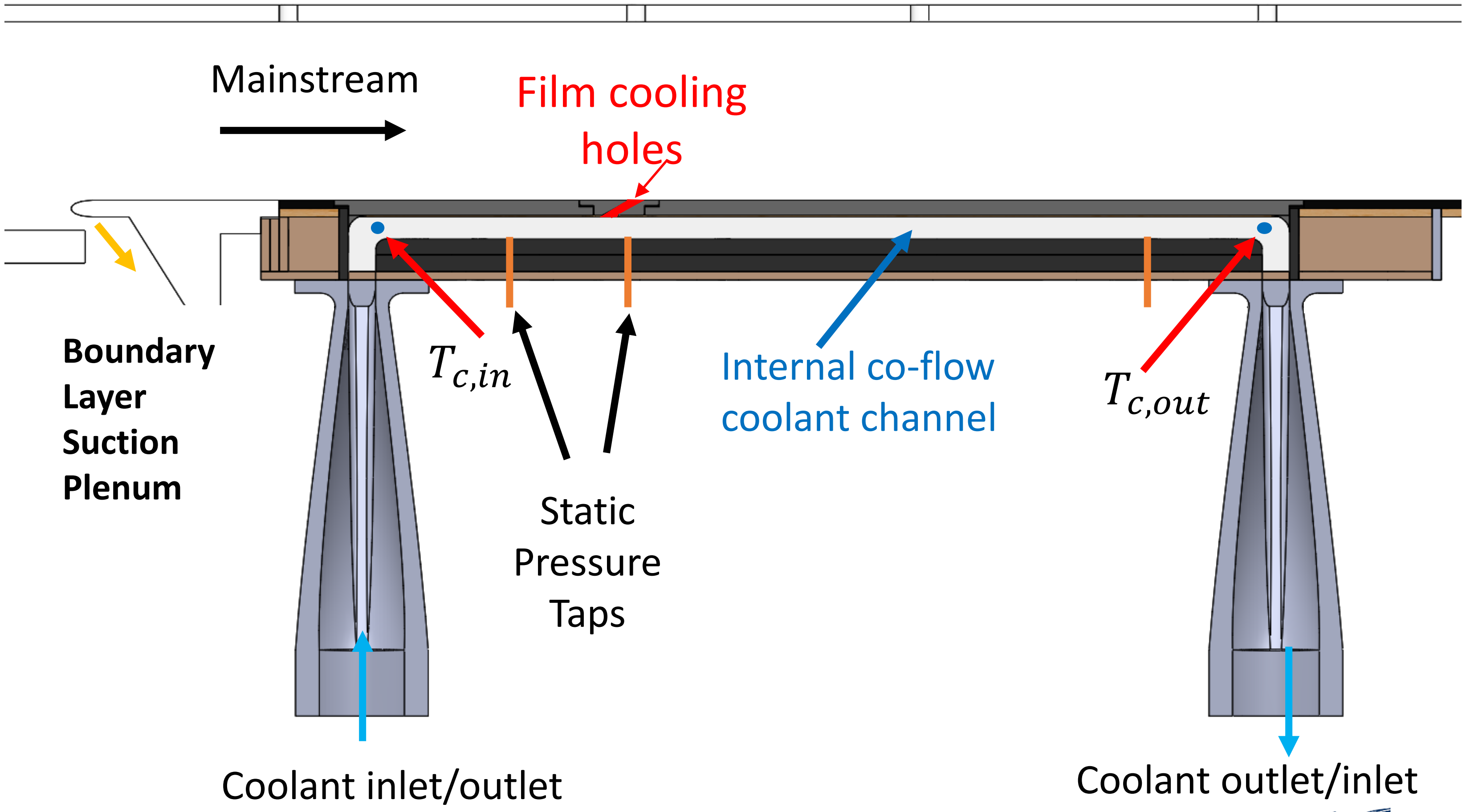
Experiments utilized UT Austin low-speed flat plate wind tunnel facility

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



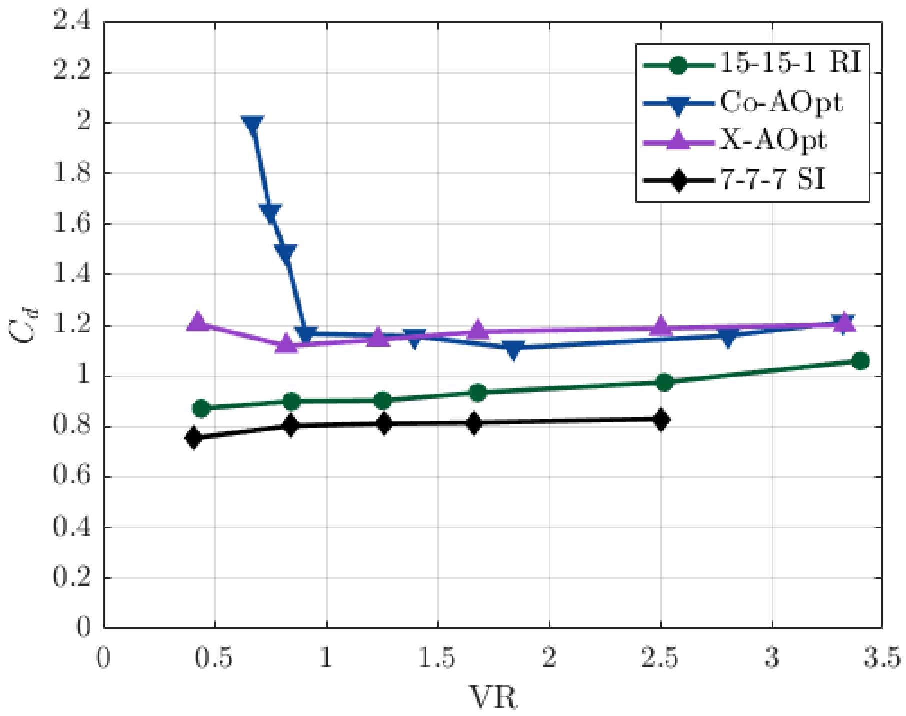
Schematic of test section used for measurements of overall and adiabatic film cooling effectiveness performance for various film cooling hole and internal cooling configurations.

- Turbulence grid upstream (Tu = 5%).
- Density ratios DR = 1.2 to 1.8
- Two test surfaces are used:
  - “Adiabatic” low conductivity polyurethane
  - Matched-Bi Corian
- 5X scale film cooling hole coupons additively manufactured using low conductivity and high conductivity materials.

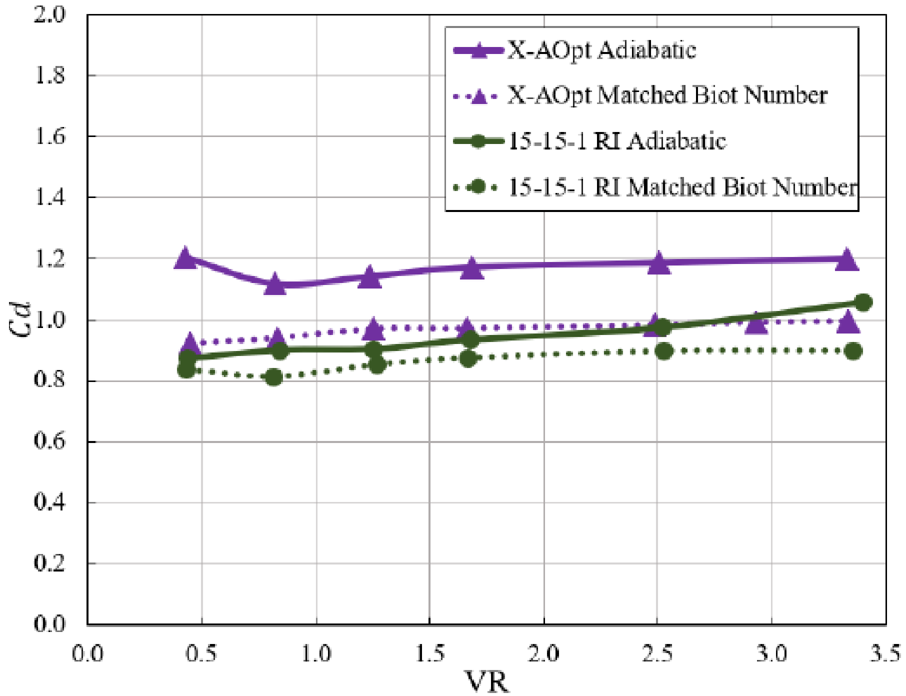


Measurements of C_d showed significantly higher values for the adjoint optimized holes.

C_d distributions for adiabatic models



Comparison of C_d distributions for adiabatic and conducting models



- Optimized geometries showed an increase in C_d by 50% when compared to 7-7-7 SI hole geometry.
- The large increase in C_d at low *VR* for the C0-AOpt hole is an artifact due to the low pressure region generated over the hole.

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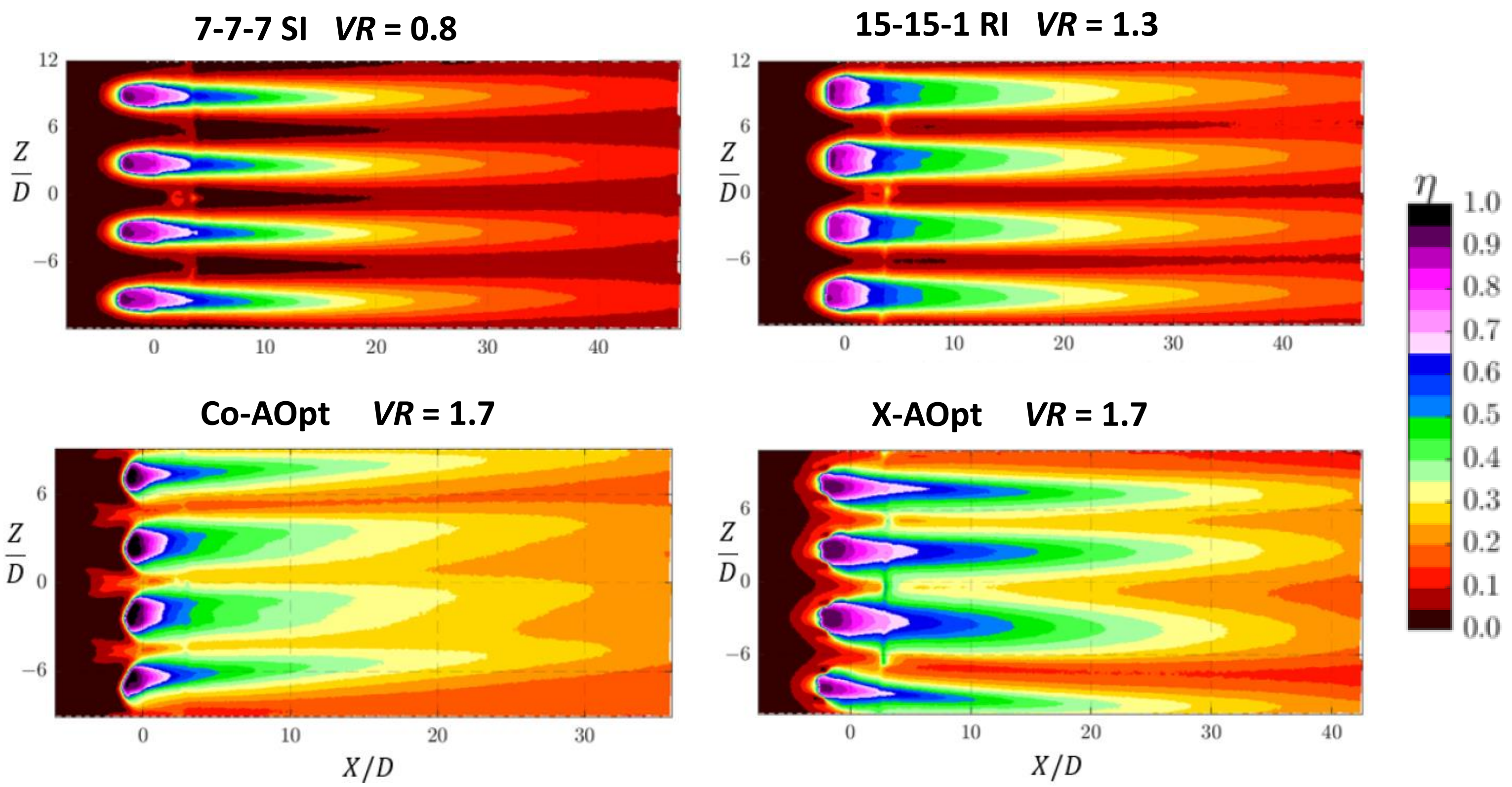
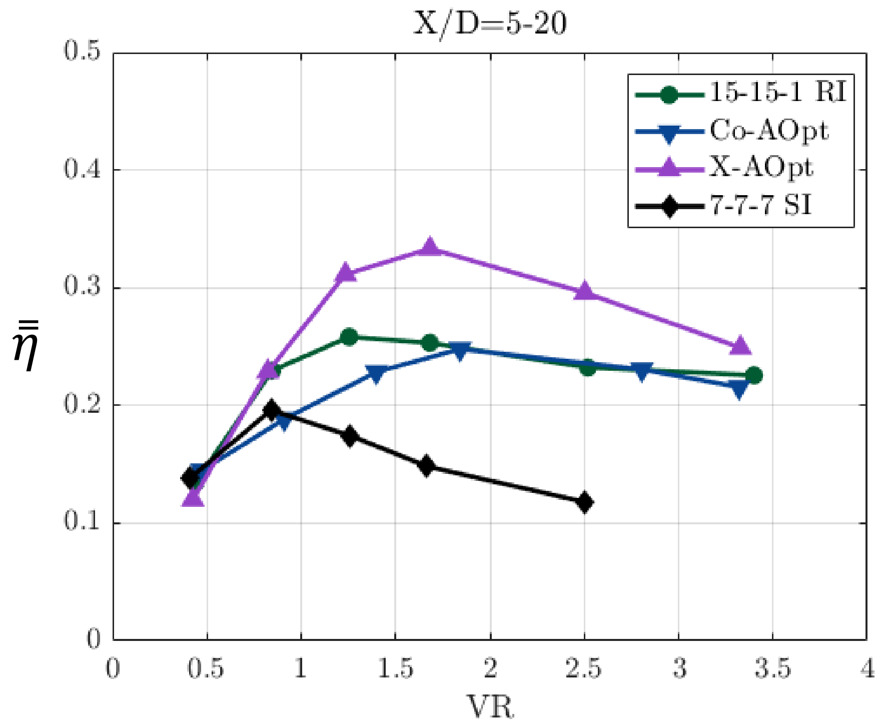
Comparisons of adiabatic effectiveness performance for the four hole geometries

Contour plots at the optimum *VR*

$VR_c = 0.2$

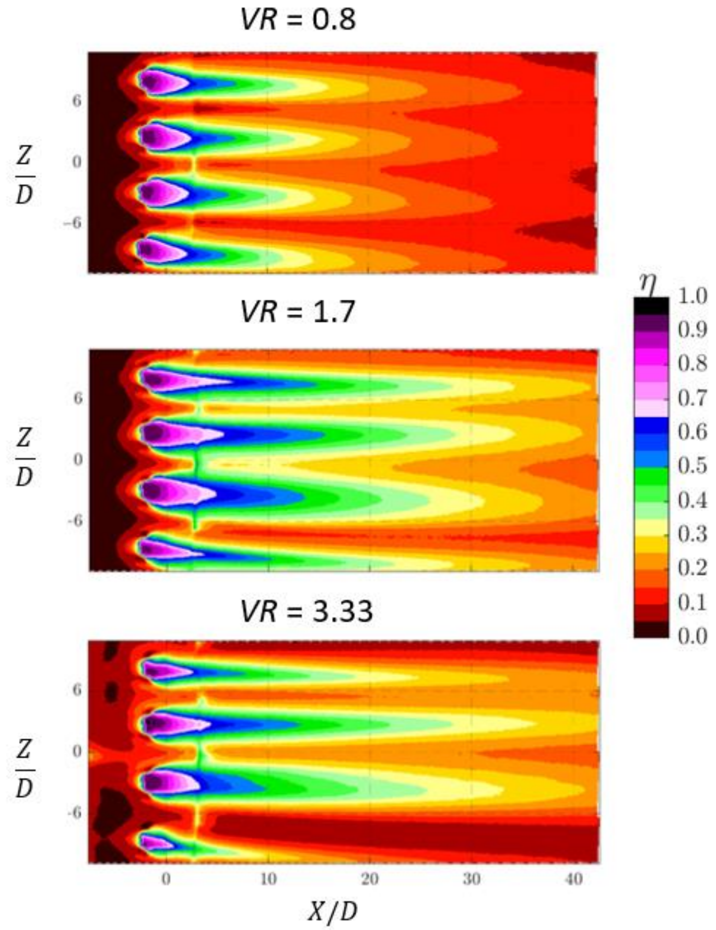




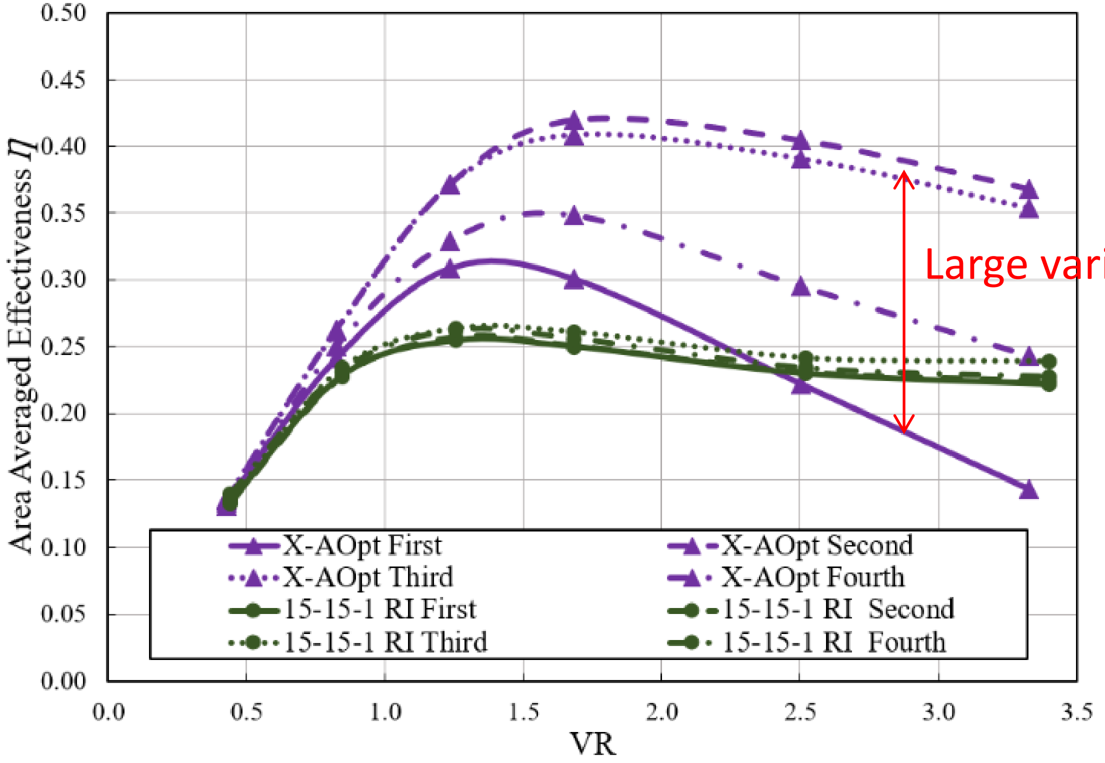
Area averaged $\bar{\bar{\eta}}$ shows that the X-AOpt hole has significantly greater adiabatic effectiveness over a wide range of *VR.*

Investigation of hole to hole variation for η for the X-AOpt holes.

Contours for the X-AOpt holes



Comparisons of $\bar{\eta}$ for each of four holes for the 15-15-1 RI and the X-AOpt hole geometries



Large variance at high *VR*

Multiple experiments showed that these results were repeatable. This indicates that, for holes that started performing poorly at high *VR,* small imperfections in the hole AM build had a large effect on performance.

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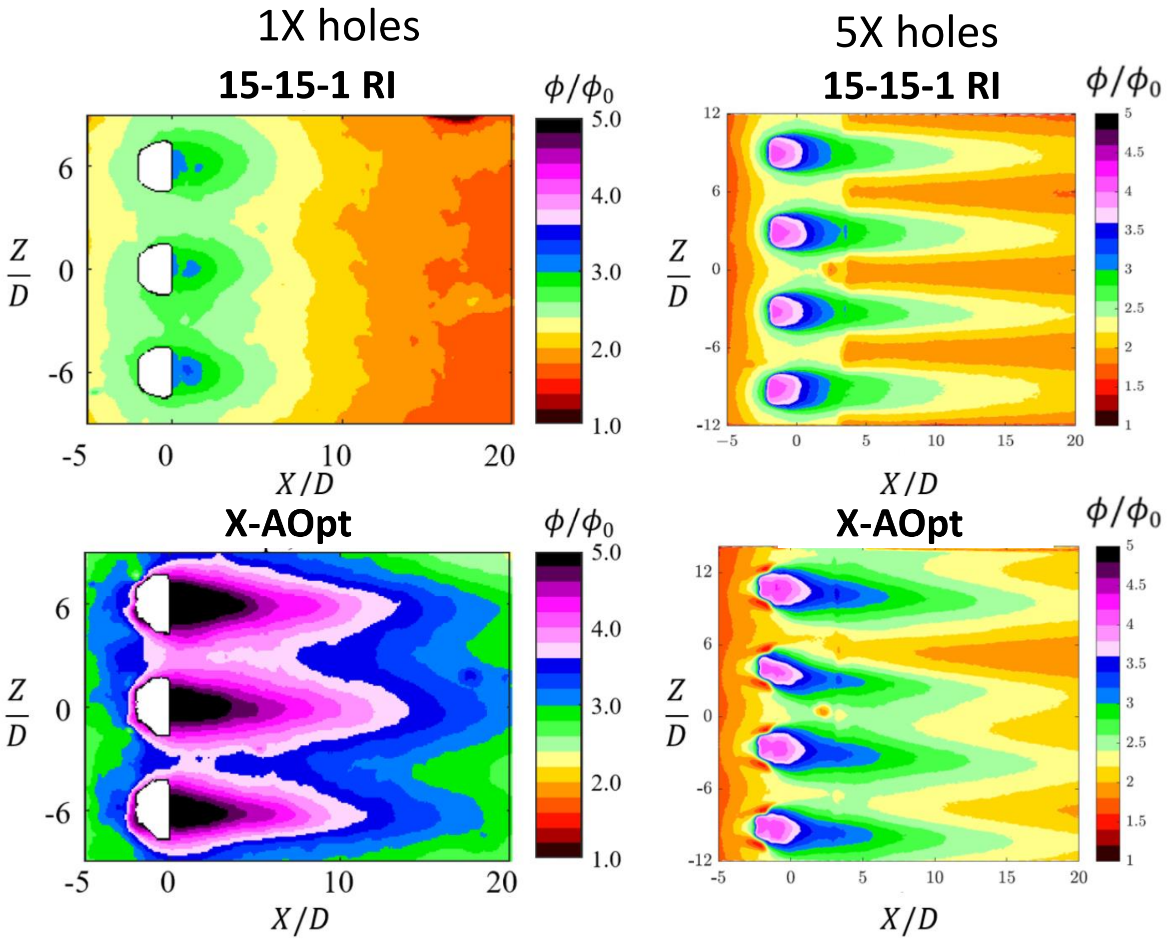
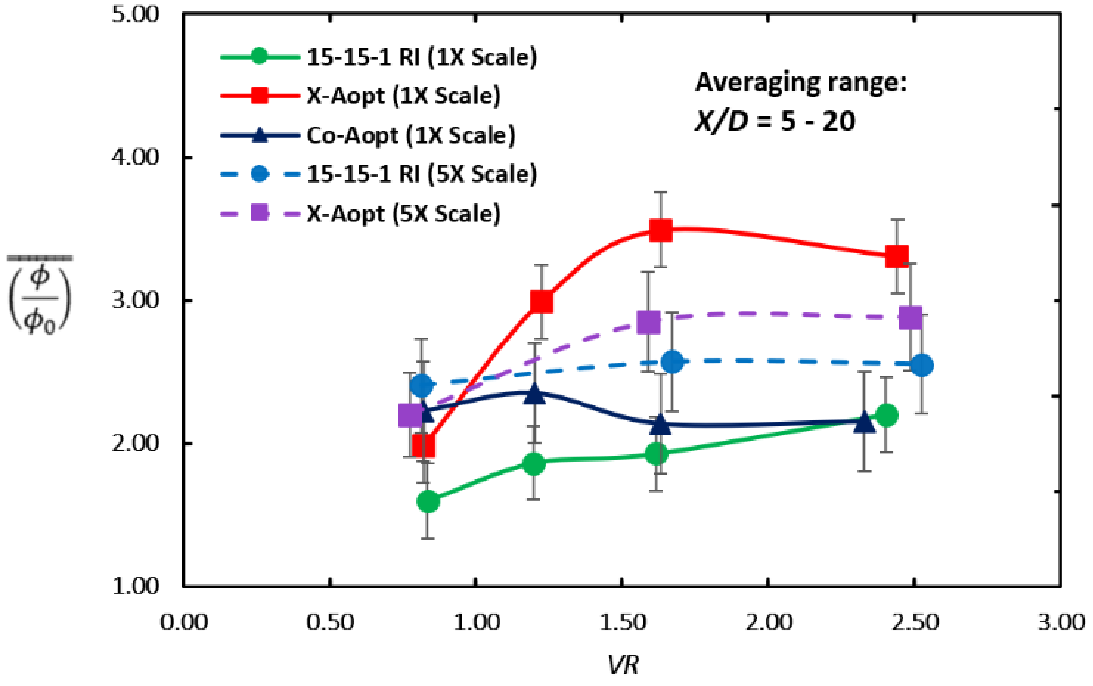
Overall effectiveness results for 1X models (engine scale) and 5X models

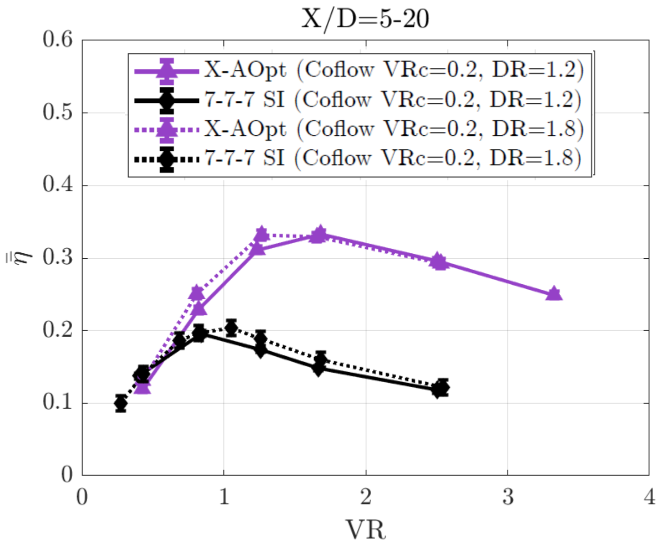
Overall effectiveness contours



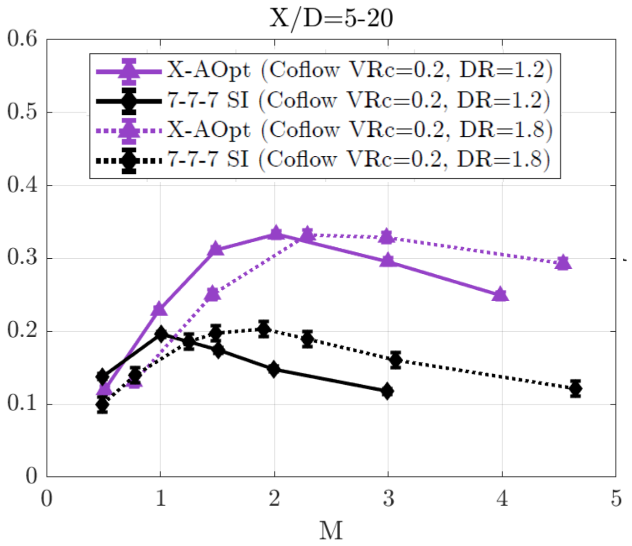


The engine scale X-AOpt hole enhanced overall effectiveness by a factor 3.5 which exceeded the as designed X-AOpt holes which enhanced overall cooling effectiveness by a factor of 3.0.

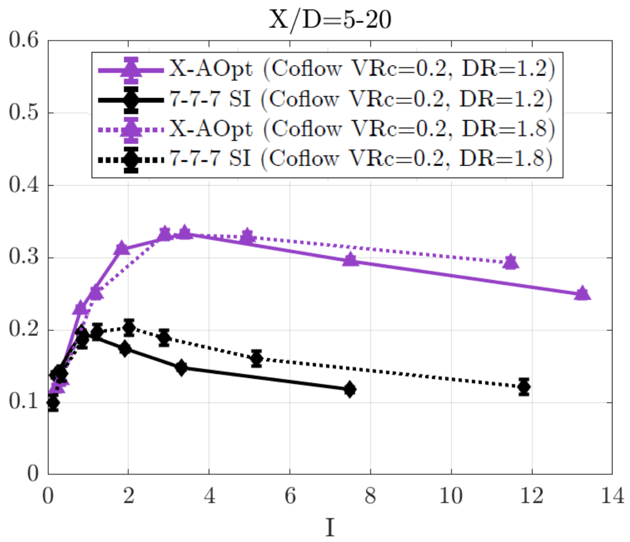
Film cooling effectiveness was best scaled by jet velocity ratio (*VR*) for density ratios varying from *DR* = 1.2 to 1.8.



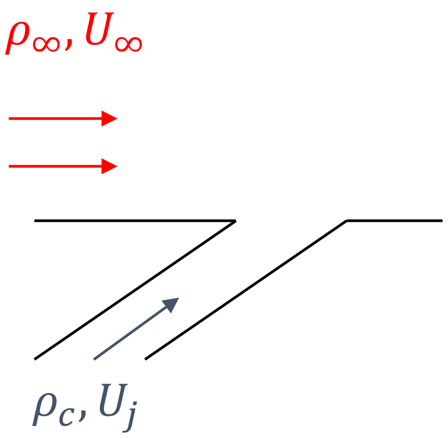
Velocity ratio, $VR = \frac{U_j}{U_\infty}$



Blowing ratio, $M = \frac{\rho_c U_j}{\rho_\infty U_\infty}$



Momentum flux ratio, $I = \frac{\rho_c U_j^2}{\rho_\infty U_\infty^2}$



- While most of our experiments are performed in $DR = 1.2$, engine-realistic *DR* is closer to $DR \approx 2$
- In addition to *DR* = 1.2 experiments, 7-7-7 and X-AOpt were run at $DR = 1.8$
- *VR* was best at collapsing both experiments. Note that most film cooling literature reports values of blowing ratio (*M*).

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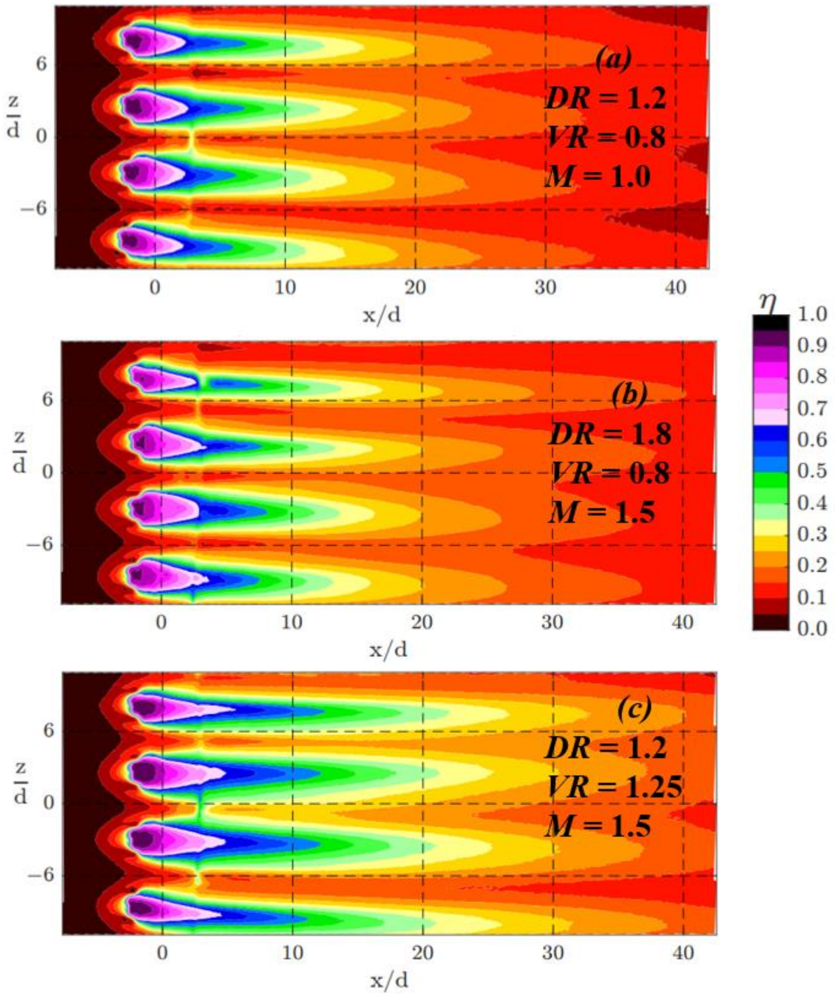
Adiabatic effectiveness contours for varying density ratios are best matched when using the same *VR* rather then the same *M.*



η contours of X-AOpt holes at *DR = 1.2* and *DR = 1.8*

- (a) and (b) have the same *VR* but different *M*. The contours look similar.
- (b) and (c) have the same *M* but different *VR*. The contours look very different.
- This confirms that results from $DR = 1.2$ experiments can be translated to engine-realistic *DR* experiments if the data are presented with *VR.*

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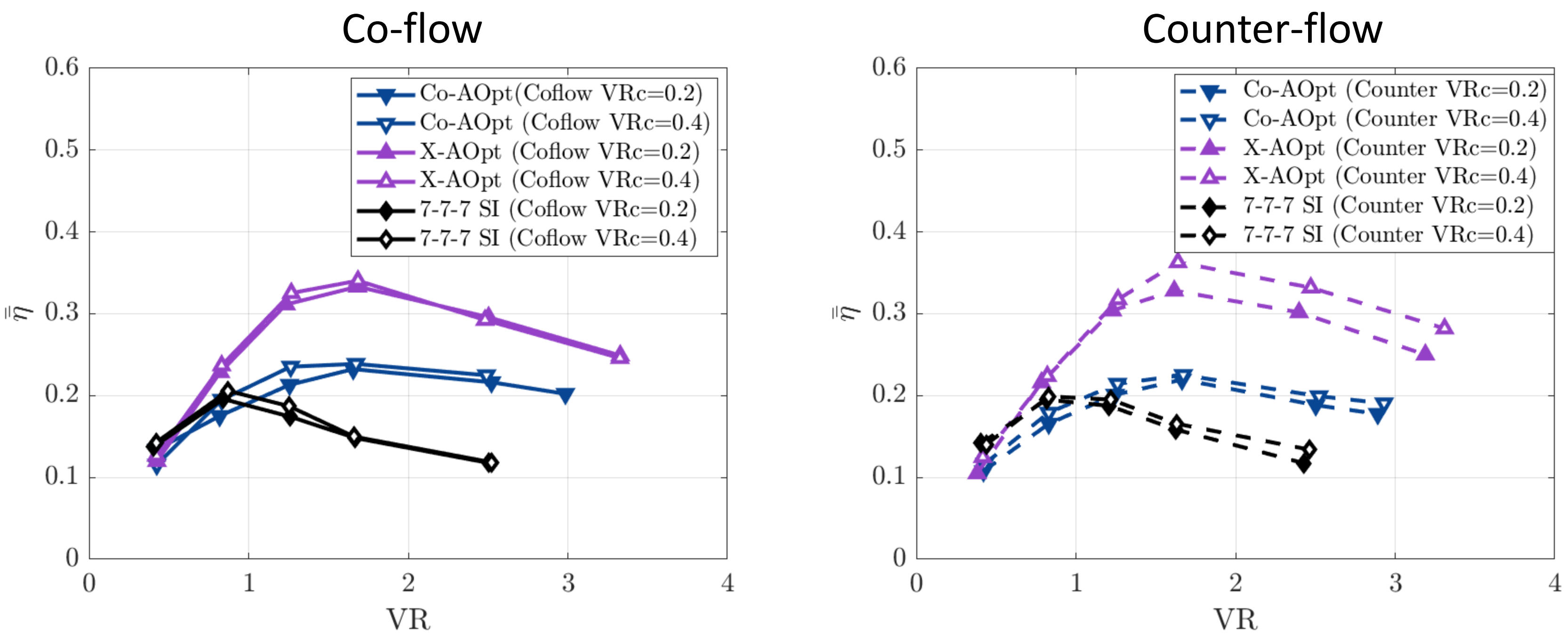
The holes were tested at VR_c = 0.2 and 0.4 in co-flow and counter-flow configurations to determine internal flow effects



VR_c effect on film cooling performance for co-flow and counter-flow fed 7-7-7 SI, Co-Aopt, and X-Aopt holes

$$VR_c = \frac{U_{channel}}{U_\infty}$$

- VR_c does not have a noticeable effect for co-flow configuration
- For X-AOpt holes, there was a noticeable effect of VR_c in counter-flow configuration, with a 12% increase for $VR_c = 0.4$ case compared to $VR_c = 0.2$ case

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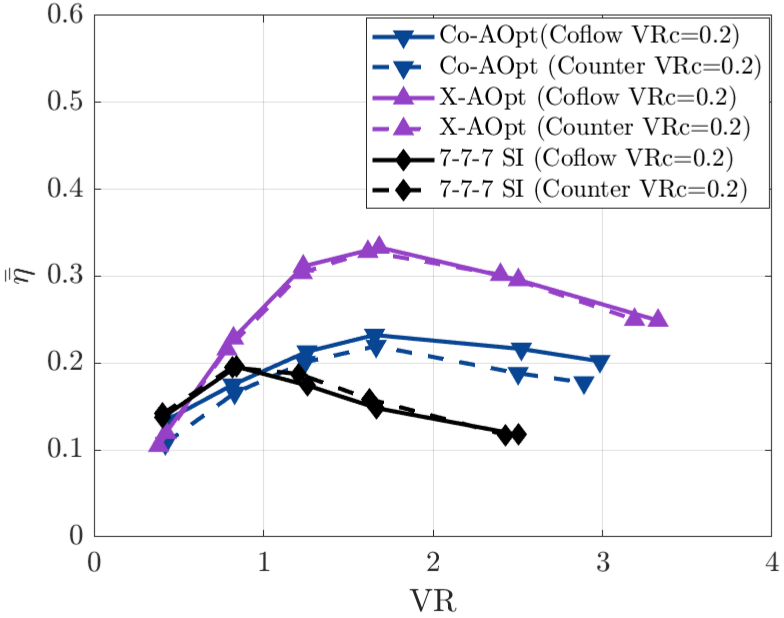
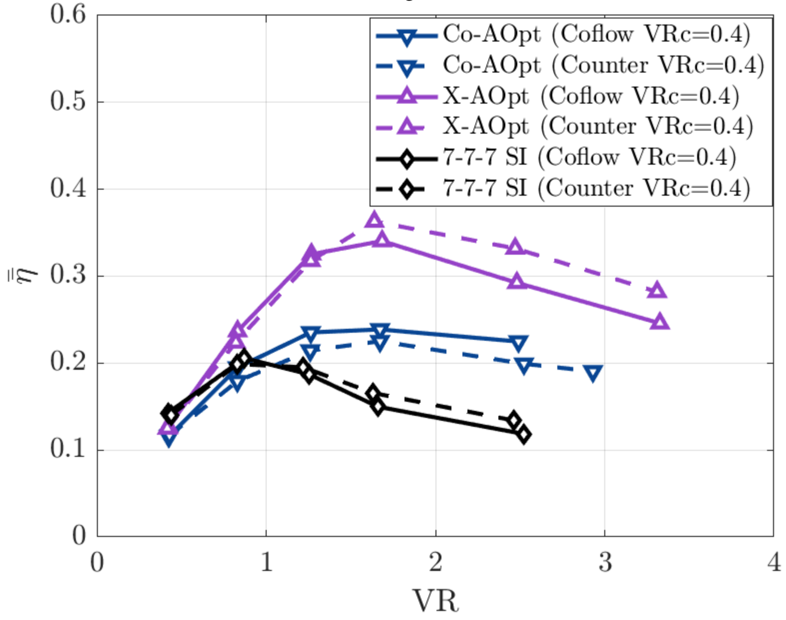
In general the performances of all holes were very similar for co-flow and counter-flow feed of the coolant holes at both velocity ratios.

VR_c = 0.2



VR_c = 0.4



Flow direction effect on film cooling performance for the 7-7-7 SI, Co-Aopt, and X-Aopt holes with VR_c = 0.2 and 0.4

$$VR_c = \frac{U_{channel}}{U_\infty}$$

- For VR_c= 0.2 there were negligible effects on the 7-7-7 SI and X-AOpt holes, but counter-flow causes a slight degradation for the Co-AOpt hole.
- At VR_c = 0.4 the X-AOpt hole performs noticeably better with counter-flow feed for *VR* > 2.

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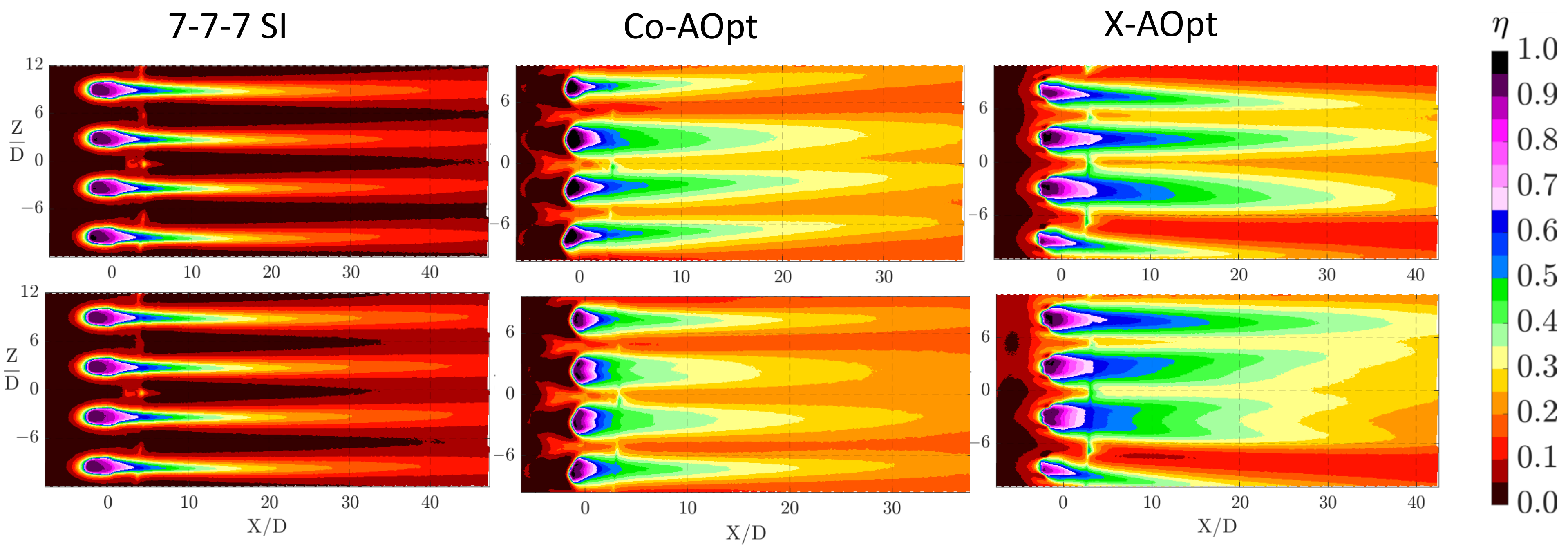
Adiabatic effectiveness contours show differences in performance for co-flow and counter-flow feed at $VR_c = 0.4$.

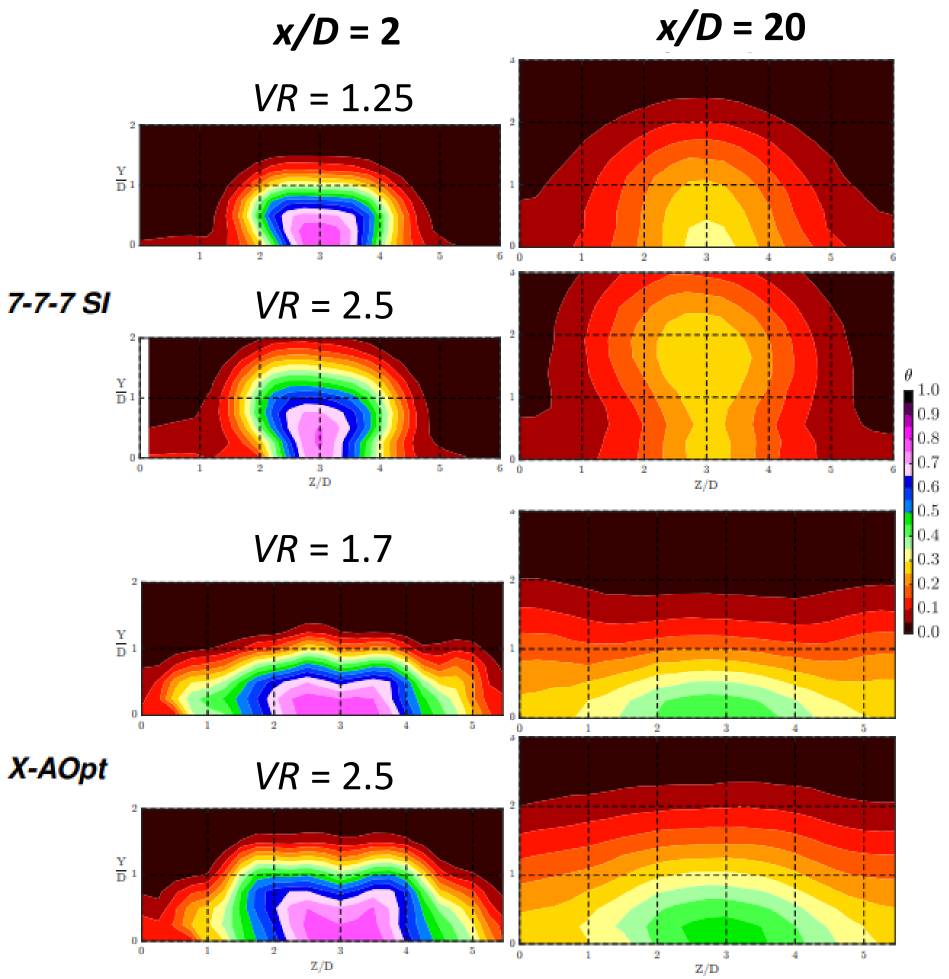
$VR \approx 2.5$
$VR_c = 0.4$
Co-flow

$VR \approx 2.5$
$VR_c = 0.4$
Counter-flow

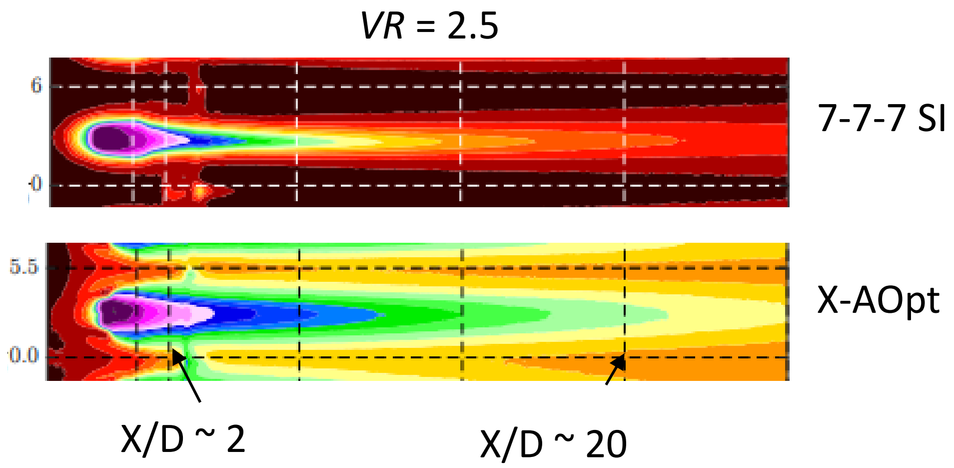


- For the 7-7-7 SI hole, the performance is very consistent whether it is in co-flow or counter-flow
- For the Co-AOpt hole, the jets seem more prone to separation when fed in counter-flow
- For the X-AOpt hole, there is a noticeable broadening of the adiabatic effectiveness distribution. However, the very poor performance of the bottom hole is unchanged.

Off-wall thermal field measurements at *x/D* = 2 and 20 show that the coolant jet from the X-AOpt hole remains attached to the surface and has less dispersion of the coolant compared to the 7-7-7 hole.



$$\theta = \frac{T_\infty - T}{T_\infty - T_c}$$



A fine wire thermocouple probe measured the thermal fields at *x/D* ≈ *2* and 20. An optimal *VR* and a high *VR* were chosen for comparison

7-7-7 showed clear detachment of the jet at high *VR*, whereas X-AOpt showed a flat profile in both *VR's*

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Conclusions

- The new film cooling holes designed using adjoint methods for optimization of the hole geometries had as much as 70% improvement in adiabatic effectiveness compared to convention film cooling hole geometries.
- Holes constructed with metal AM at engine scale were verified to have similar improvement in performance.
- Tests at density ratios of *DR* = 1.2 and 1.8 showed that testing at low density ratios matched performance at high density ratios when matching *VR*.
- Testing with co-flow and counter-flow in the coolant channels feeding the film cooling holes at VRc = 0.2 and 0.4 showed little effect on performance.
- Thermal field measurement of coolant jet profile above the wall showed the effectiveness of the X-AOpt hole in keeping coolant jets attached and reducing the dispersion of coolant.

Thermal fields for the X-AOpt holes