AerE545/AerE445 class notes

Lecture 11: Pressure Sensitive Paint (PSP) & Temperature Sensitive Paint (TSP) - Part 02

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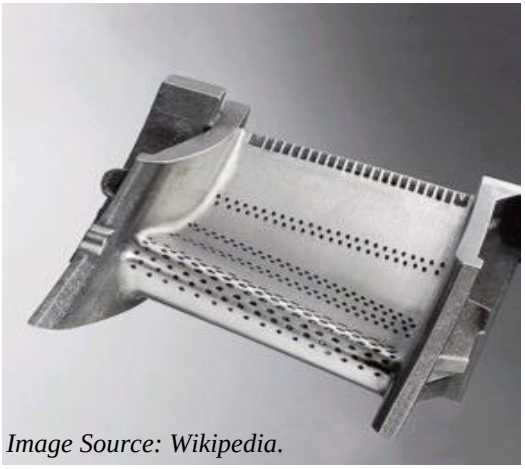
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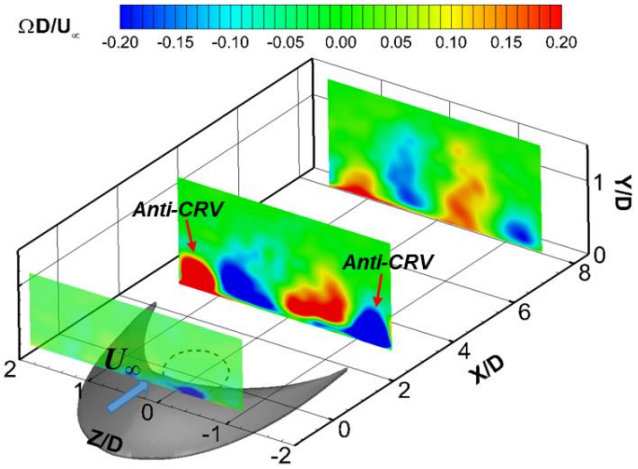

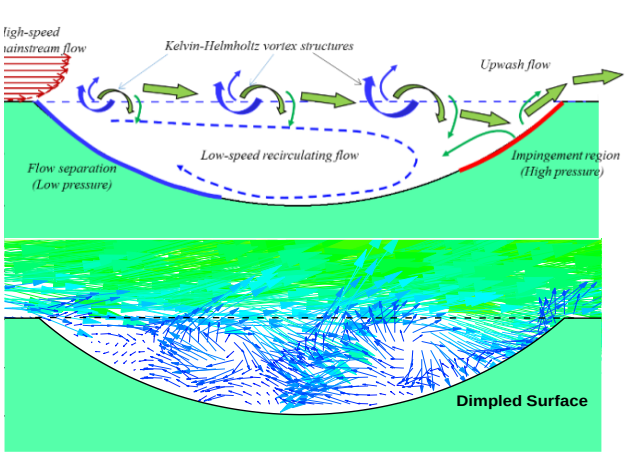

A PSP application to Evaluate Novel Cooling Designs for Better Protection of Gas Turbine Blades

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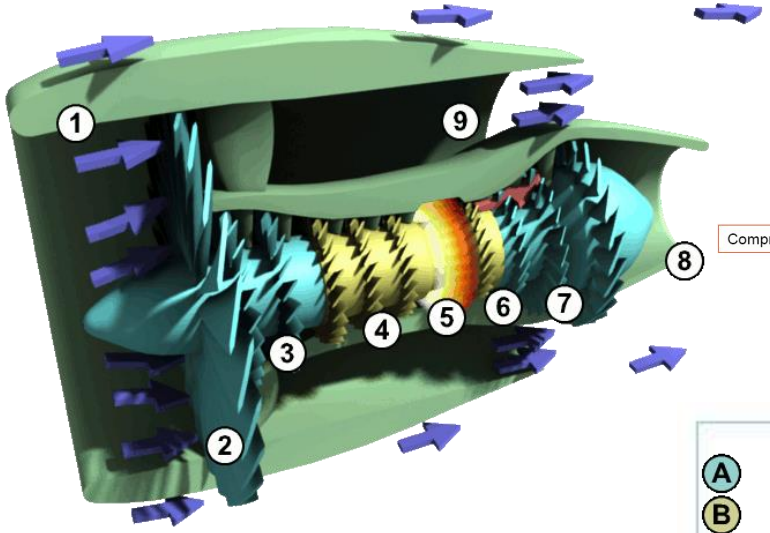
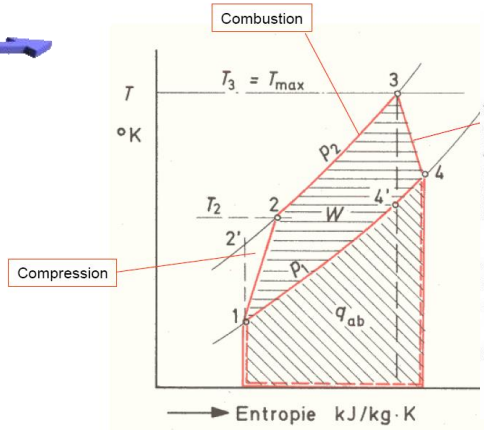
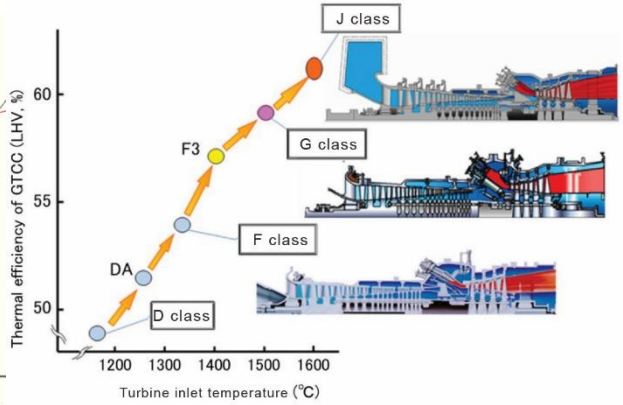
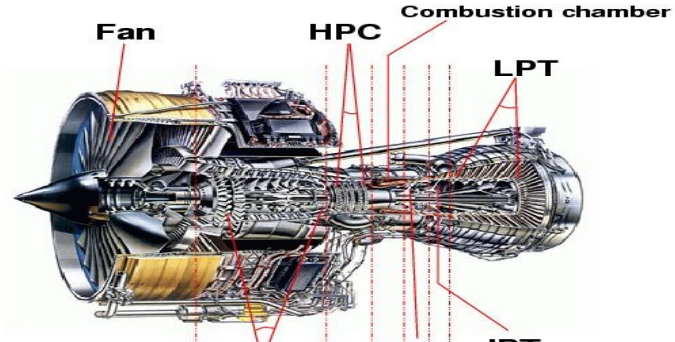
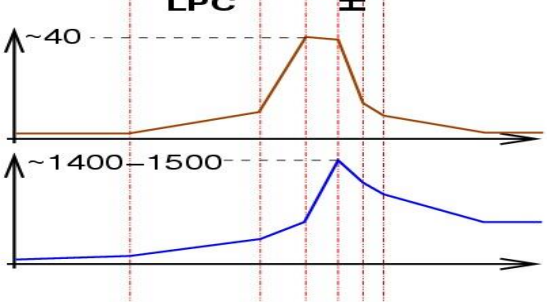
Gas Turbines and Turbine Inlet Temperature











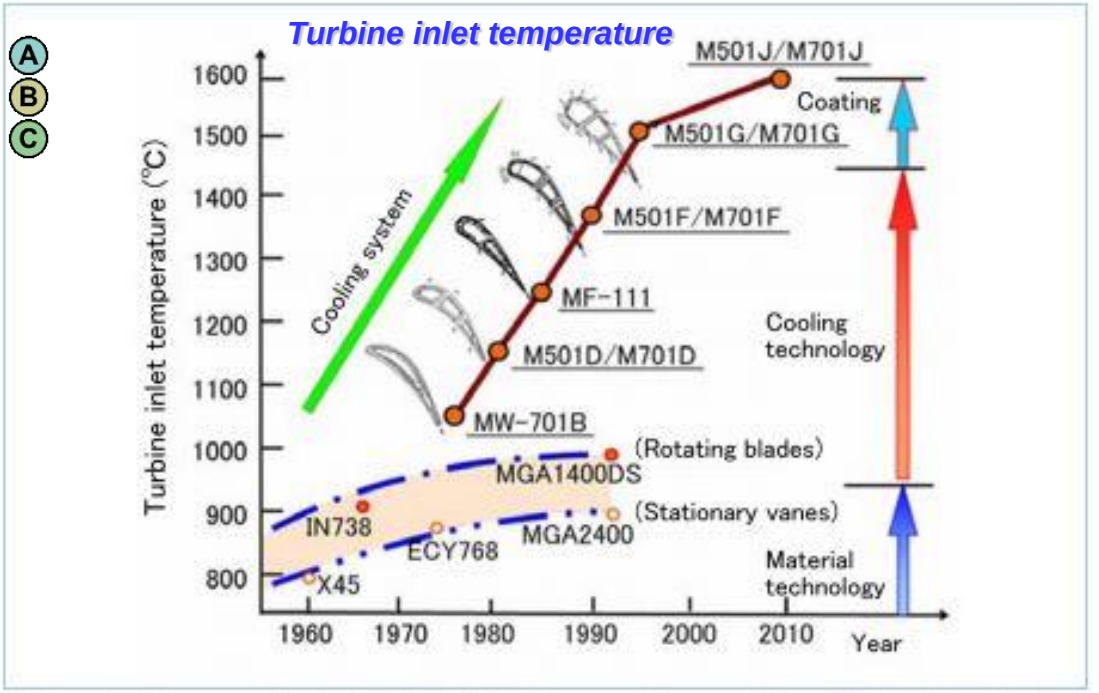
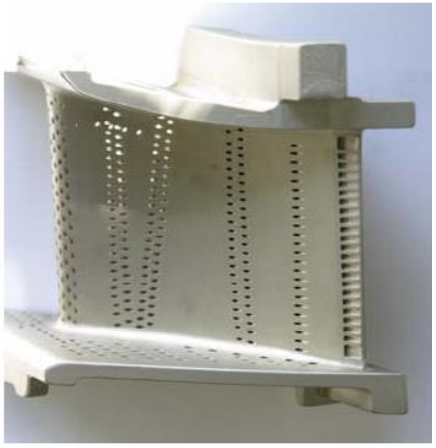
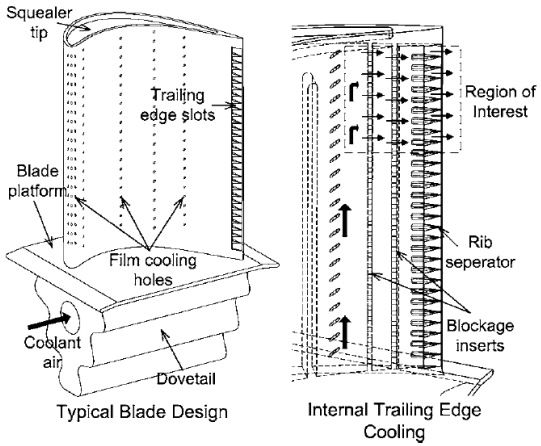


Figure 1 Increase in the turbine inlet temperature and transition of applied materials and technologies

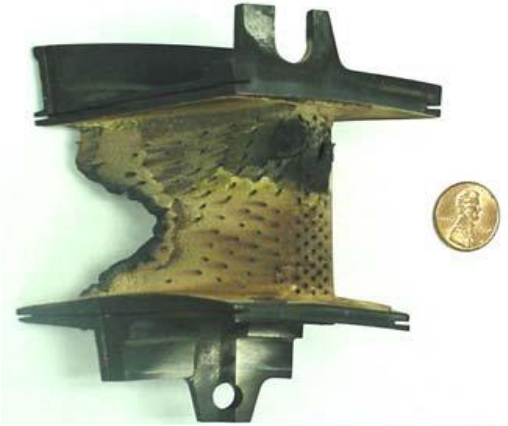
Cooling Technologies for Gas Turbine Blades

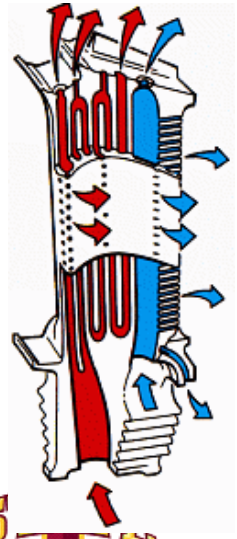
- *Turbine entry temperature: ~ > 3000 ^{O}F (>1650 ^{O}C)*
- *Melting point of metal: ~ 2400 ^{O}F (1300 ^{O}C)*

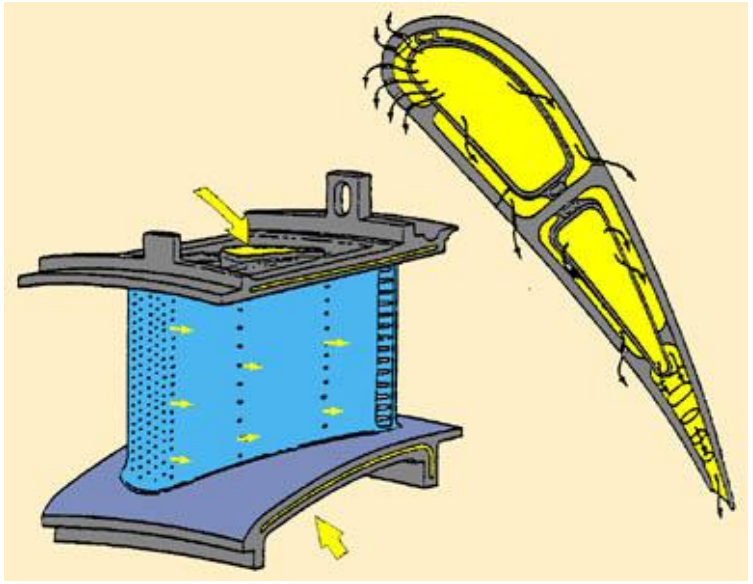




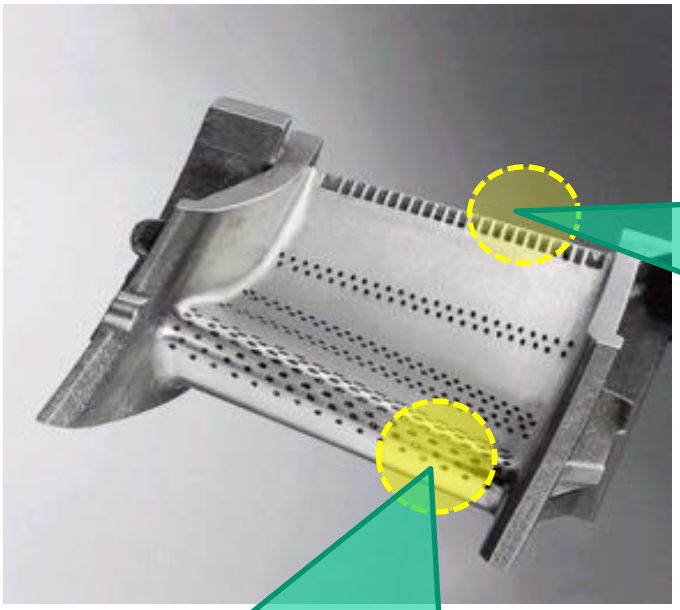
- *Protect turbine blades from damage:*
  - *New material to endure higher temperature*
  - *State-of-art cooling techniques for film cooing and trailing edge cooling.*







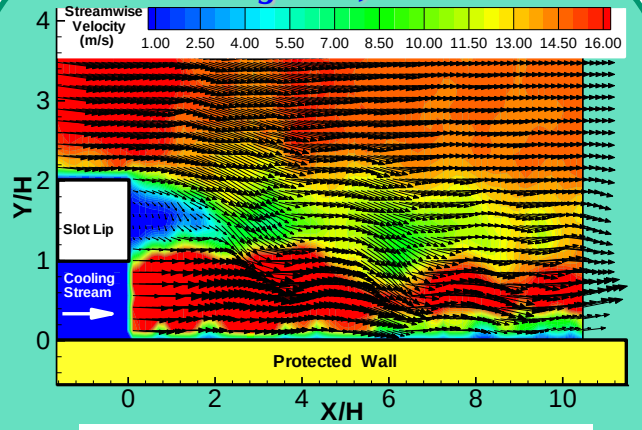
Cooling of Gas Turbine Blades



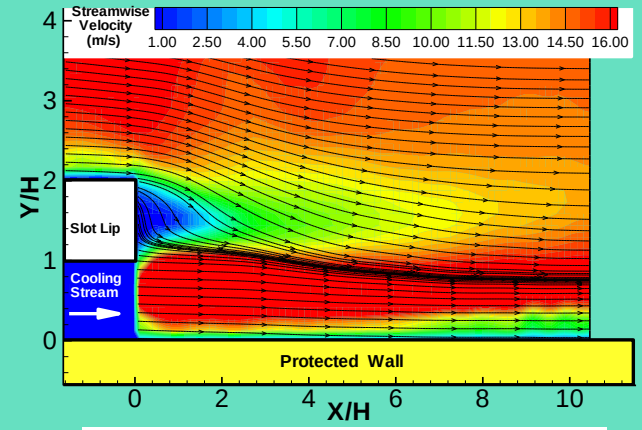
Trailing edge cooling

- *Heat transfer*
- *Mass transfer*
- *Momentum transfer*
- *….*

Blowing ratio, M=1.60

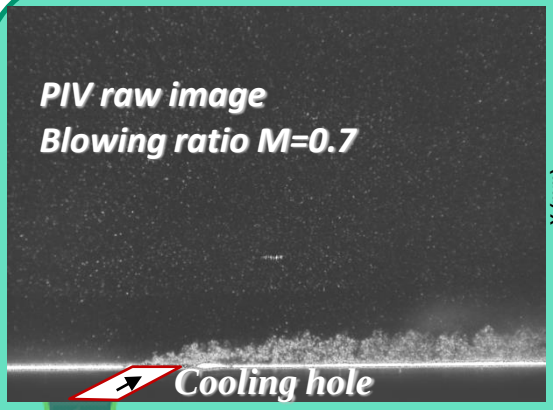


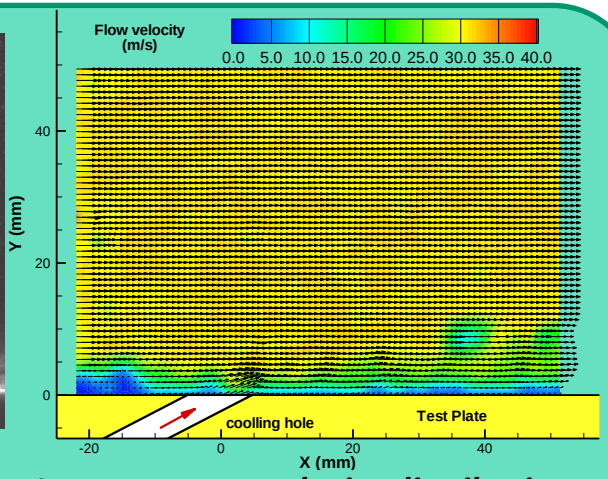
Instantaneous velocity distributions



Time-averaged velocity distribution

Film cooling





Instantaneous velocity distribution

Background of Film Cooling Effectiveness

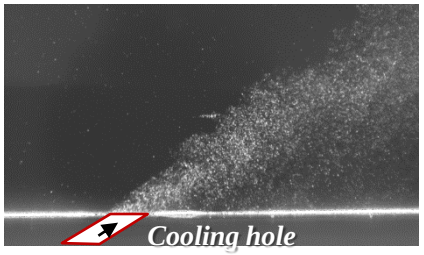
- ***Traditionally, the film cooling efficiency is defined based on temperature ratio:***

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c}$$

T_{aw} : ***adiabatic wall temperature***
T_∞ : ***the mainstream temperature***
T_c : ***the temperature of coolant.***

- ***Film cooling effectiveness is greatly affected by following factors***

Coolant/mainstream conditions	***Hole geometry and configuration***	***Blade geometry (Cascade)***
Mass flux ratio $M = \rho_c V_c / \rho_\infty V_\infty$	Shape of hole	Cooling hole location and distribution
Density ratio $DR = \rho_c / \rho_\infty$	Injection angle and compound angle	Leading edge and blade tip, so on
Momentum flux ratio $I = \rho_c V_c^2 / \rho_\infty V_\infty^2 = M^2 / DR$	Hole spacing and entry length	Surface roughness
Mach number	Spacing between rows	Curvature of blade
Rotation		



Film Cooling Effectiveness – Conventional Measurement Techniques

- *Film cooling effectiveness is defined by the ratio of the temperature differences*

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c}$$

where T_{aw} *is the adiabatic wall temperature*
T_∞ *is the mainstream temperature*
T_c *is the temperature of the coolant*

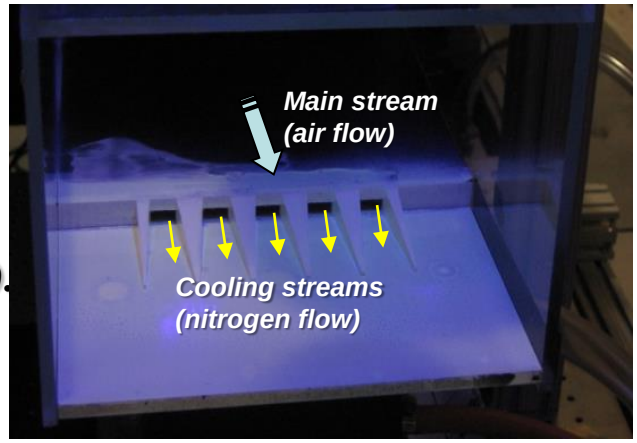
- *Traditionally, the film cooling effectiveness is determined by conducting heat transfer experiments to directly measure these three temperatures with various thermal measurement techniques, such as :*
  - *Surface thermocouple measurements*
  - *IR Thermography*
  - *Thermochromic crystals*
  - *Temperature-Sensitive Paint (TSP)*

- *Since it is very difficult, if not impossible, to ensure that* T_{aw} *can be measured accurately due to heat conduction within the solid test models. The measured cooling effectiveness from heat transfer experiments are always over-predicted.*

Mass Transfer Analogy to Quantify Film Cooling Effectiveness

- ***Mass Transfer Analogy:*** ***the cooling effectiveness can be expressed in terms of the concentration distribution of some species on the protected surface through mass transfer.***
  - ***For example, oxygen concentration on the protected surface measured by using PSP technique (Wright et al, 2005; Han et al, 2005)***

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} = \frac{C_\infty - C_{mix}}{C_\infty - C_C}$$

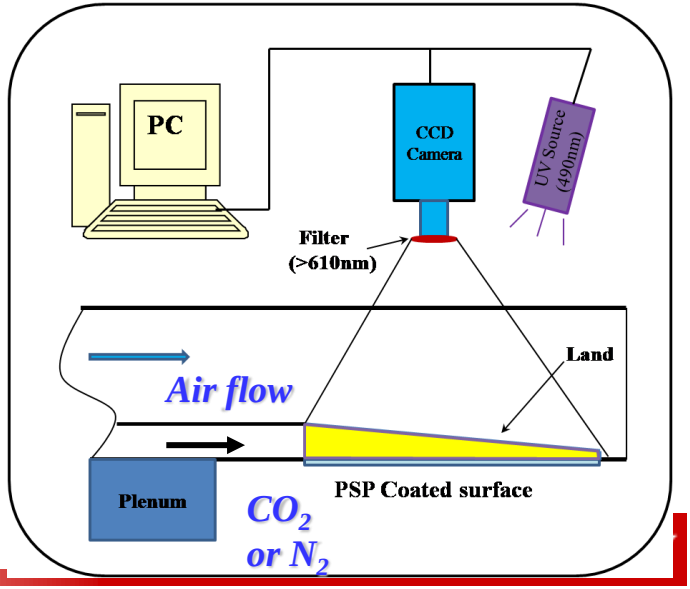


- C_{mix} : *Oxygen concentration on the test surface (between 0 ~ 21%).*
- C_∞ : *Oxygen concentrations of the main stream flow (~ 21%).*
- C_c : *Oxygen concentration of the coolant flow.*

- ***According to Charbonnier et al. (2009), if main stream is airflow, and CO_2 or N_2 is used as coolant stream, then :***

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} = \frac{C_\infty - C_{mix}}{C_\infty} = \frac{(P_{O_2})_{air} - (P_{O_2})_{mix}}{(P_{O_2})_{air}}$$

$$= 1 - \frac{1}{\left[\frac{(P_{O_2})_{air}}{(P_{O_2})_{mix}} - 1\right]\frac{\rho_{coolant}}{\rho_{air}} + 1}$$

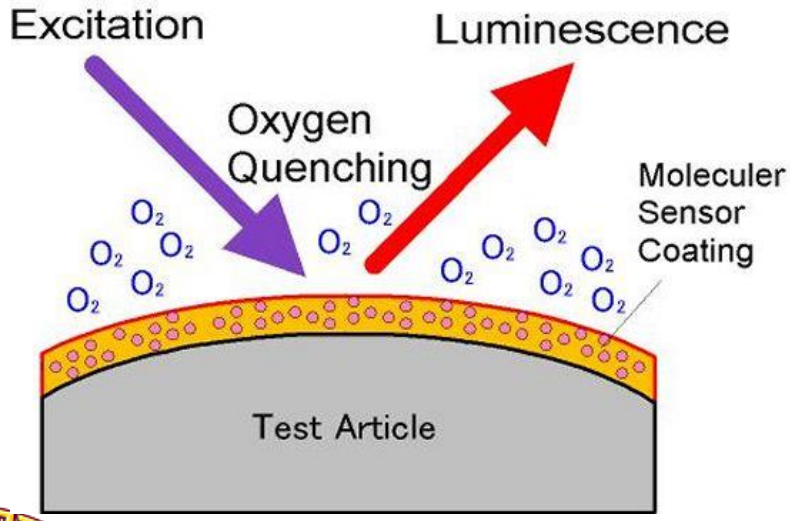


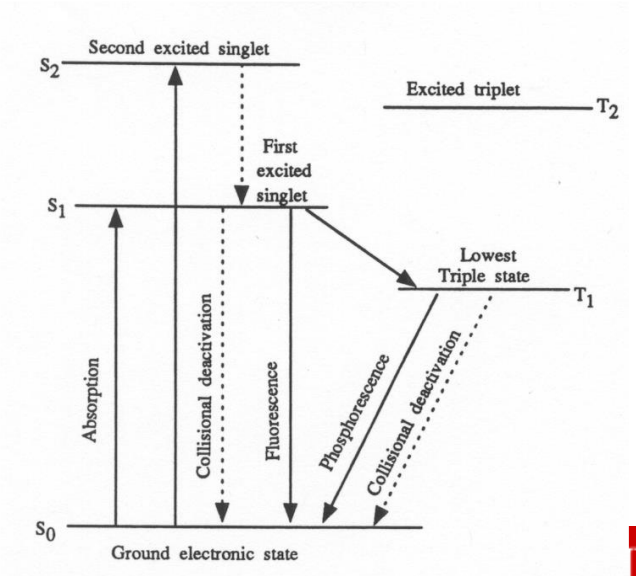
Basic Principles of Pressure Sensitive Paint (PSP)

- *PSP is based on the sensitivity of certain luminescent molecules to the presence of oxygen.*
  - *For some materials, oxygen can interact with the molecule so that the transition to the ground state is radiationless, this process is known as oxygen quenching.*
  - *For oxygen quenching, the intensity decrease can be described by the Stern-Volmer equation:*

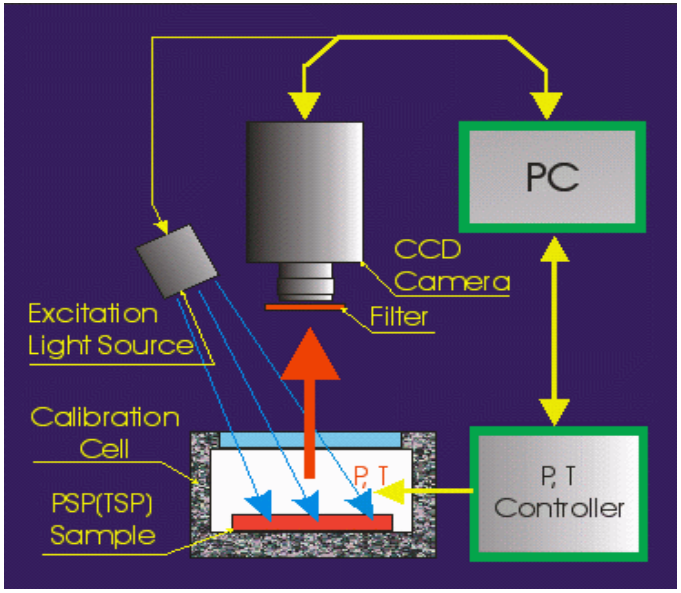
$$\frac{\tau_0}{\tau} = 1 + K_{SV} Q \qquad \text{or} \qquad \frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2}$$

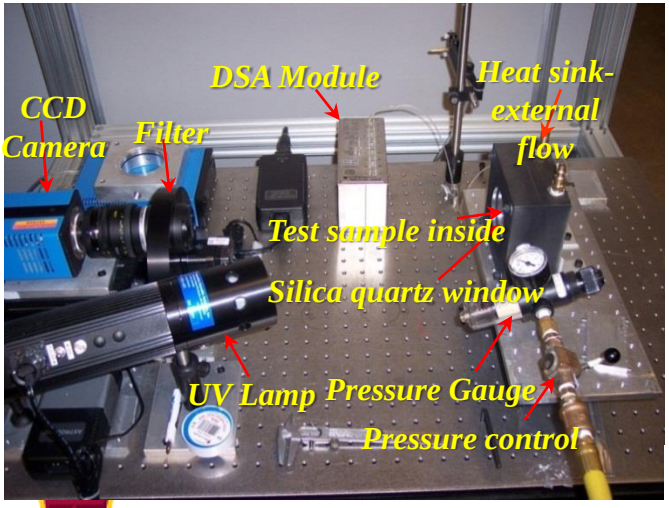
  - *Volume fraction of oxygen in air is fixed at 20.95%, higher partial pressure or concentration of oxygen would indicate higher local air pressure.*
  - *The air pressure distribution on the painted surface can be determined based on the intensity distribution of the acquired image of the oxygen sensitive molecules.*

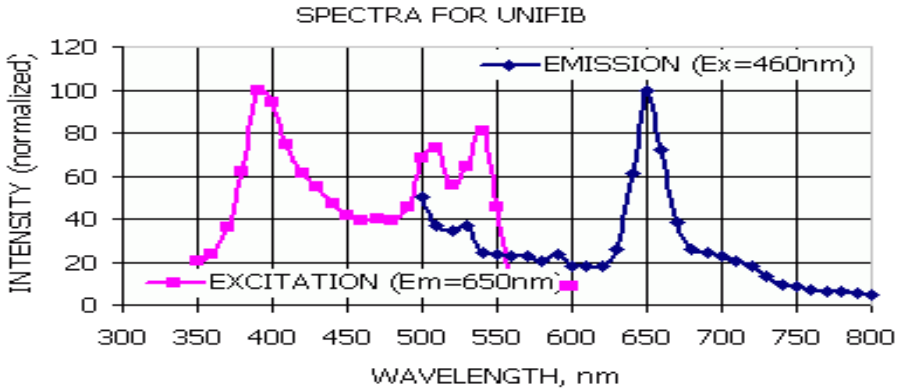




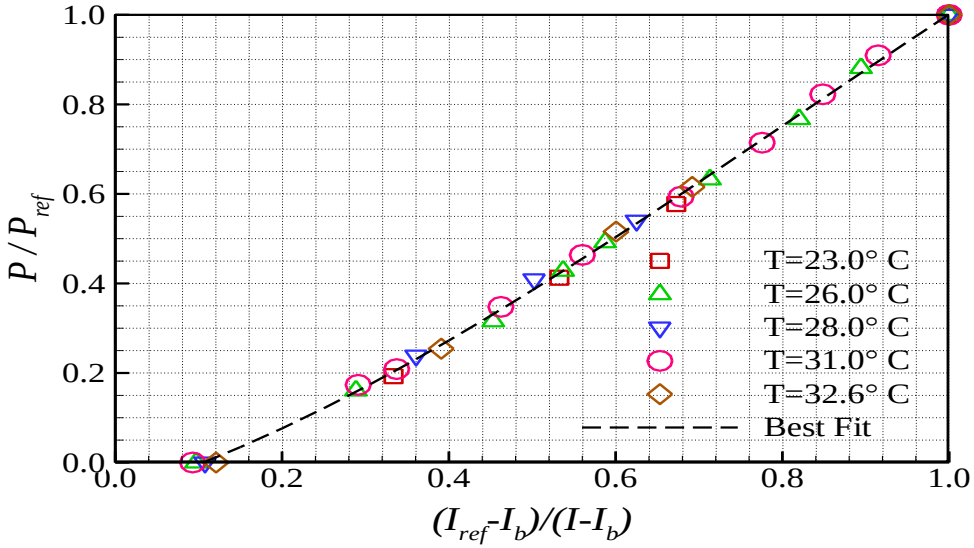
Calibration procedure for PSP Measurements





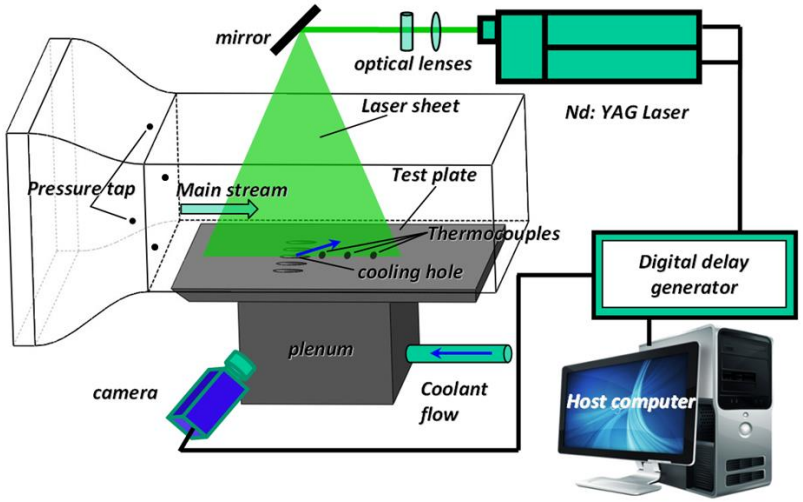


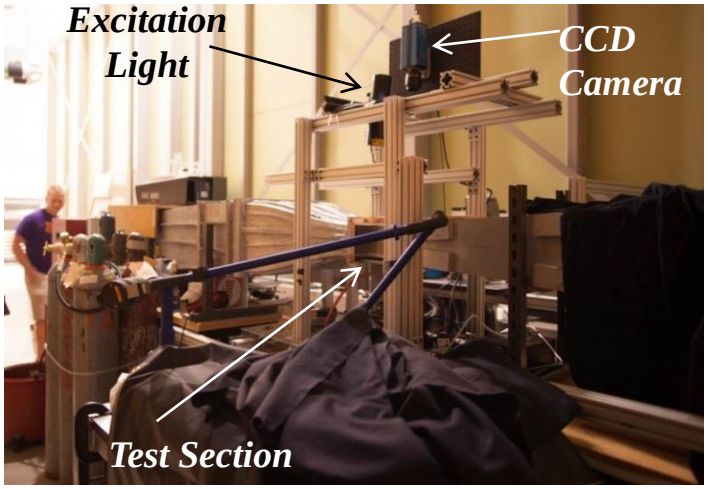
- ***PSP paint illuminated (excited) by using 390 nm LED light source;***
- ***Emission light isolated by using 610 nm long-pass filter.***



- ***N_2 flush to gather zero O_2-pressure calibration point.***
- ***Under appropriate normalization, the calibration curve is almost temperature-independent.***

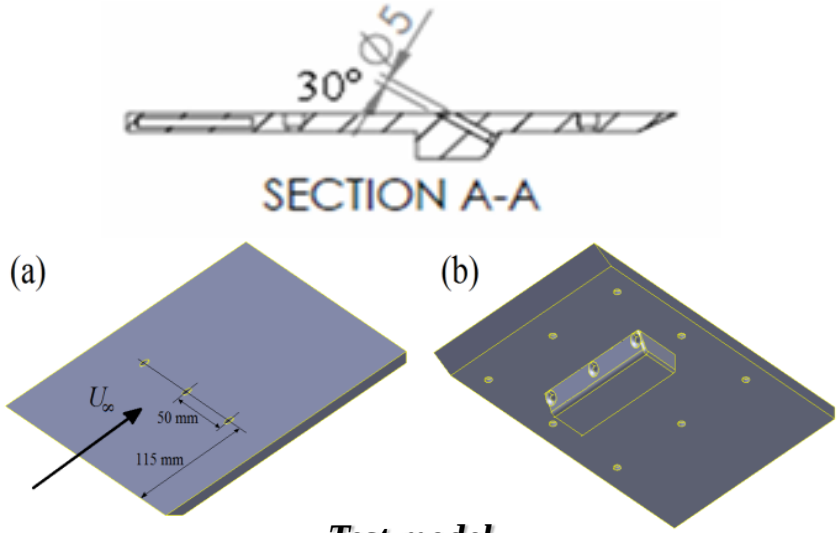
Experimental Setup for PIV and PSP Measurements





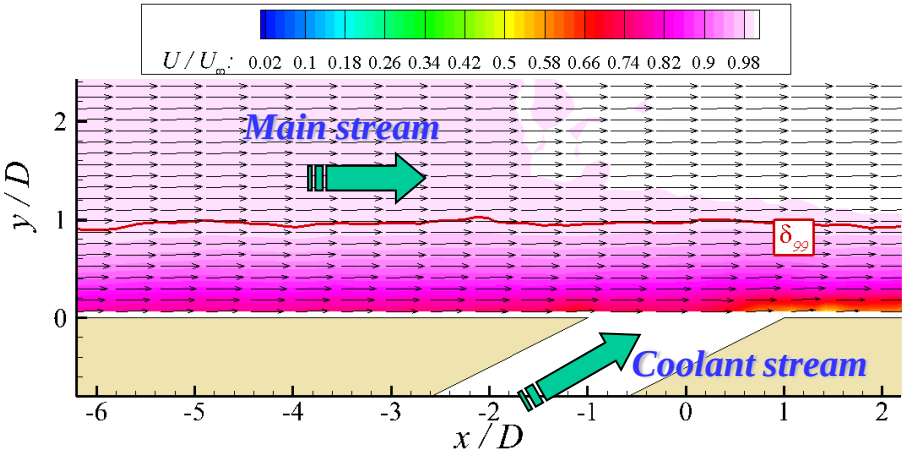
Experimental Setup for PIV measurements

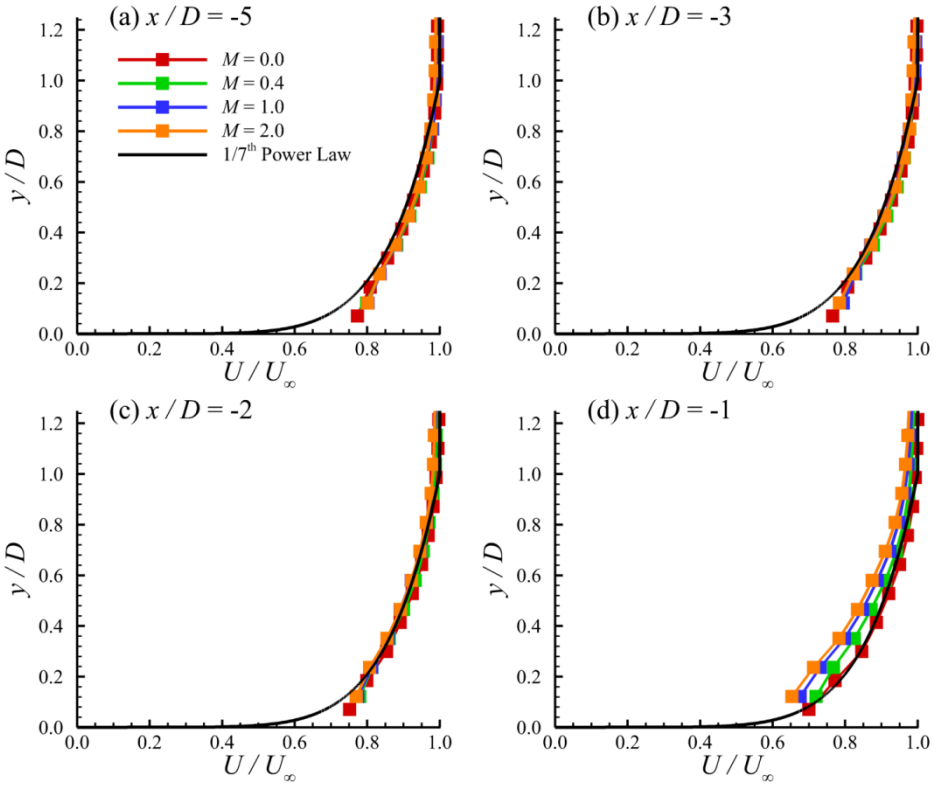
- *Open-circuit wind tunnel for main flow (U_∞ = 0~ 40 m/s)*
- *Test plate model, painted with PSP, as the floor of test section*
- *Compressed gas system drives coolant jet (air, N_2, or CO_2)*
- *Blowing Rate: $M = (\rho V)_{jet} / (\rho U)_\infty$ of 0 ~ 2.0*
- *Flow conditions essentially isothermal (coolant and mainstream at ambient temperature)*



Test model

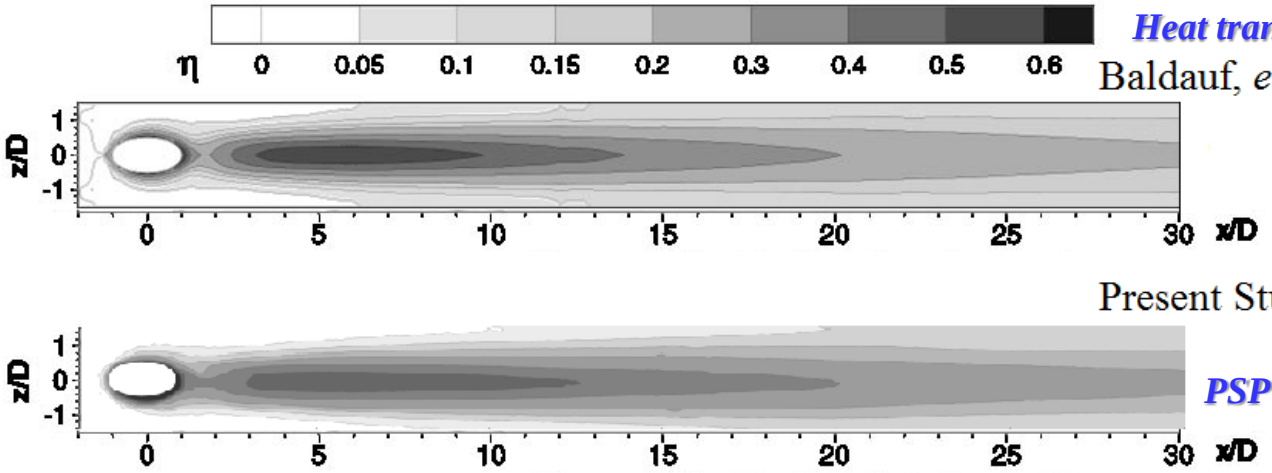
Boundary Layer Condition of the Oncoming Flow





- *In the absence of coolant flow (M = 0), a 1/7th power law closely approximates the oncoming flow at the leading edge of the coolant hole (x/D = -1)*
- *Main stream turbulence intensity is ~1%*
- *Boundary layer thickness δ_{99} measured at X/D = -1.0 was found to be about 0.85D.*
- *Displacement thickness δ^* measured at X/D = -1.0 was found to be about 0.10D.*
- *The oncoming flow conditions approximately match those of Baldauf et al. (2001)*
- *Increasing M causes the BL to thicken, adding to the velocity deficit, especially close to the hole.*

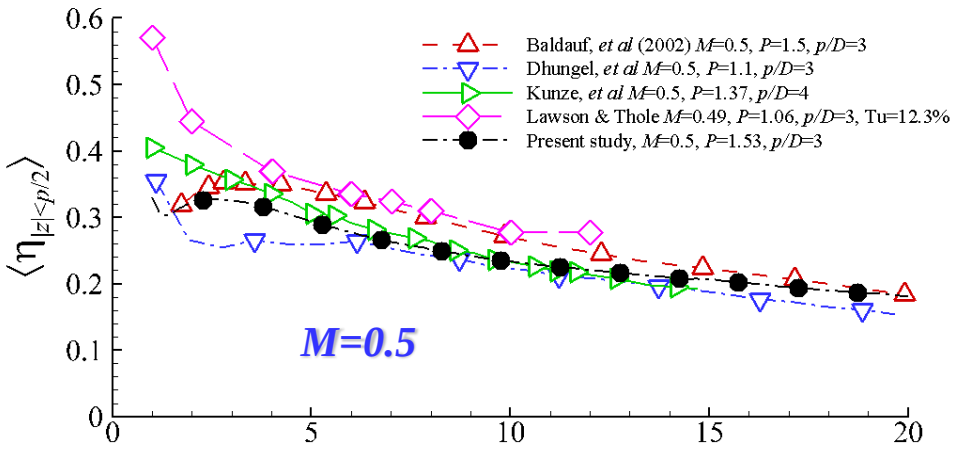
Film Cooling Effectiveness: PSP vs. Conventional IR Thermography

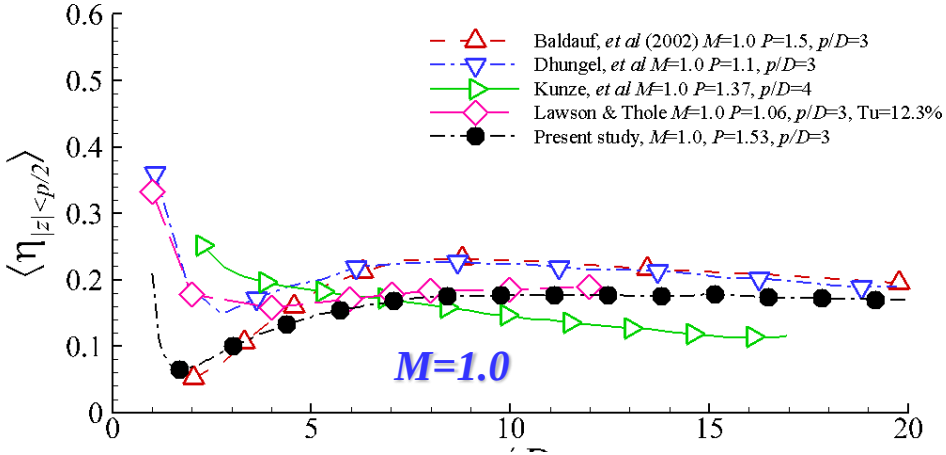


Heat transfer experiment

PSP measurements

$M = 0.85$
$P = 1.5$
$L/D = 6.0$
Tu = 1.5%
$\delta_{99} = 0.85D$
$\delta^* = 0.1D$

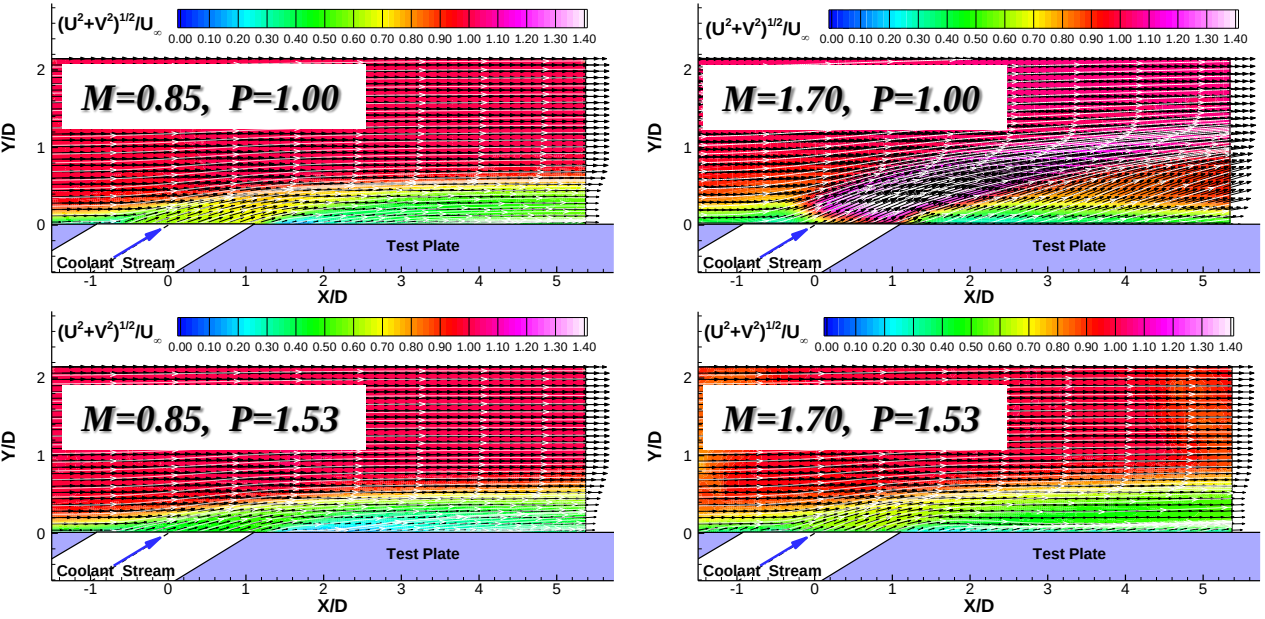


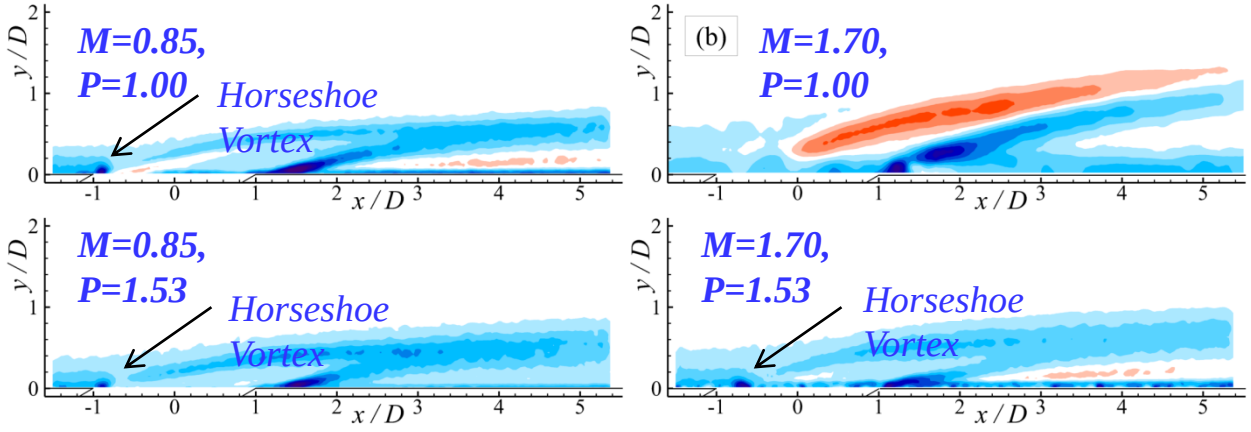


PSP results vs. conventional IR Thermography results available in literature

- ***Baldauf, S., Schulz, A, and Wittig, S. 2001. "High-Resolution Measurements of Local Effectiveness from Discrete Hole Film Cooling." Journal of Turbomachinery. Vol. 123, pp. 758–765.***

Density Ratio (P) Effect: Mean Velocity Field and Swirling Strength



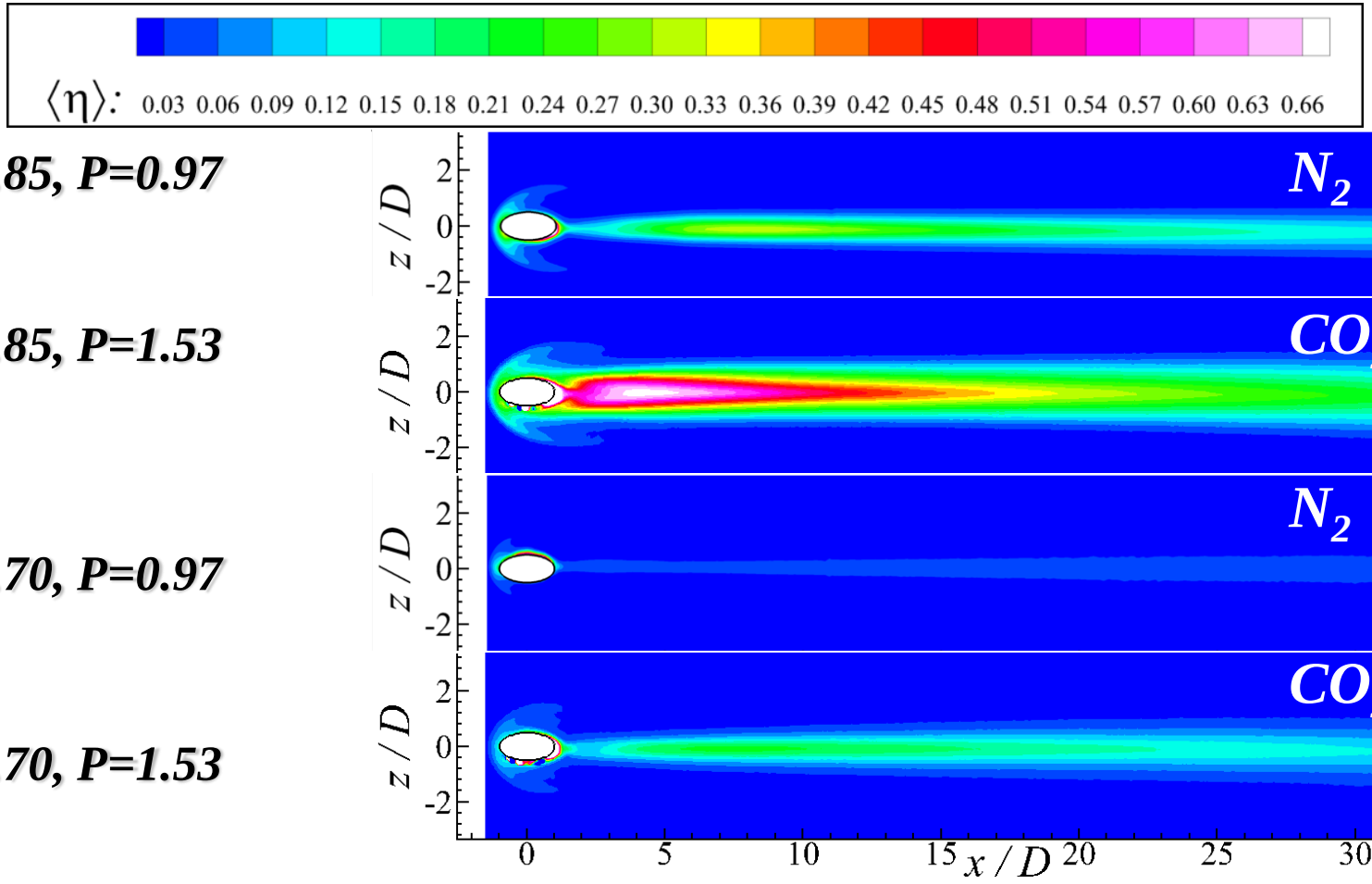


Swirling Strength < λ_{ci} >

- *Jet lift-off (separation) is observed at M=1.70 for P=1.00 (air as coolant jet) but not for P=1.53 (CO_2 jet).*
- *Increase in P for M=0.85 results in slower flow within the coolant sublayer.*
- *Lower M for fixed P results in slower flow velocity throughout the coolant sublayer for jets that remain attached.*

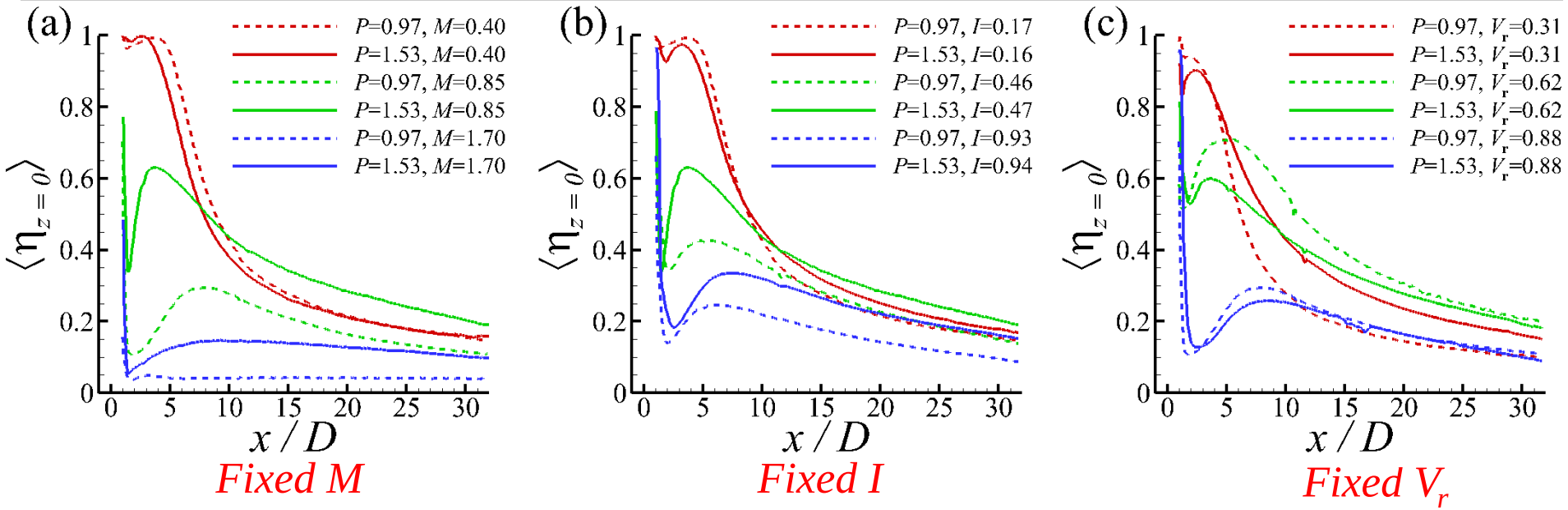
- *λ_{ci} is imaginary part of eigenvalue of velocity gradient tensor, signed by w_z*
- *Negative swirl (blue) indicates clockwise rotational motion*
- *Horseshoe vortex noted for all cases except P=1.00 & M=1.70 case*
- *That case also shows strong counter-clockwise rotation in leading-edge shear layer*

Density Ratio (P) Effect: Film Cooling Effectiveness



- *Higher P significantly increases effectiveness for fixed M*
- *M may not be an ideal scaling quantity*
- *Jet that separates provides very little cooling*
- *Horseshoe vortex causes coolant advection "halos"*

Comparison of Scaling Parameters for Varying *P*



Density Ratio: $P=\rho_{coolant}/\rho_{\infty}$

Velocity Ratio: $V_r=V_{coolant}/U_{\infty}$

Momentum Flux Ratio: $I=PV_r^2=M^2/P$

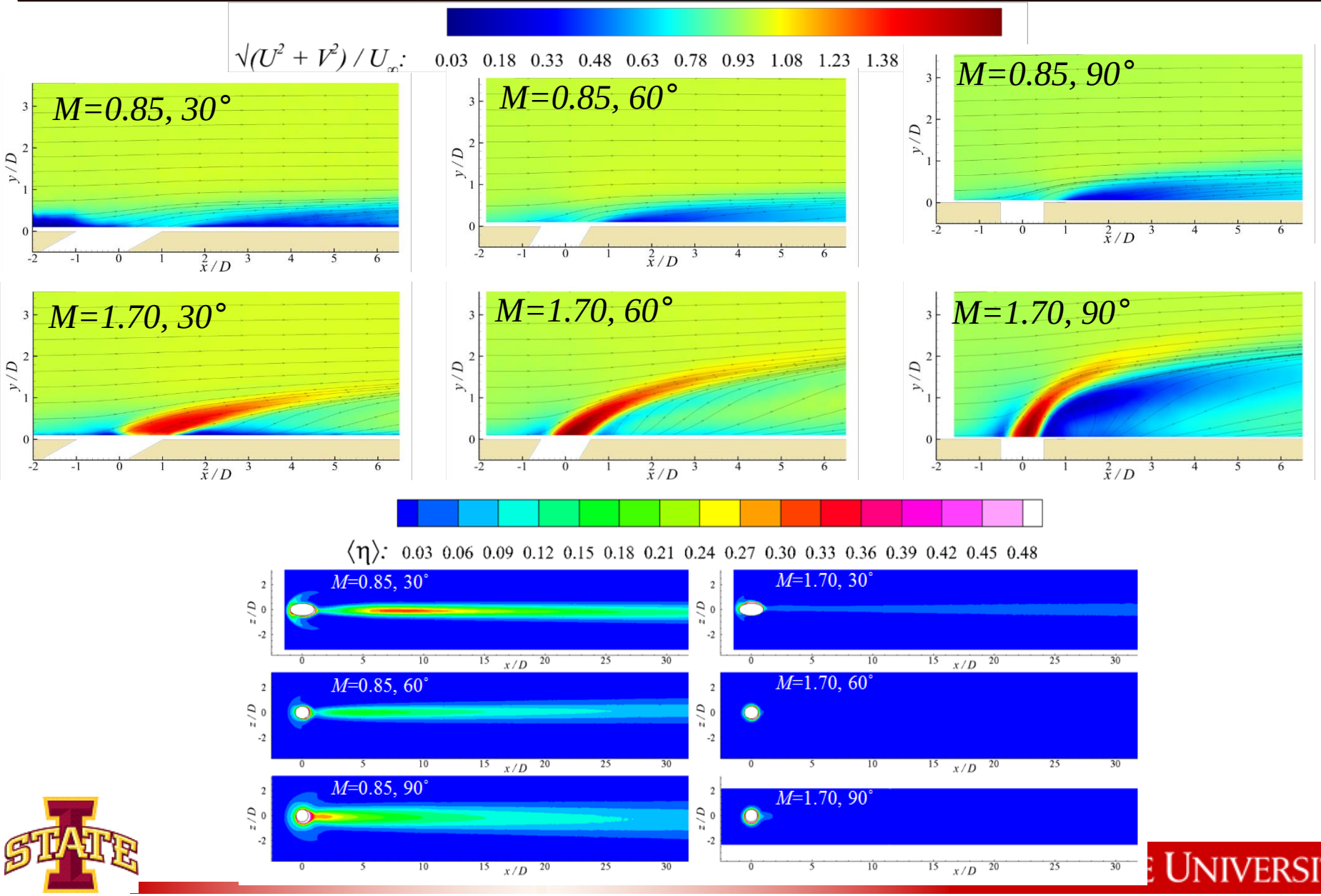
Blowing Rate (mass flux ratio): $M=PV_r$

Kinematics ↑ ↓ *Dynamics*

- ***Quantities that give more weight to P (I and then M) have more success to collapse data for varying P at low coolant flow rates.***
- ***Bulk velocity ratio V_r may be used with some success to scale the cooling effectiveness from jets of higher velocities .***

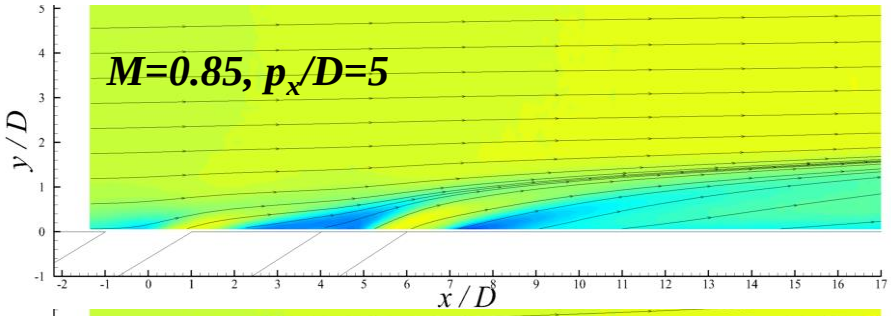
*(**Johnson, W. Tian, K. Zhang and H. Hu,** International Journal of Heat and Mass Transfer, Vol. 76, pp. 337-349, 2014.)*

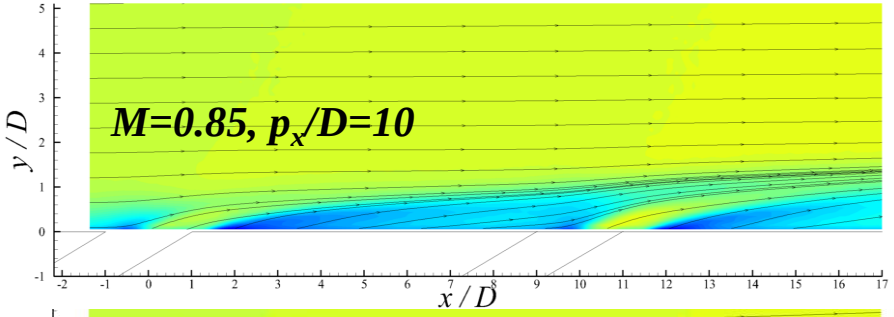
Effects of Injection Angle of the Coolant Injection Holes

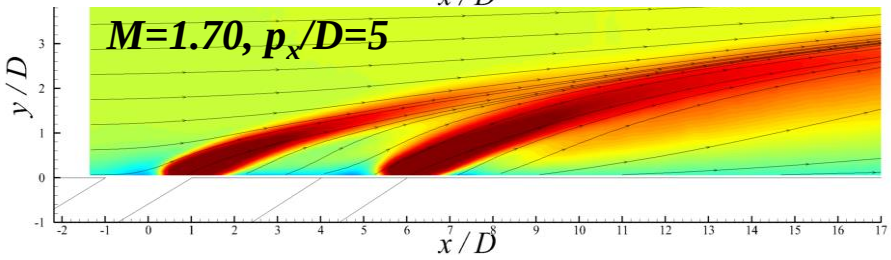


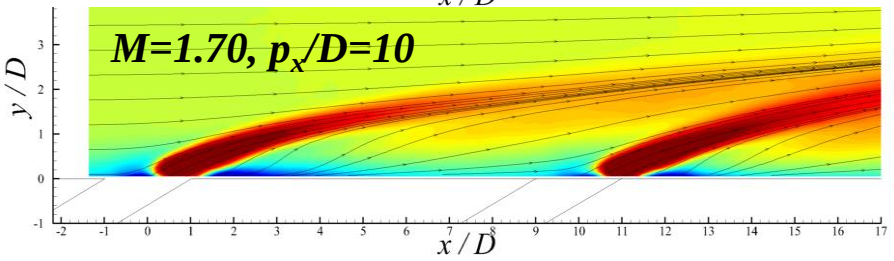
Effects of Streamwise Spacing Between the Coolant Injection Holes

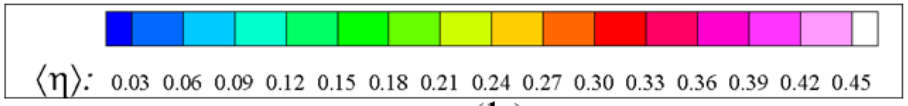
$(U^2 + V^2)^{1/2} / U_\infty$: 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7





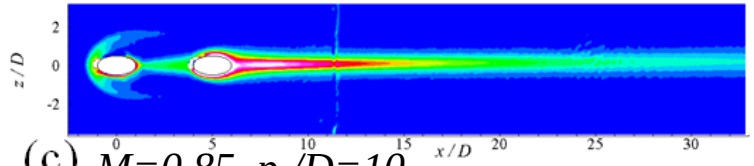




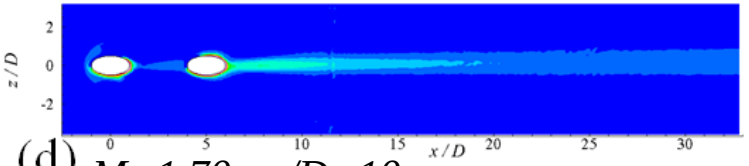


$\langle\eta\rangle$: 0.03 0.06 0.09 0.12 0.15 0.18 0.21 0.24 0.27 0.30 0.33 0.36 0.39 0.42 0.45

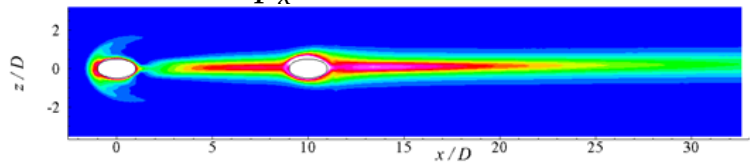
(a) *M=0.85, p_x/D=5*



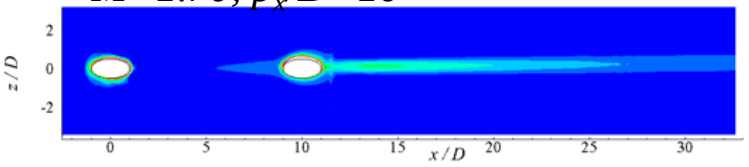
(b) *M=1.70, p_x/D=5*



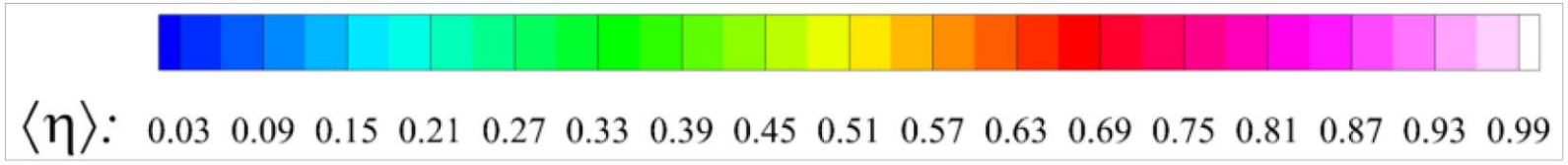
(c) *M=0.85, p_x/D=10*

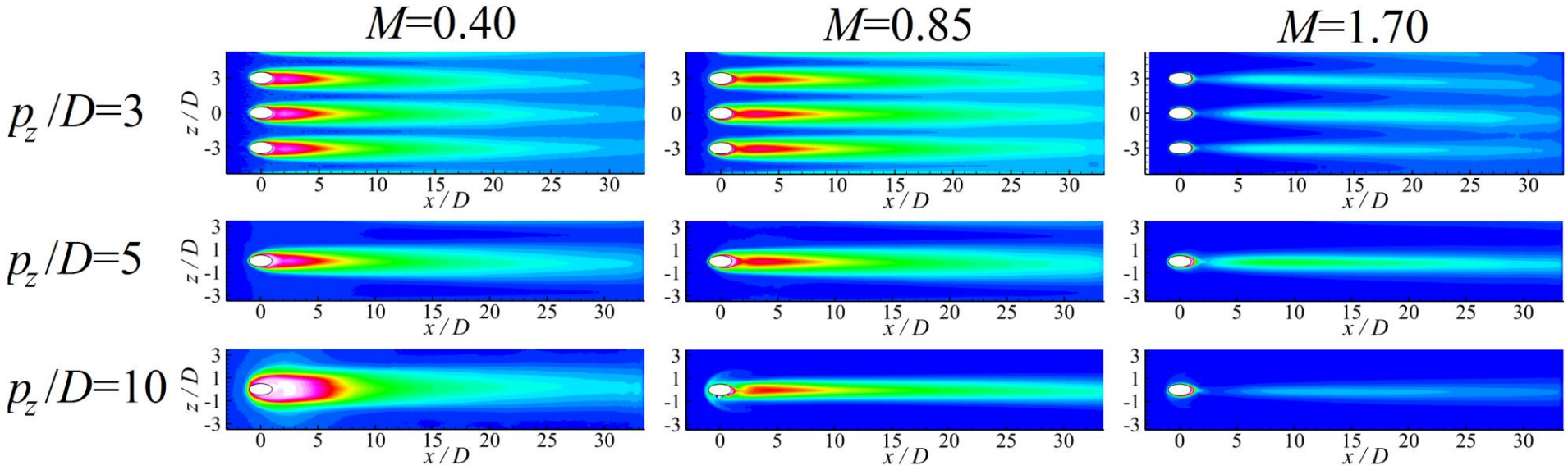


(d) *M=1.70, p_x/D=10*



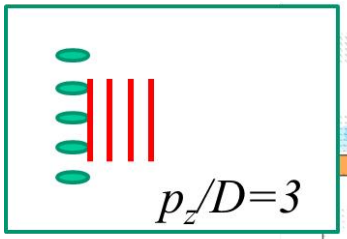
Effects of Spanwise Spacing Between the Coolant Injection Holes

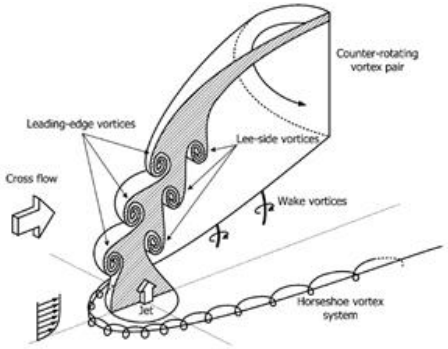


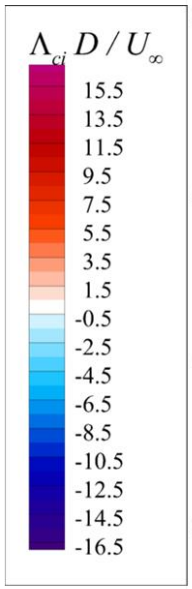


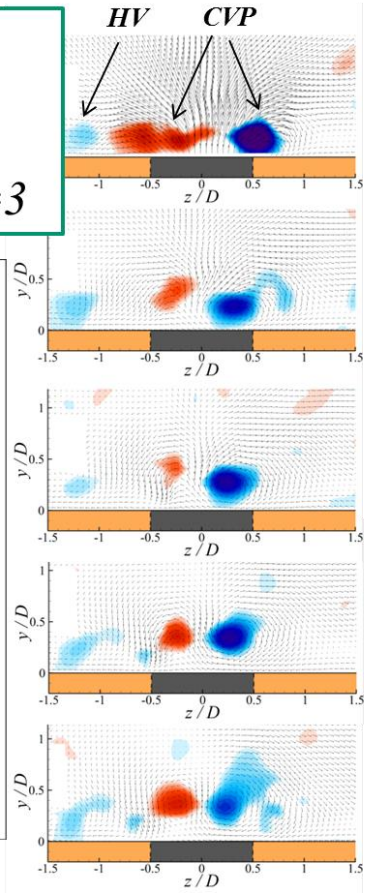
- ***$p_z/D=3$ and $p_z/D=5$ hole spacings have similar behavior regardless of M.***
- ***A qualitative difference is noted for $p_z/D=10$.***
  - ***Much higher effectiveness around the hole.***
  - ***M=0.85 case suggests that the horseshoe vortex may contribute to this increase in spanwise effectiveness.***

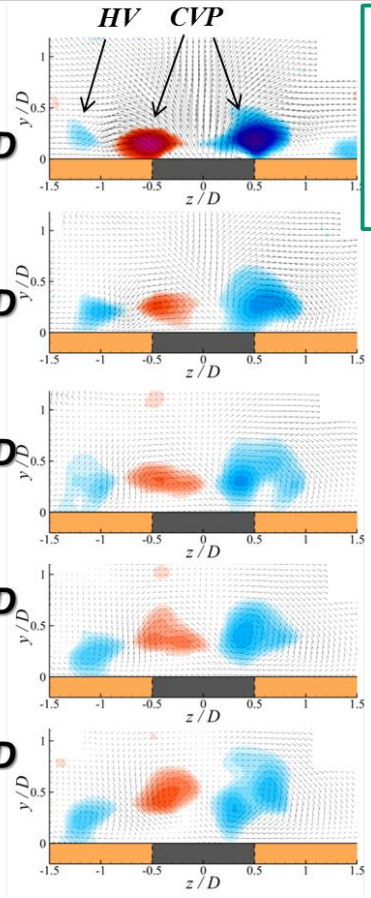
Basic Flow Structure: Jet in Cross-Flow

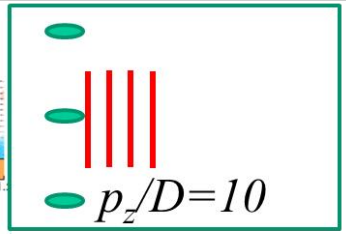




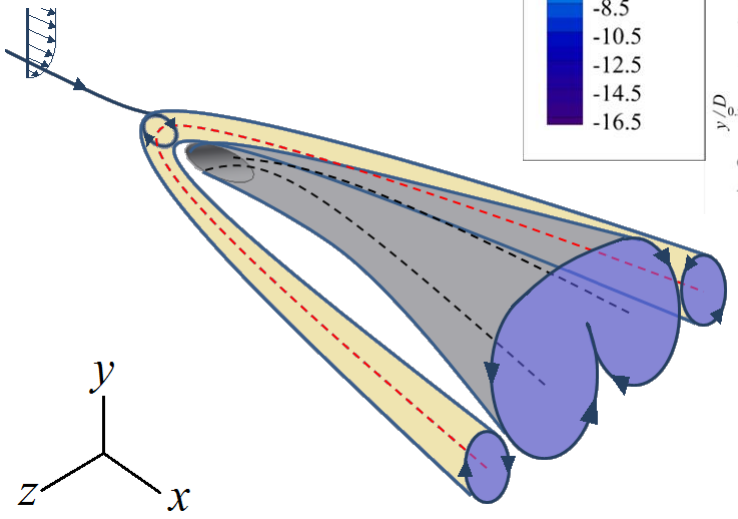








- *P_z/D=3 case has stronger CVP than P_z/D=10 case.*
- *CVP more compact for P_z/D=3 case.*
- *CVP diffuses more for P_z/D=10 case.*
- *P_z/D=10 case has stronger horseshoe vortex than p_z/D=3 case.*

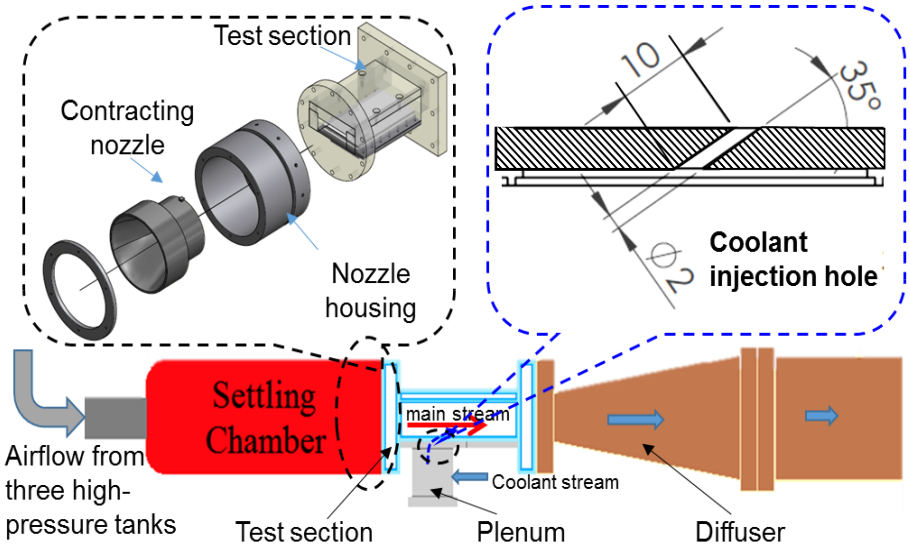


Four prominent structures :

- ***Counter-Rotating Vortex***
- ***Jet Shear-Layer Vortices***
- ***Wake Vortices***
- ***Horseshoe Vortex***

Compressibility Effects on the Film Cooling Effectiveness

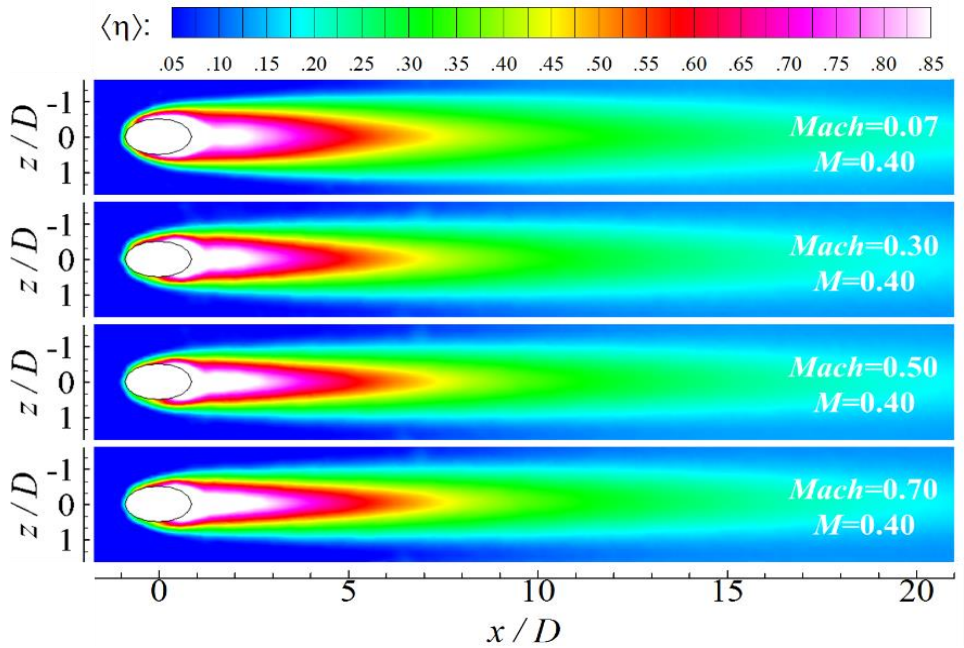
- ***Most of previous studies were conducted at relatively low Mach number (Ma<0.15), while flow passing turbine blade is usually transonic, little can be found in the literature that examines effects of compressibility of incoming flow on film cooling performance.***

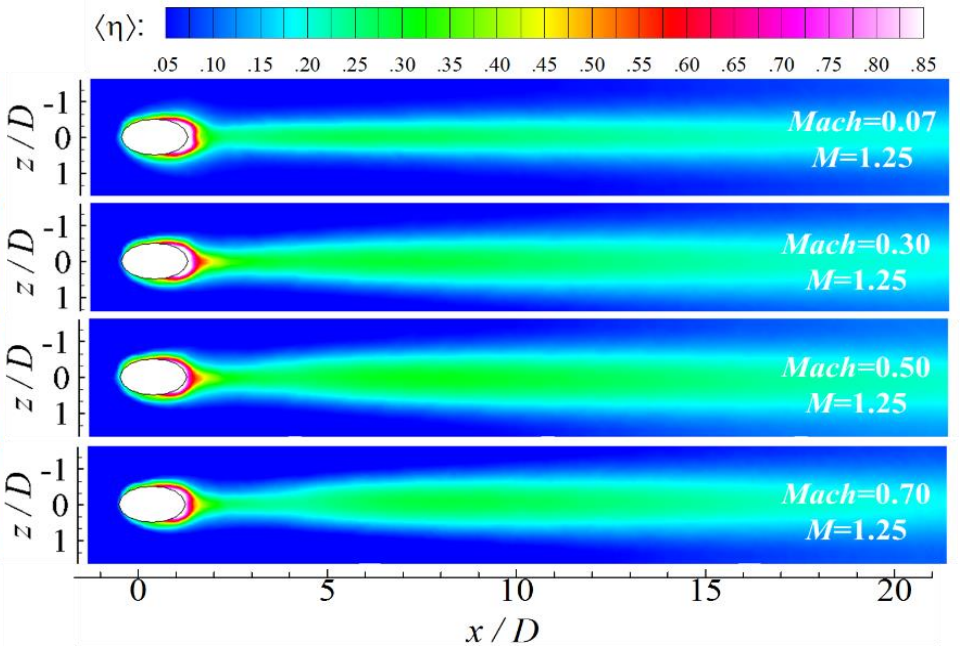


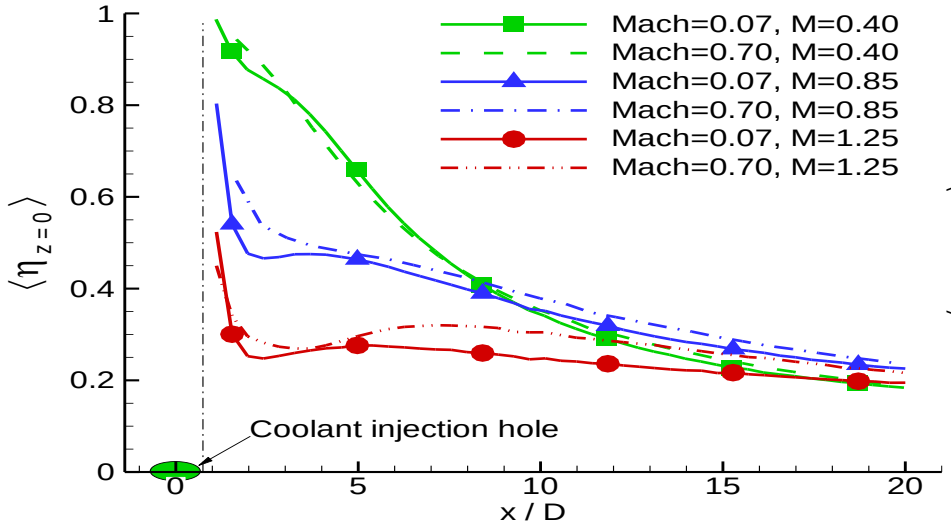
- ***Ma=0.7 can be sustained for ~5 minutes.***
- ***Test section: 63.5×25.4 mm²***
- ***The temperature variation during the test <5K.***
- ***Uni-FIB paint temperature sensitivity is 0.5%/deg.***

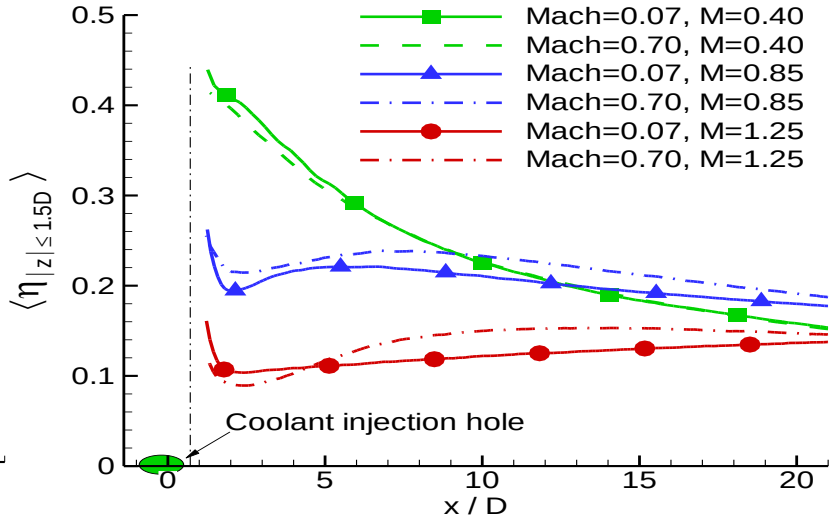
Mach number of the mainstream flow, Ma	*Density Ratio* $DR = \rho_c / \rho_\infty$	*Blowing Ratio* $M = \rho_c V_c / \rho_\infty V_\infty$
0.07	1.5	0.40, 0.85, 1.25
0.30	1.5	0.40, 0.85, 1.25
0.50	1.5	0.40, 0.85, 1.25
0.70	1.0	0.40, 0.85
0.70	1.5	0.40, 0.85, 1.25
0.70	2.0	0.40, 0.85

PSP Measurement Results with $DR = \rho_c / \rho_\infty = 1.50$





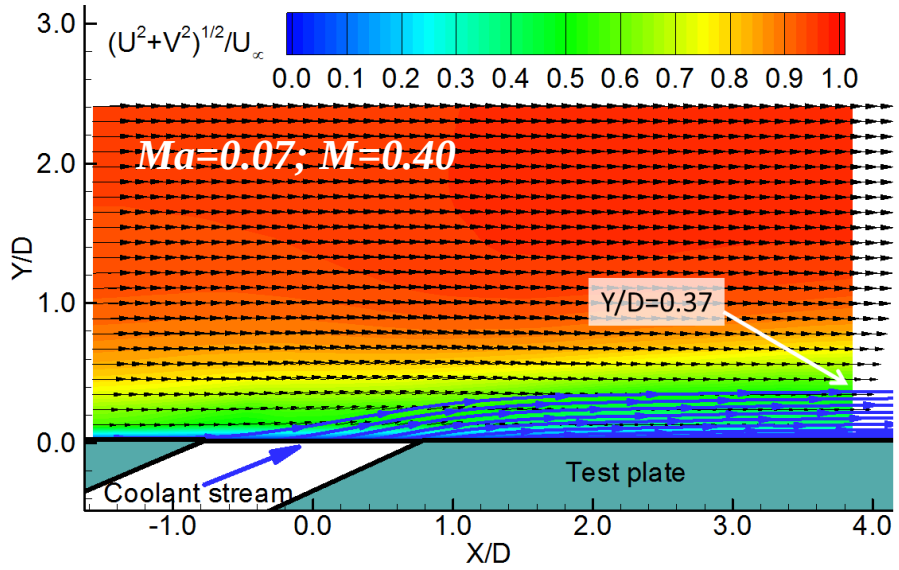


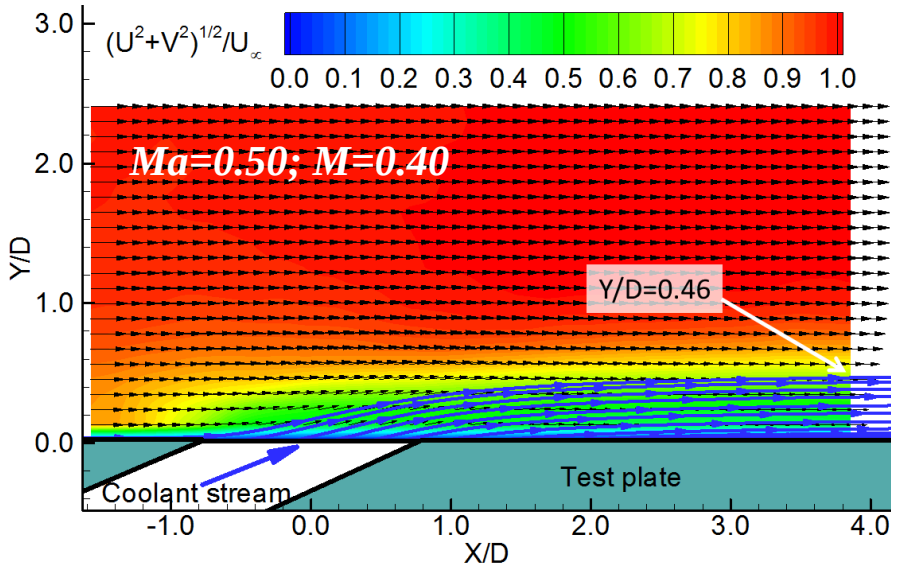


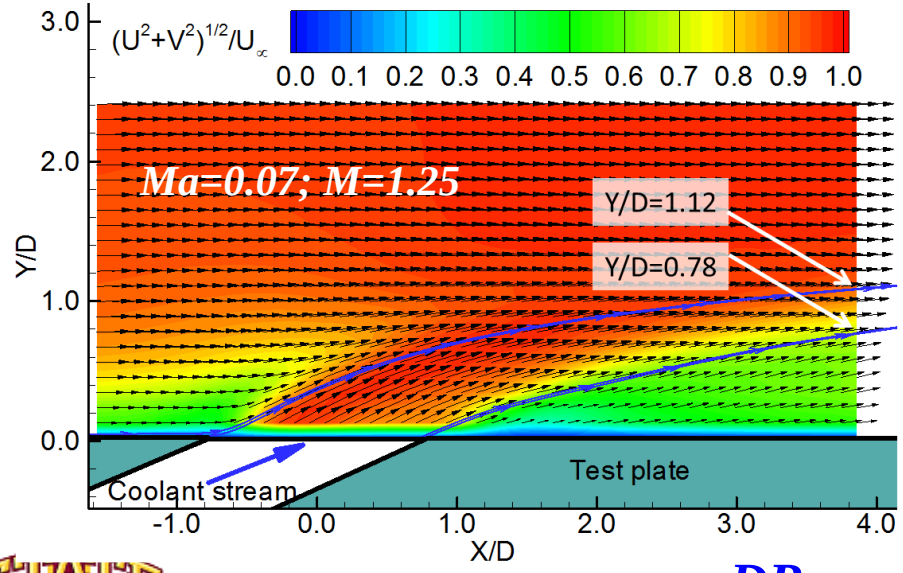
Centerline cooling effectiveness profiles

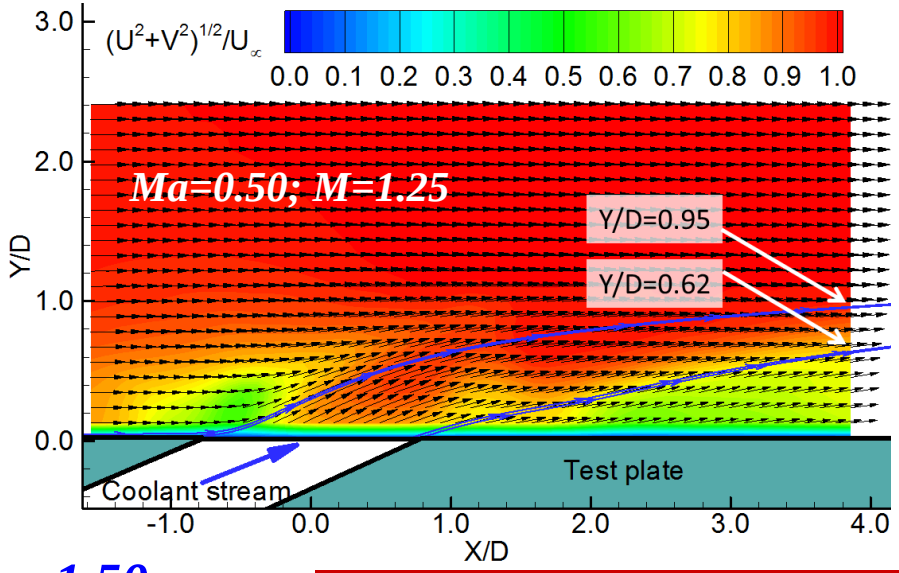
Laterally-averaged cooling effectiveness profiles

PIV Measurement Results with $DR = \rho_c / \rho_\infty = 1.50$



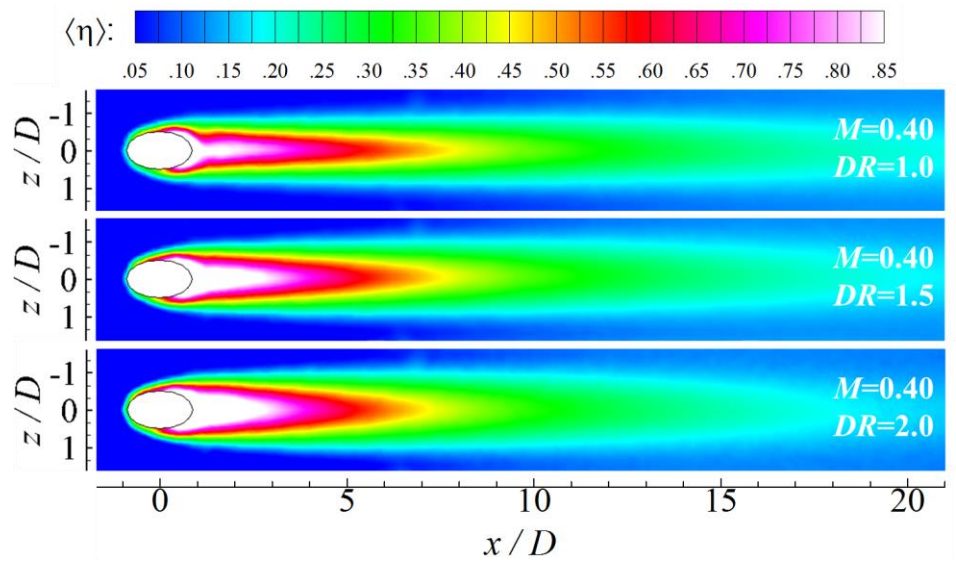


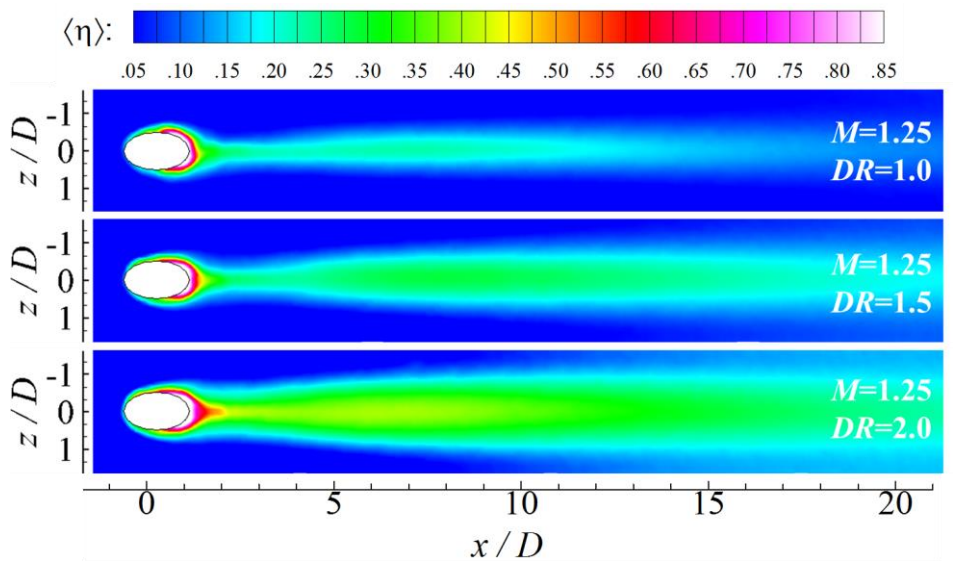


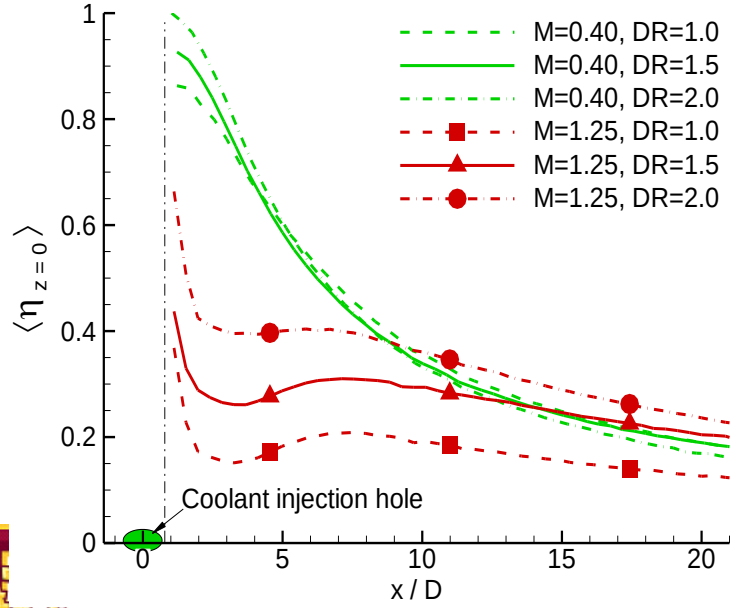


$DR = \rho_c / \rho_\infty = 1.50$

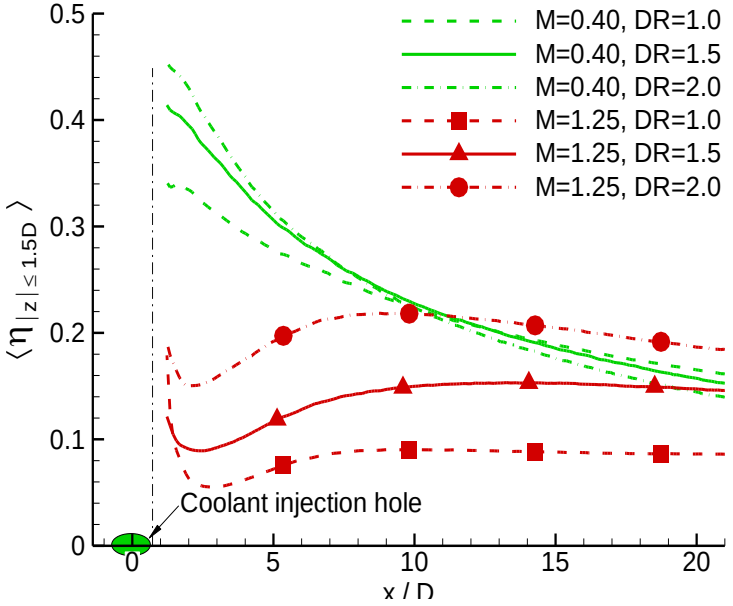
Effects of Density Ratio on Film Cooling @ Transonic condition







Centerline cooling effectiveness profiles



Laterally-averaged cooling effectiveness profiles

Barchan Dune Inspired Film Cooling Designs for Improved Cooling Effectiveness

Image Source: Sand dune search.

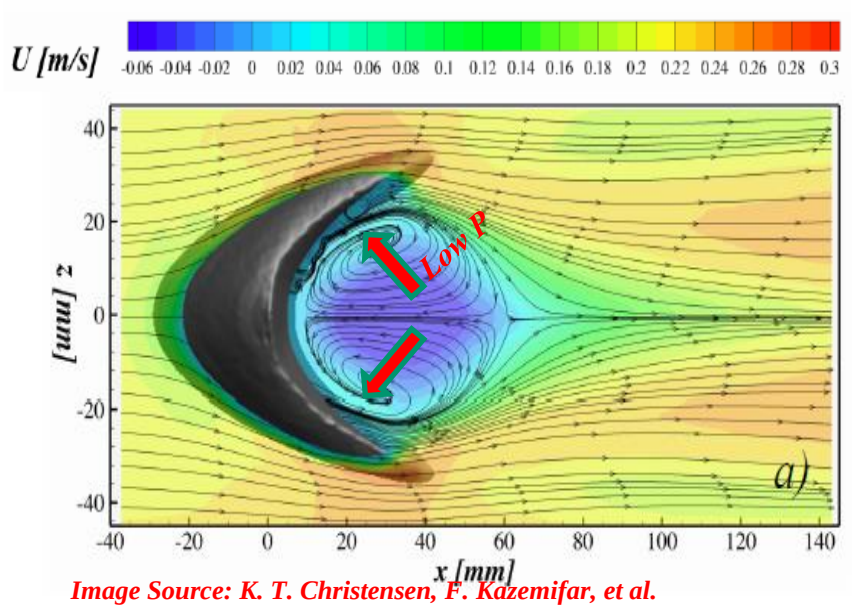


Image Source: K. T. Christensen, F. Kazemifar, et al.

Shaped Film Cooling Holes

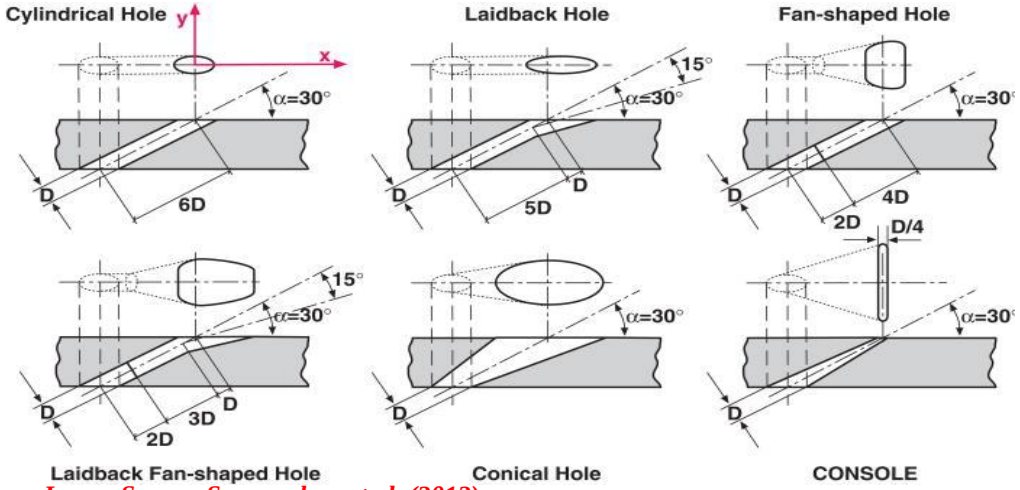


Image Source:Saumweber, et al. (2012).

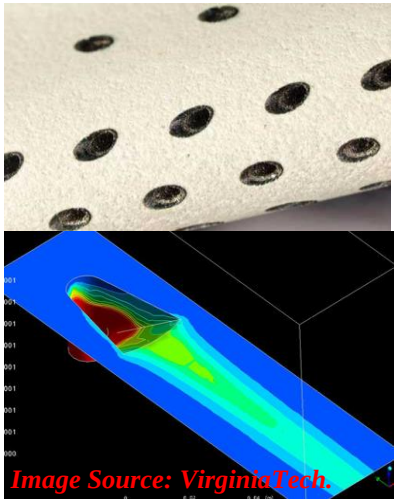
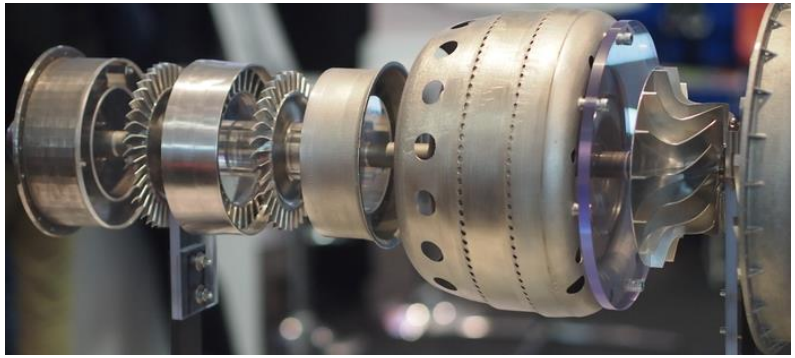


Image Source: VirginiaTech.

- *3D printing technique promotes the development of innovative cooling design.*

3D Printed titanium blade, GE (2014).

First 3D printed jet engine, engineering.com (2015).



Printed turbine blade of Morris Technologies.

- *Saumweber et al, Journal of Turbomachinery, vol. 134, Aug. 2012.*

Barchan Dune Shaped Ramp (BDSR)

Image Source: Sand dune search.

Image Source: Sand dune on Mars, News discovery.

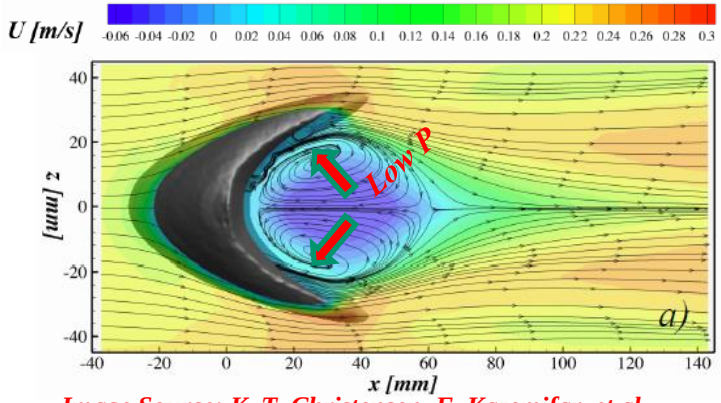


Image Source: K. T. Christensen, F. Kazemifar, et al.

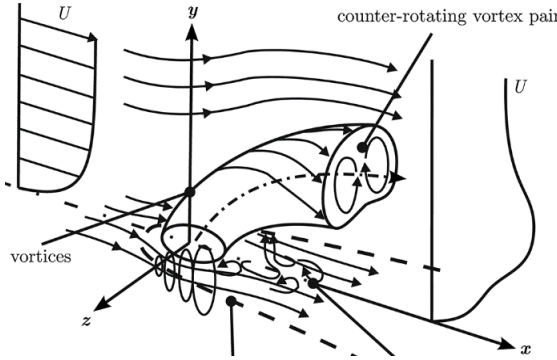


Image Source: Herbst et. al (2013).

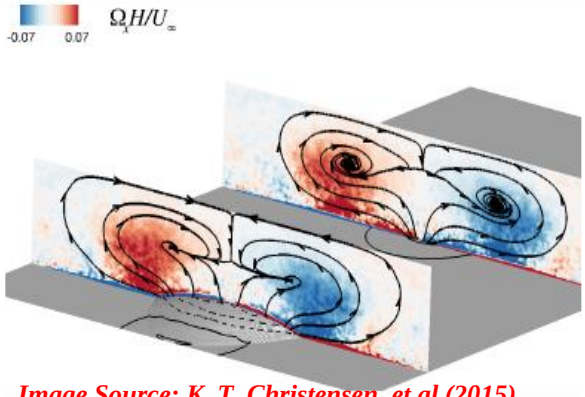


Image Source: K. T. Christensen, et al (2015).

- *Stable wake right behind dune, sand stayed on the ground.*
- *Streamline shape minimize the friction loss since it is the evolution of nature wind effect.*
- *Suction behind the dune, and Anti-CRV formed above the dune.*

Barchan-dune-shaped ramp (BDSR)

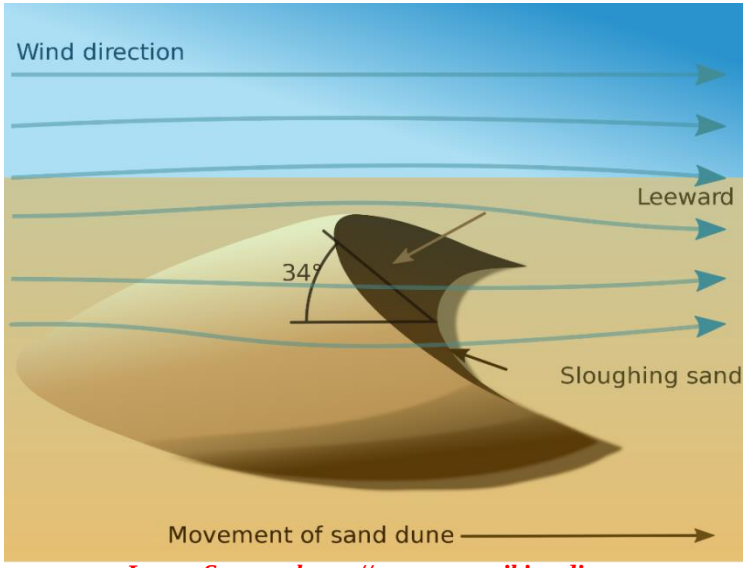
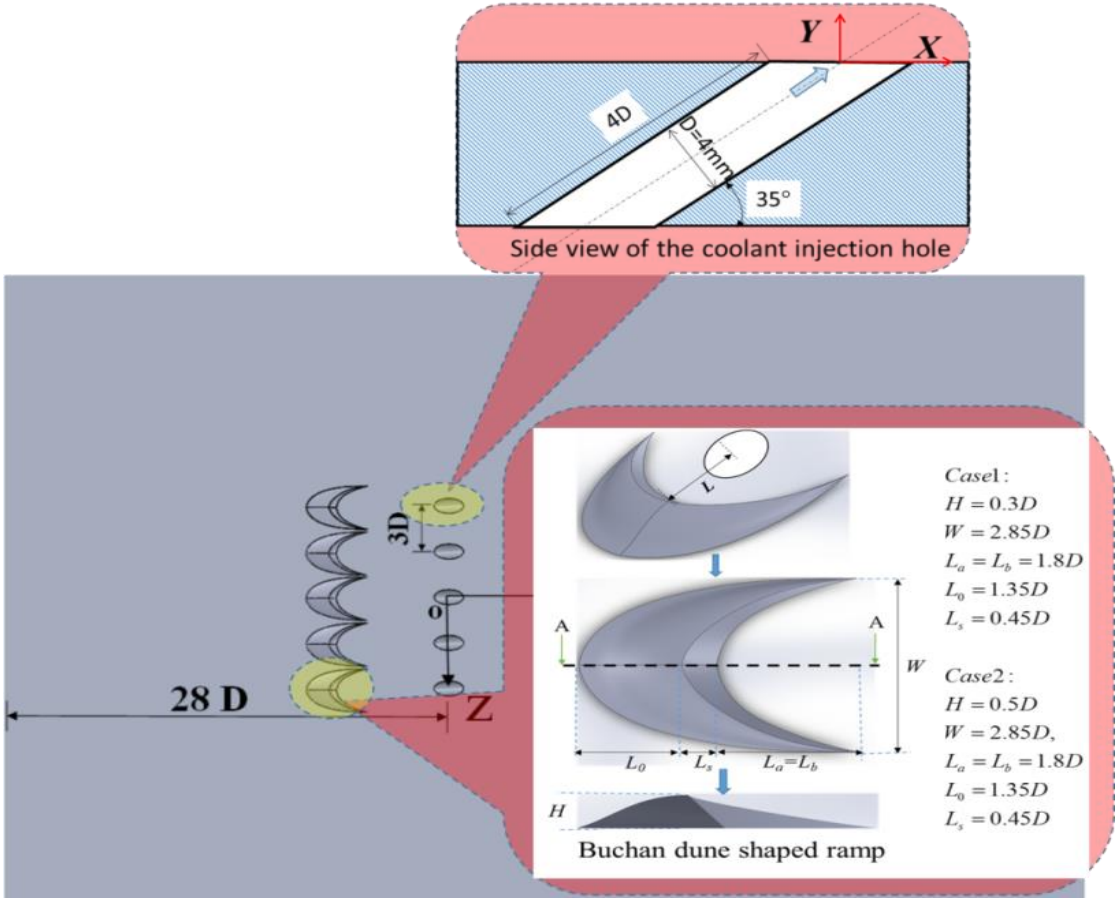


Image Source: https://commons.wikimedia.org



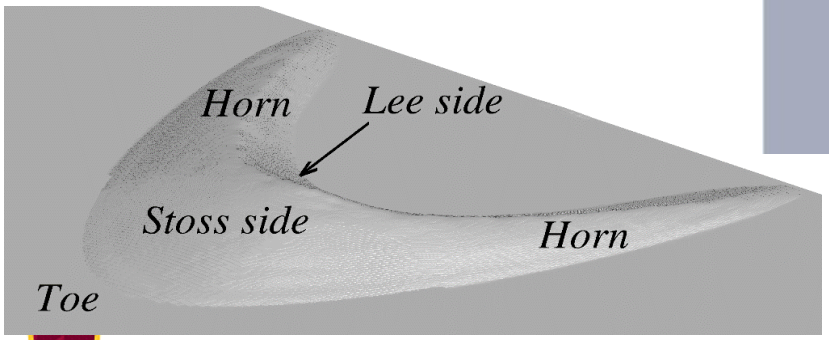
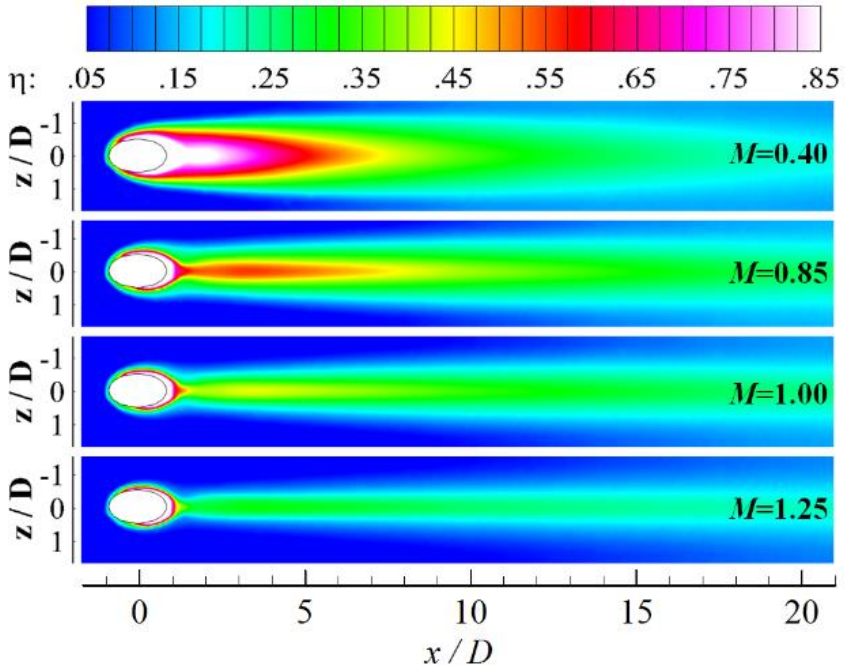
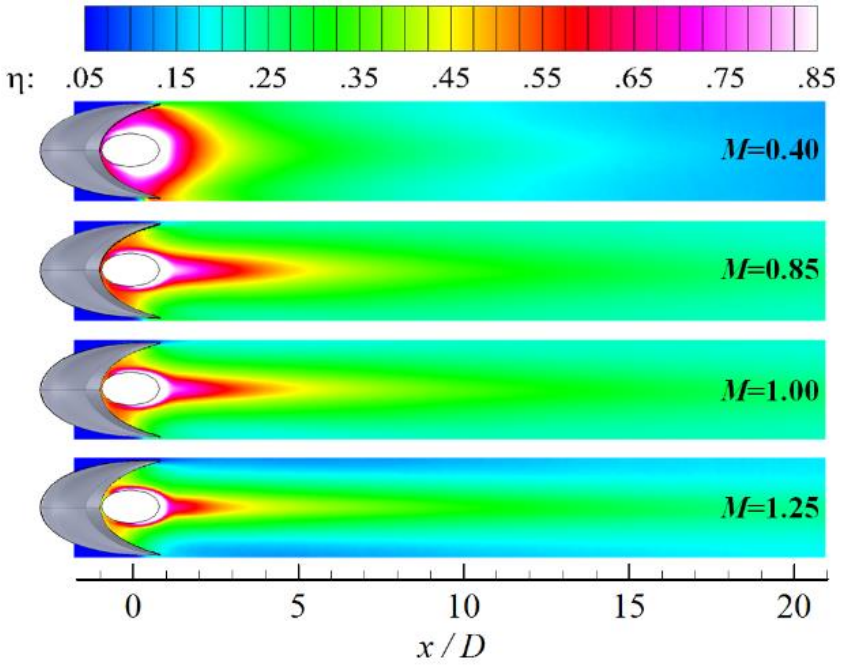
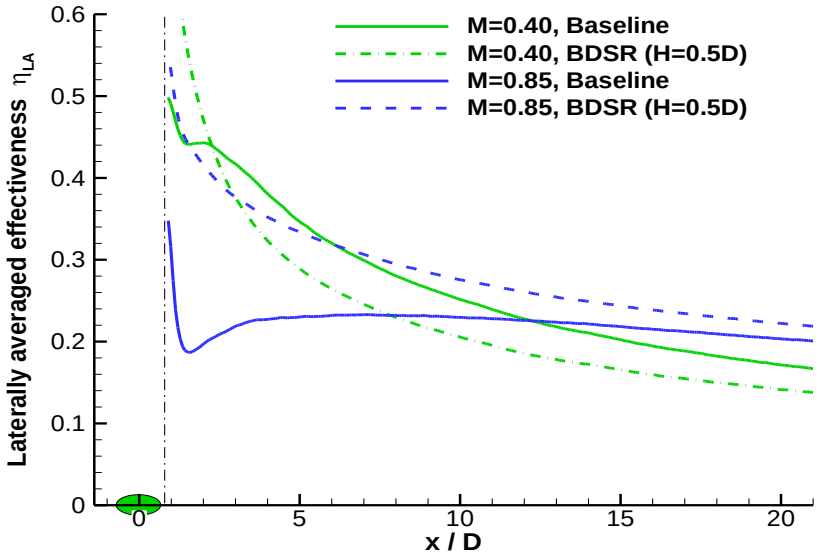


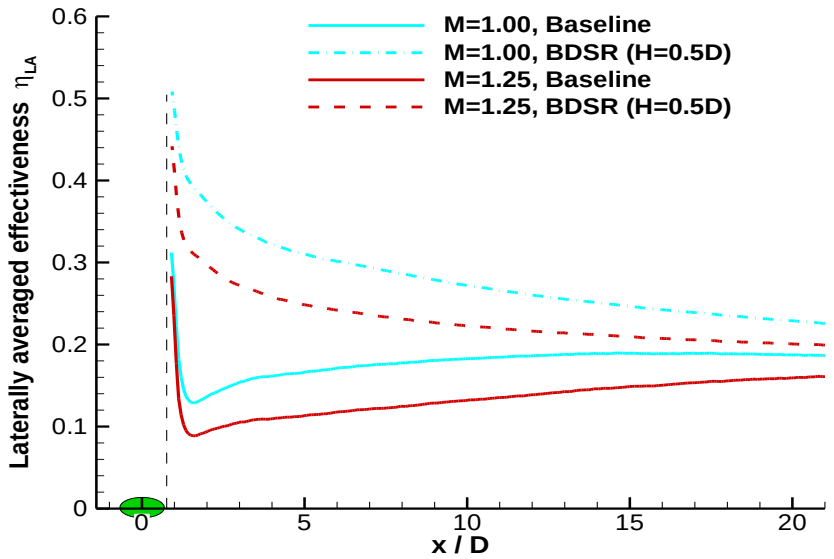
Image Source: Omidyeganeh, et al (2013).

Measured Film Cooling Effectiveness with PSP Technique

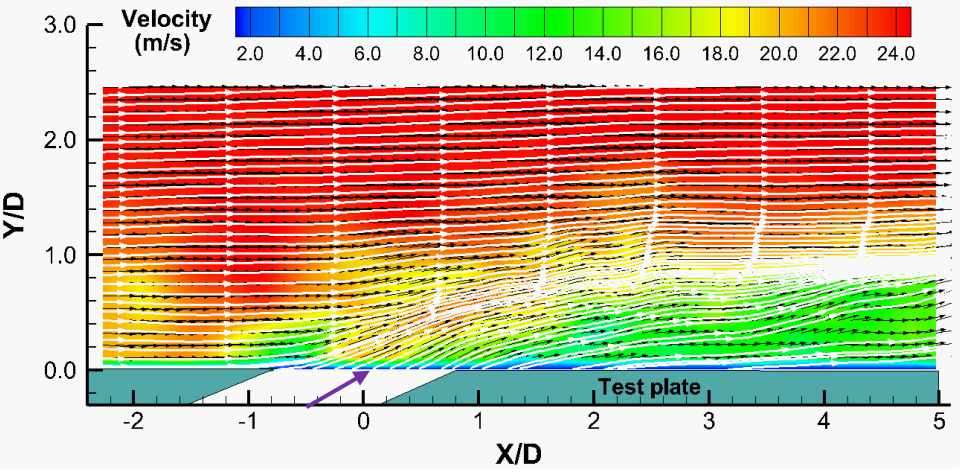




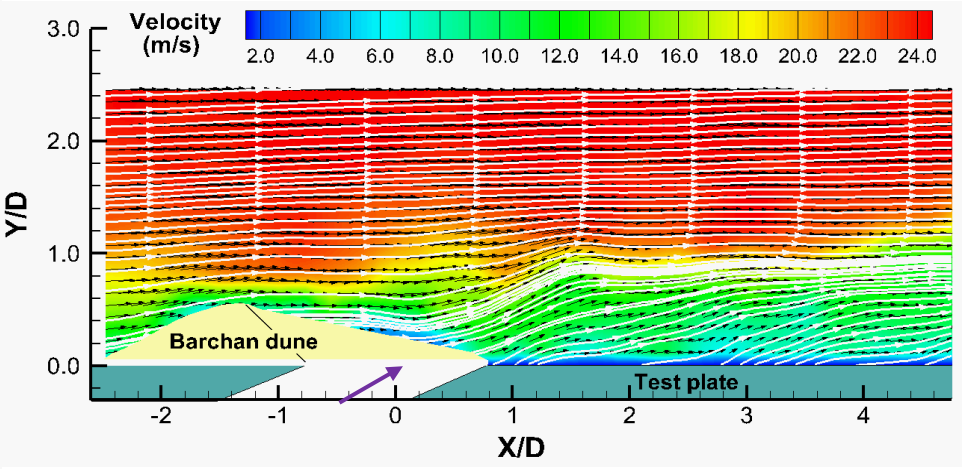




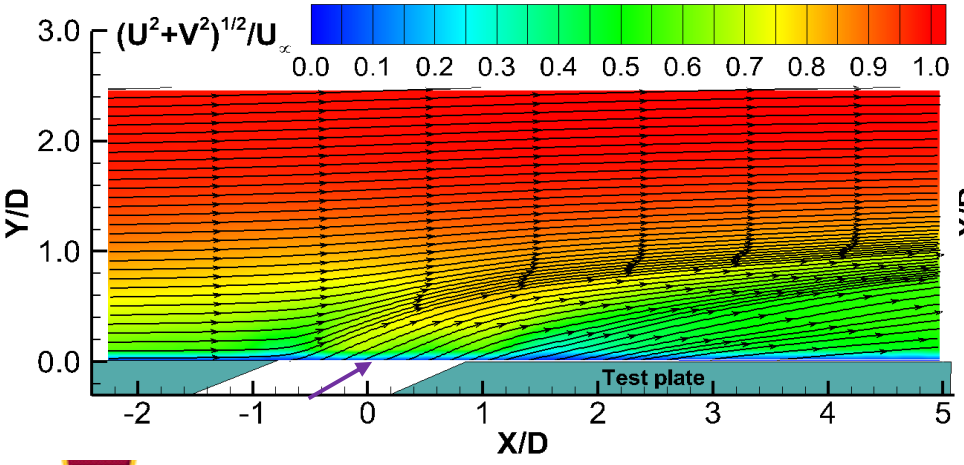
PIV Measurement Results [M=1.00]

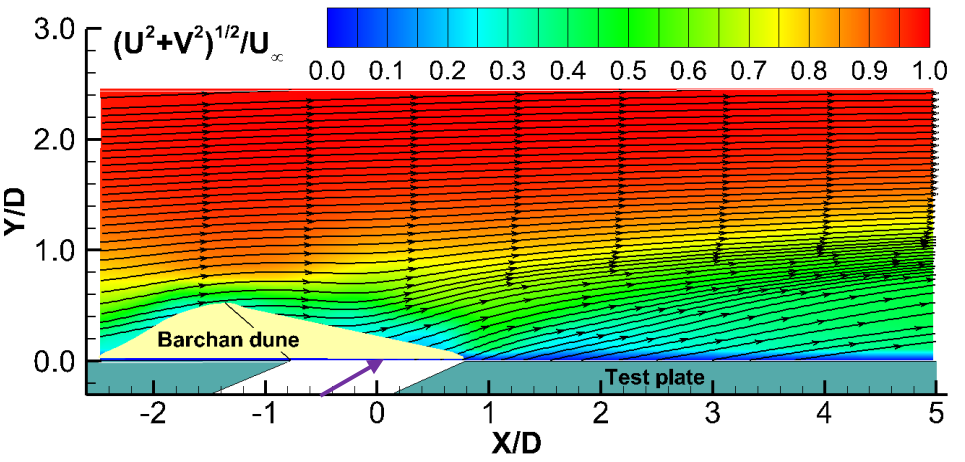


(a) Baseline case, M=1.00

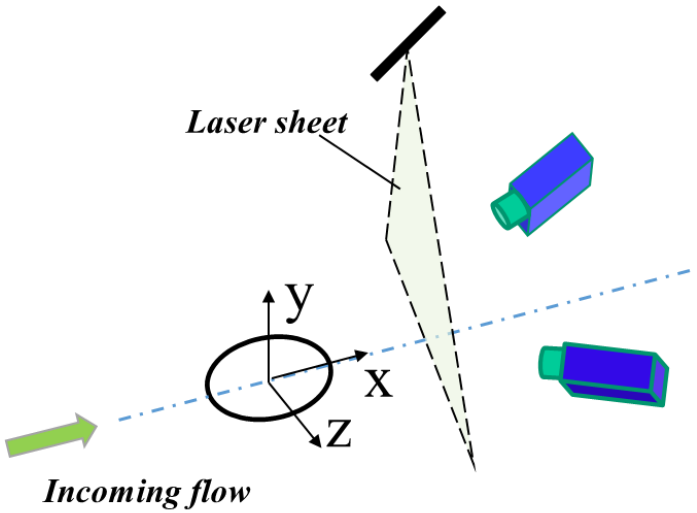


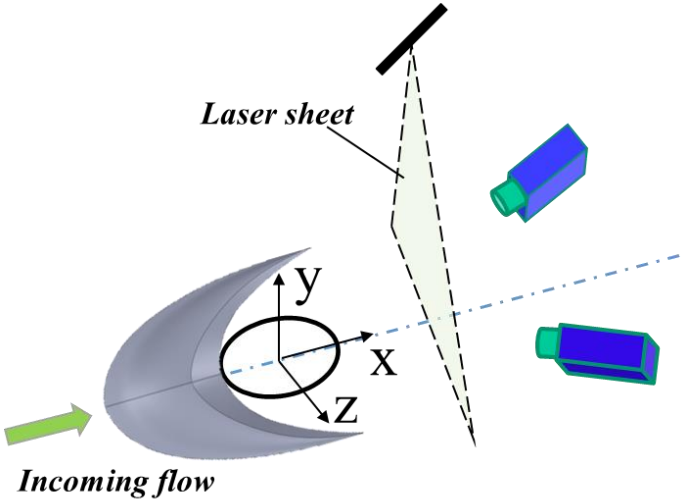
(b) BDSR, M=1.00

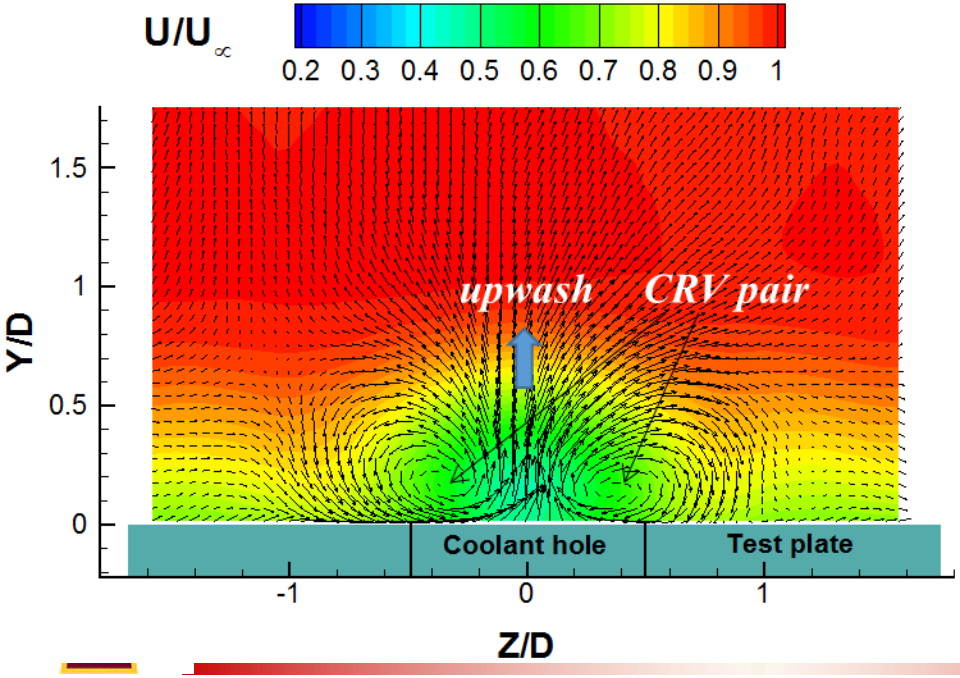


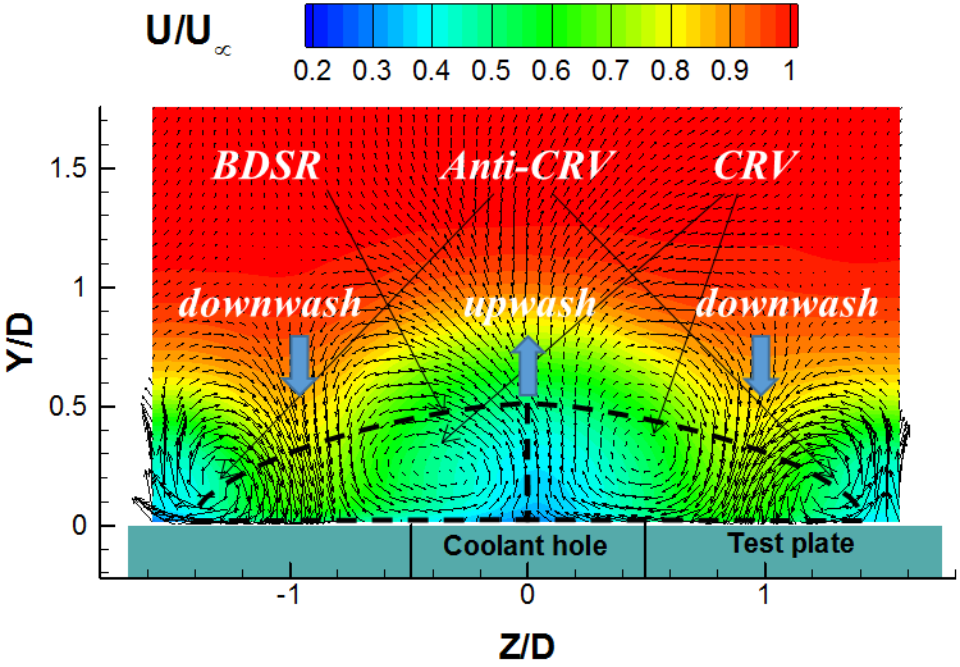


Stereo PIV Measurement (2D3C) [M=1.00]

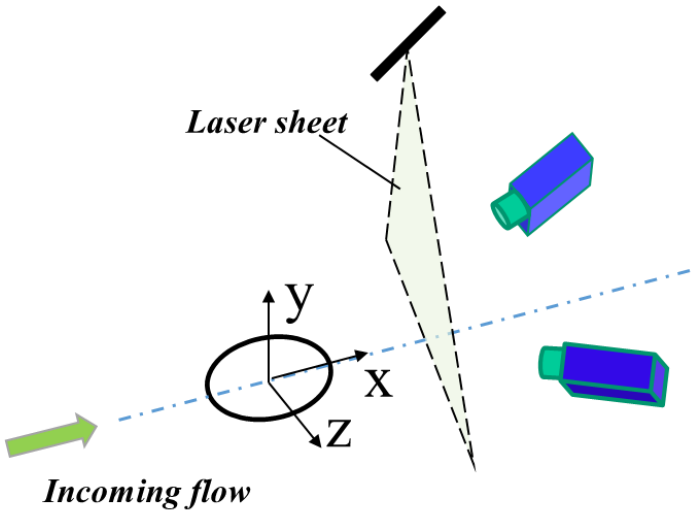


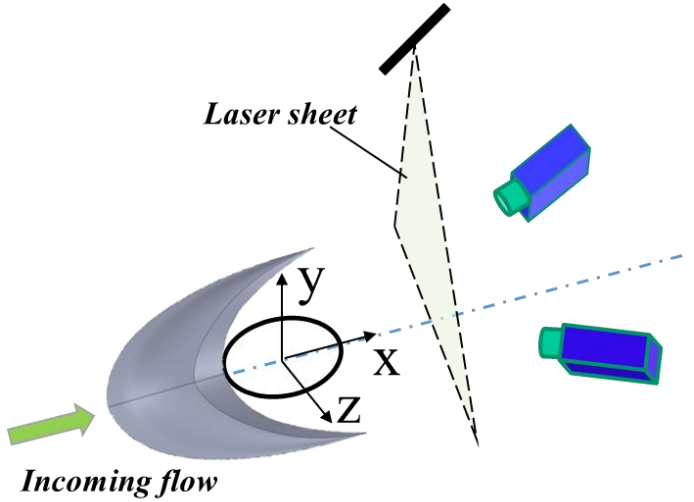


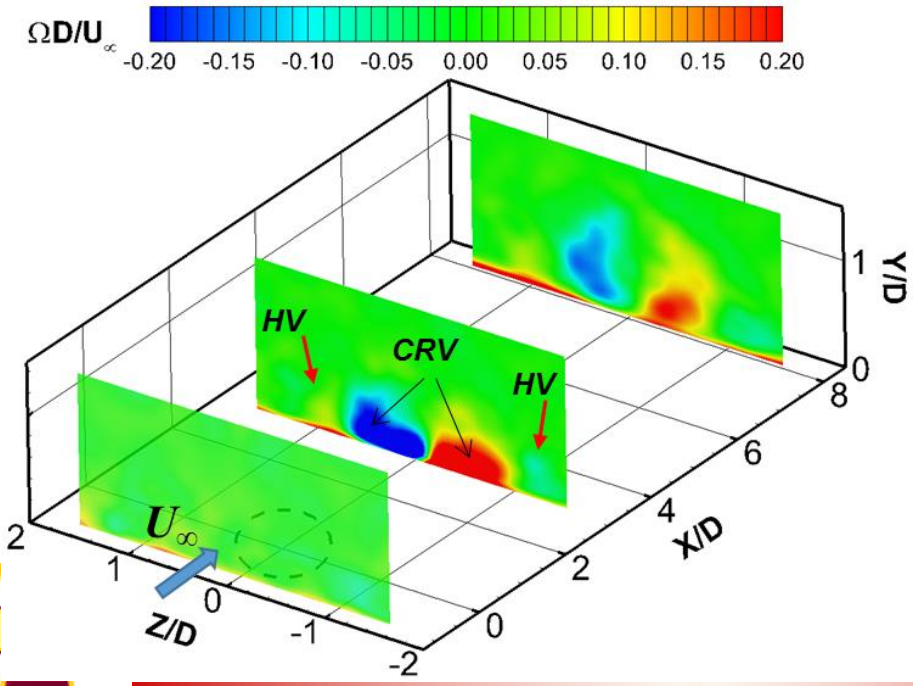


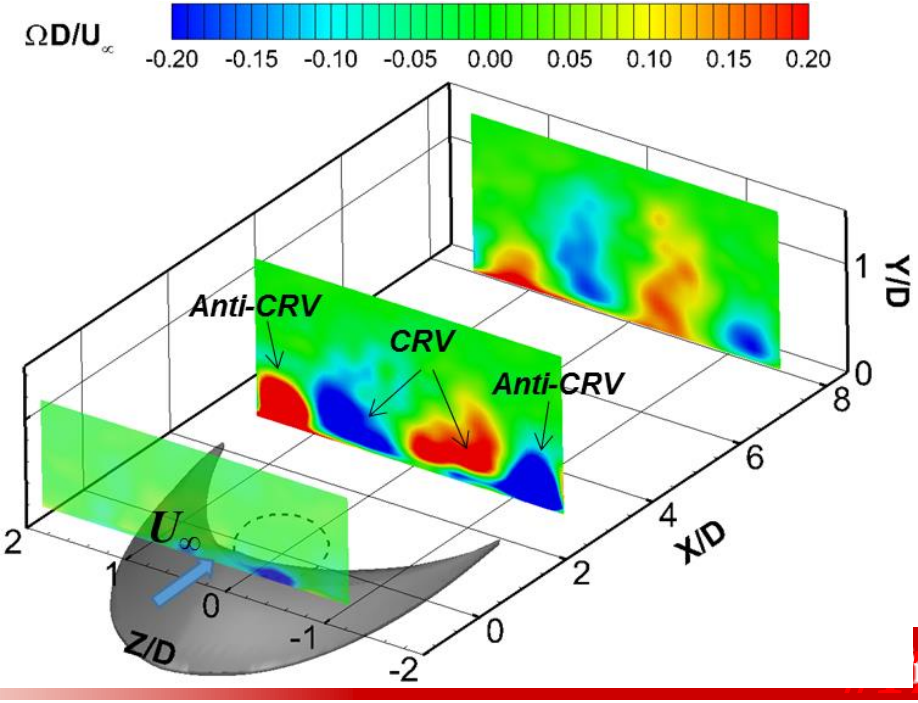


Stereo PIV Measurement (2D3C) [M=1.00]









Flow over Barchan Dune

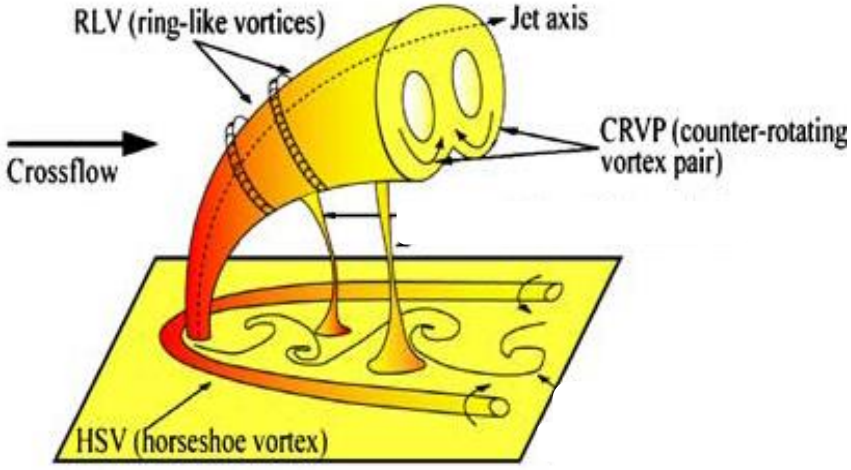
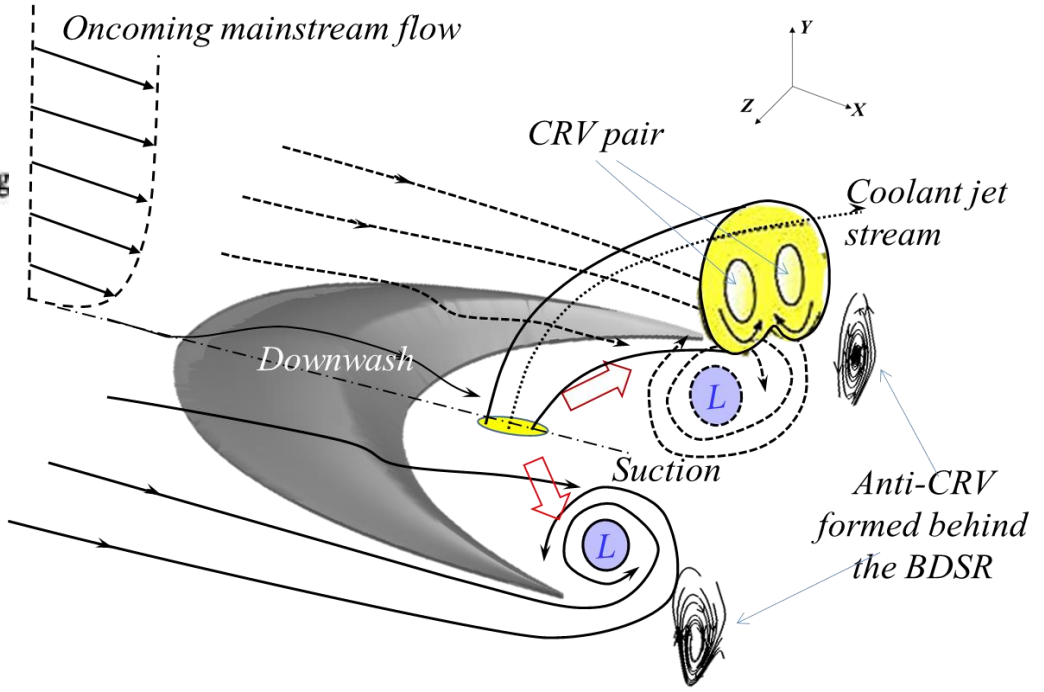


Image Source: Lehrstuhl für Thermodynamik.



Jet in cross flow for baseline case

- ***CRV** in Y-Z plane generates detrimental vortex induction and promotes the jet separation.*
- ***Circulation** in X-Z plane generates continuous suction and force the coolant to spread uniformly.*
- ***Anti-CRV** in Y-Z plane is able to counteract the vorticity effect, and retards the jet separation.*

Concept of Barchan-Dune-Shaped-Injection-Compound (BDSIC)

Image Source: Sand dune search.

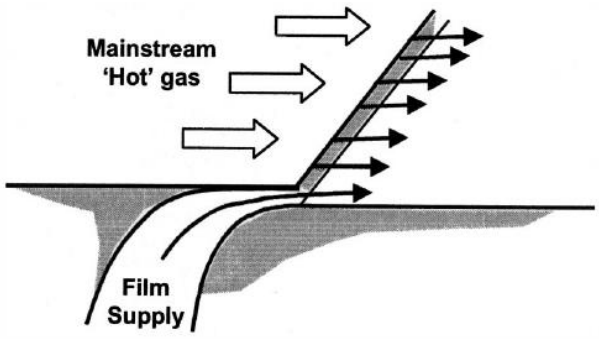
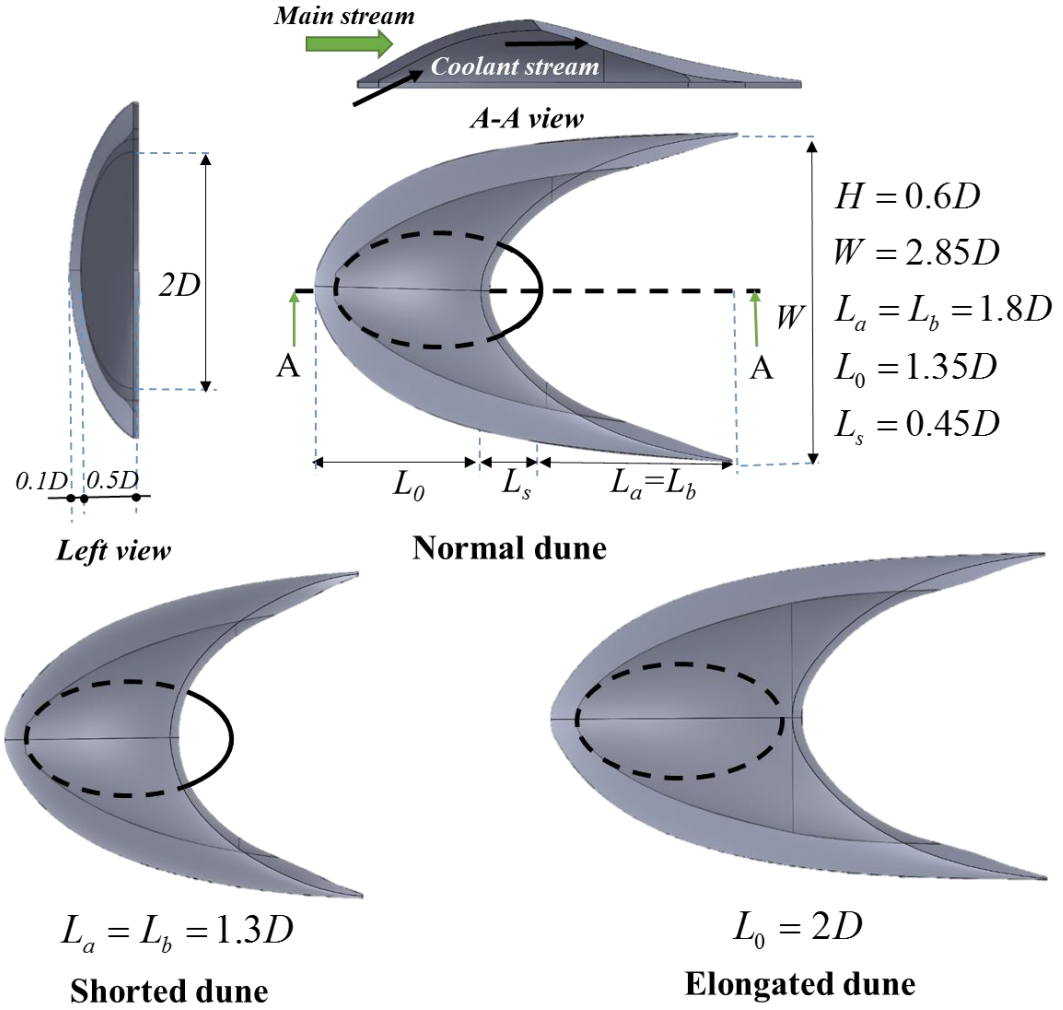


Fig. 1 Ideal tangential slot film cooling

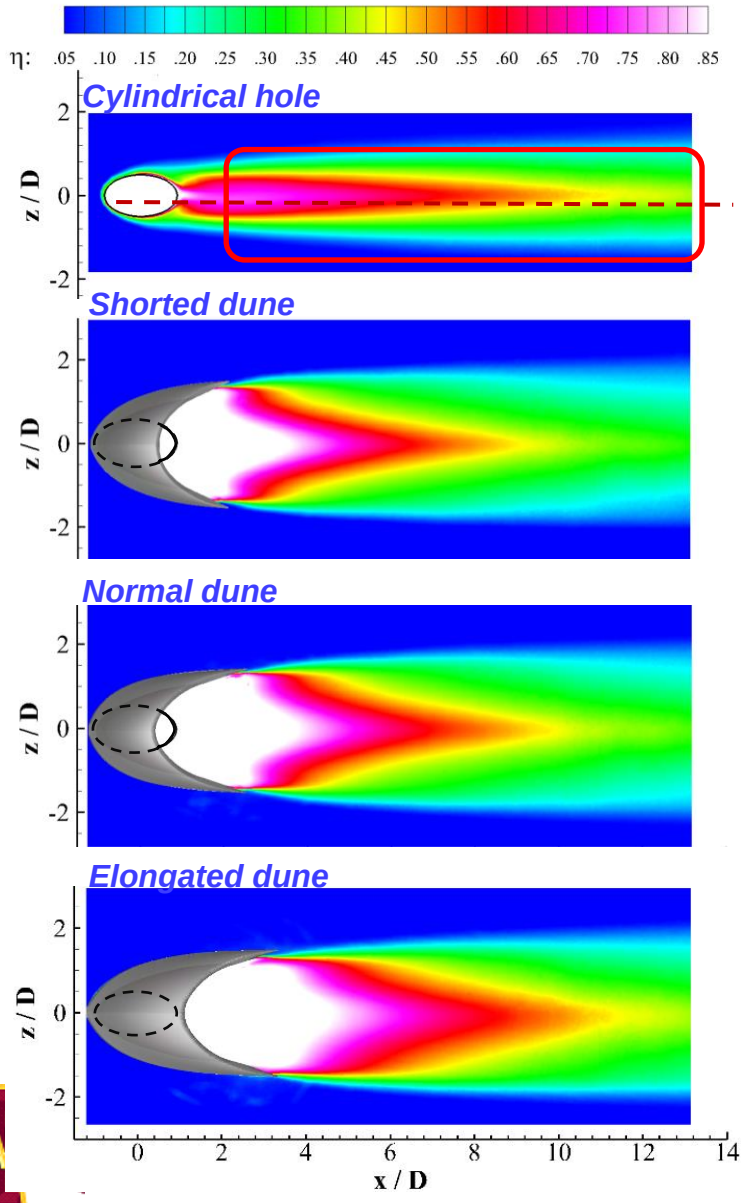
Image Source: Goldstein (1971)

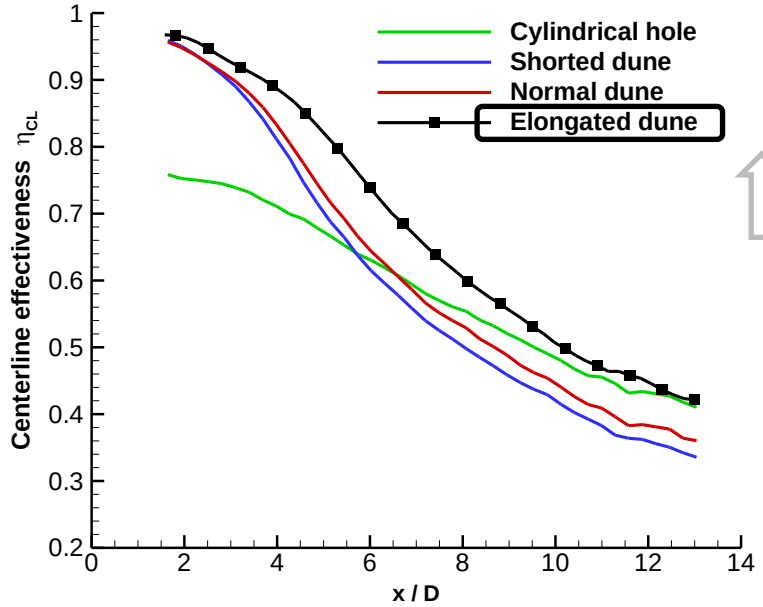
Exit area ratios remained same

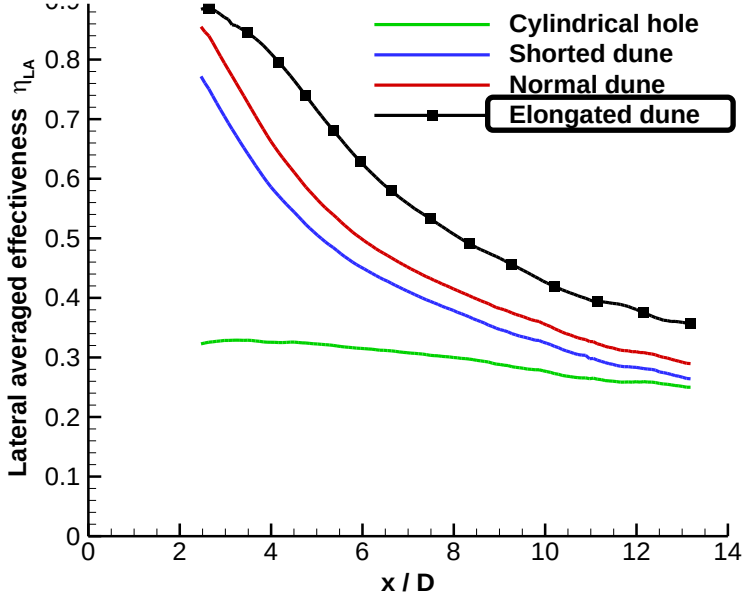


D=12 mm
Single hole

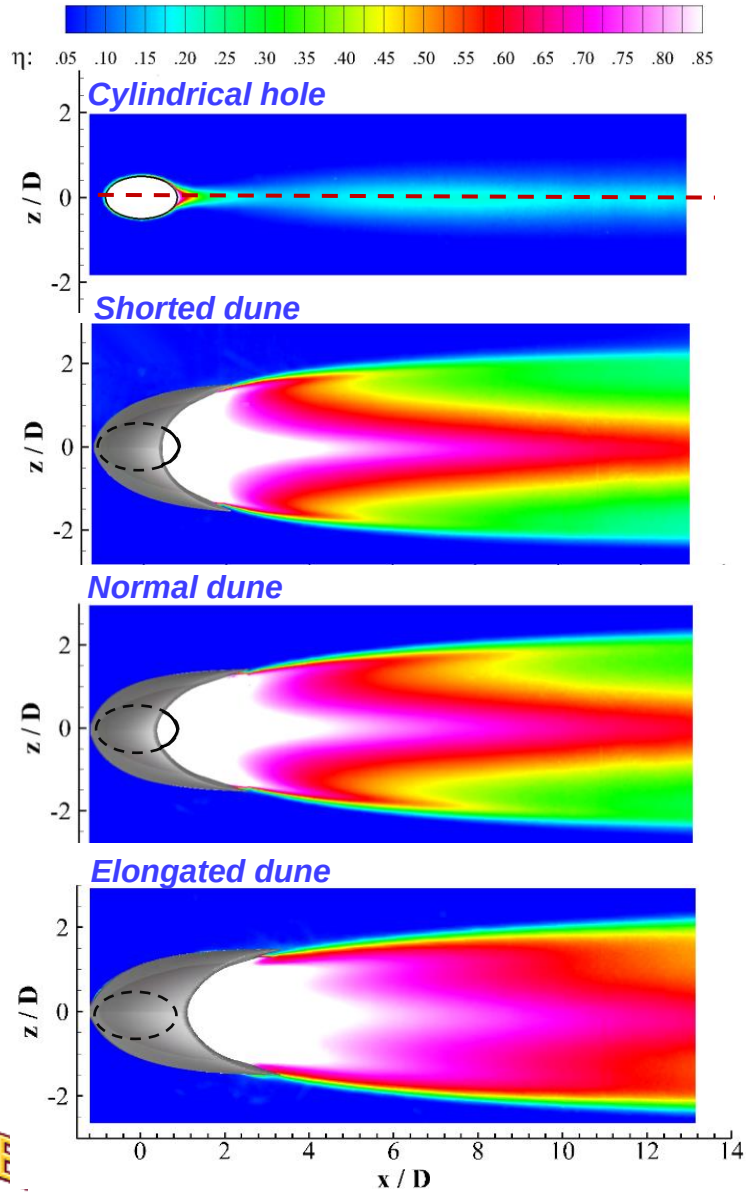
PSP Measurement Results [M=0.6]

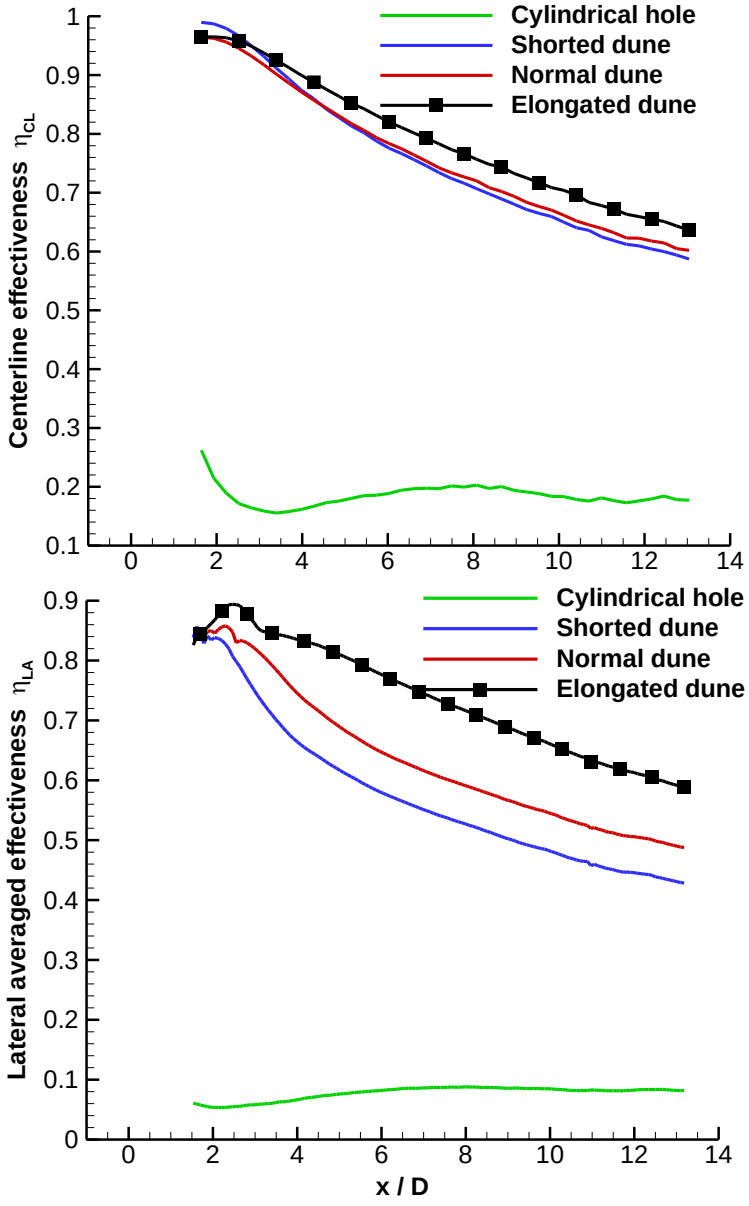




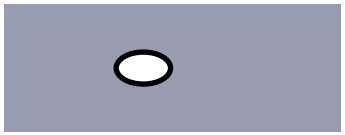


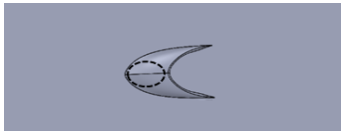
PSP Measurement Results [M=1.5]

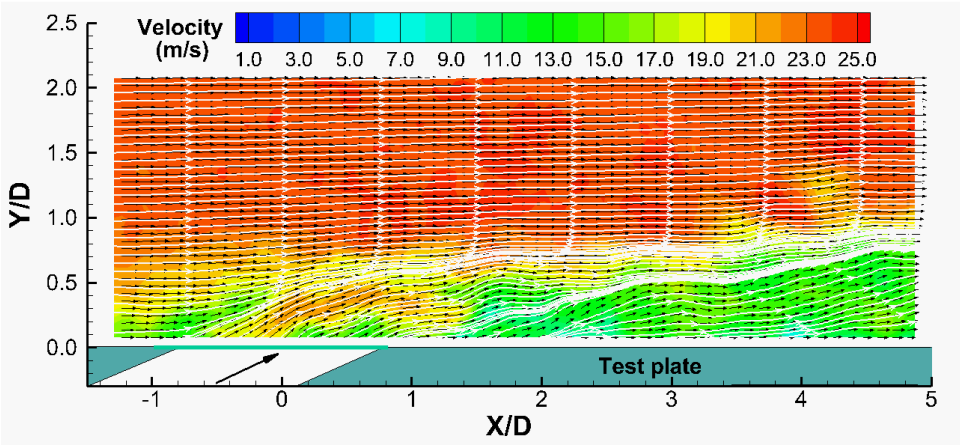


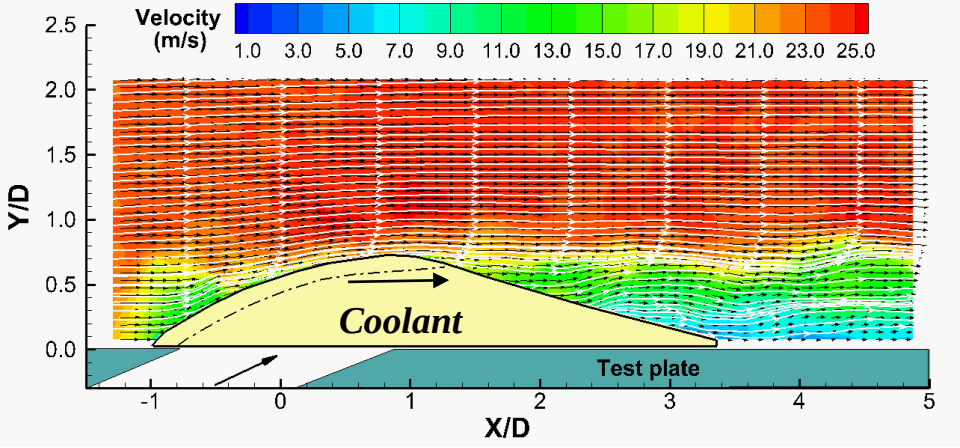


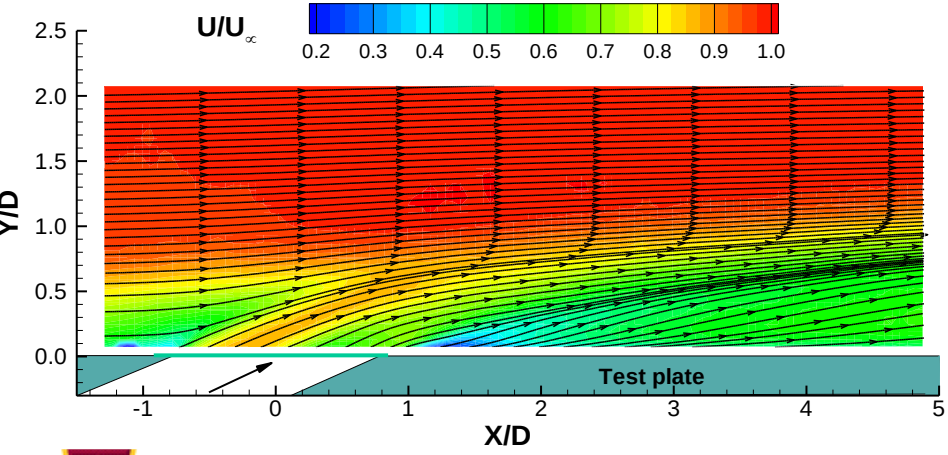
PIV Measurement Results [M=0.91]

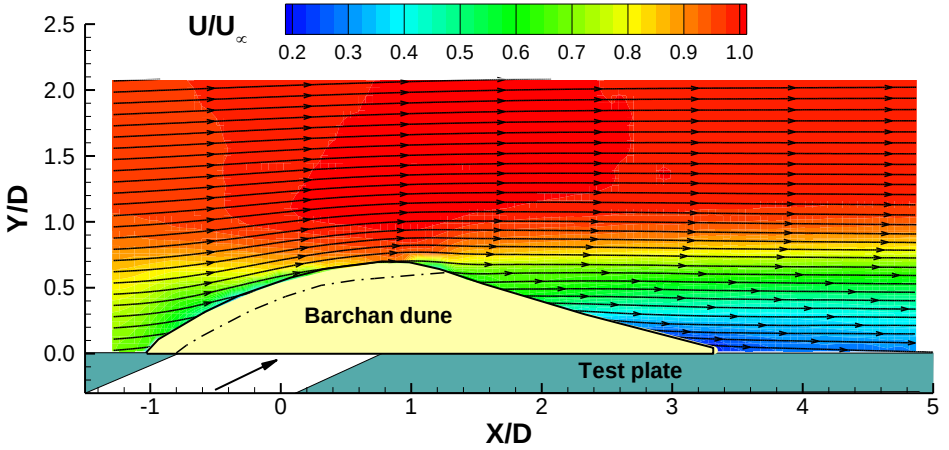






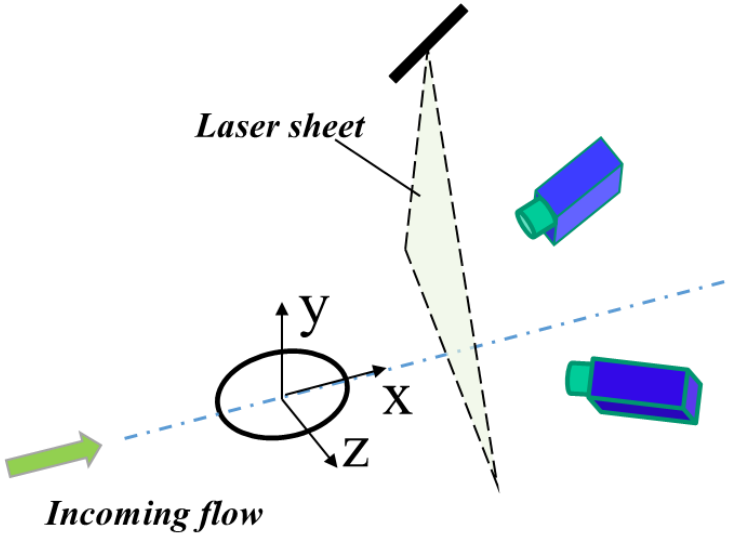


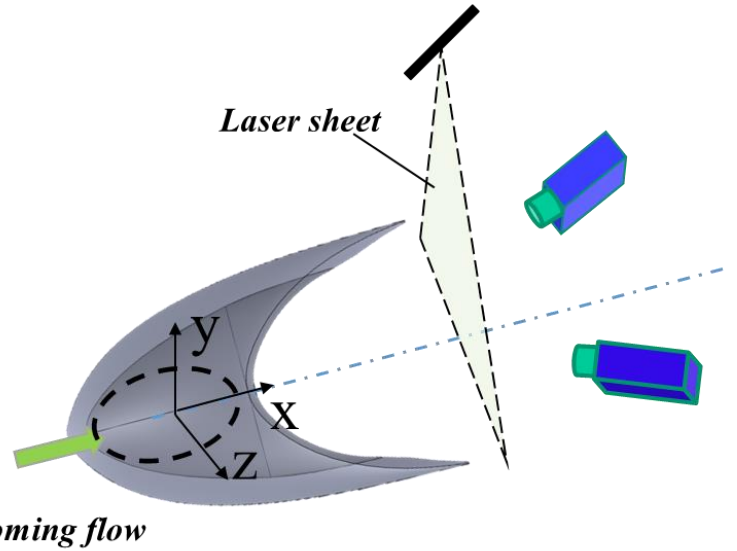


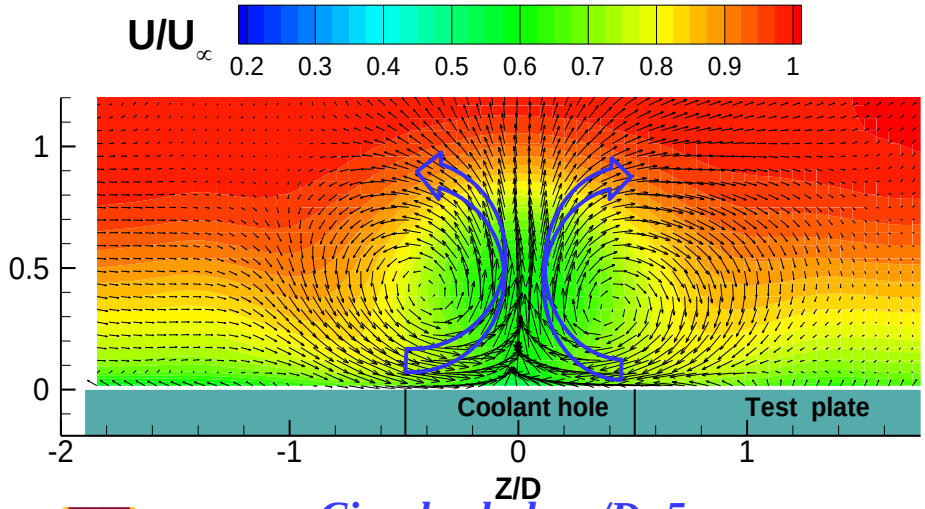


- *Circular coolant jet was found to lift off, while the BDSIC jet stayed on the surface.*

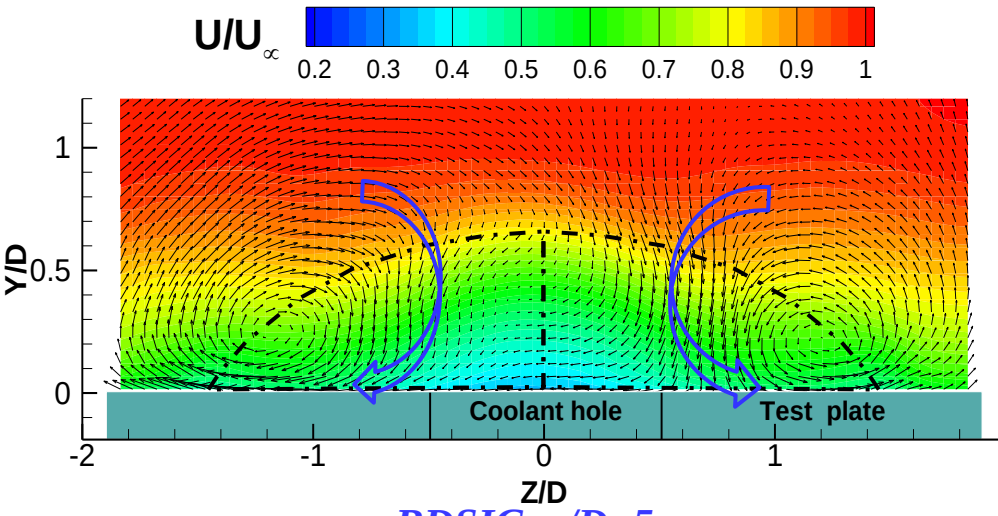
Stereo PIV Measurement (2D3C) [M=0.9]





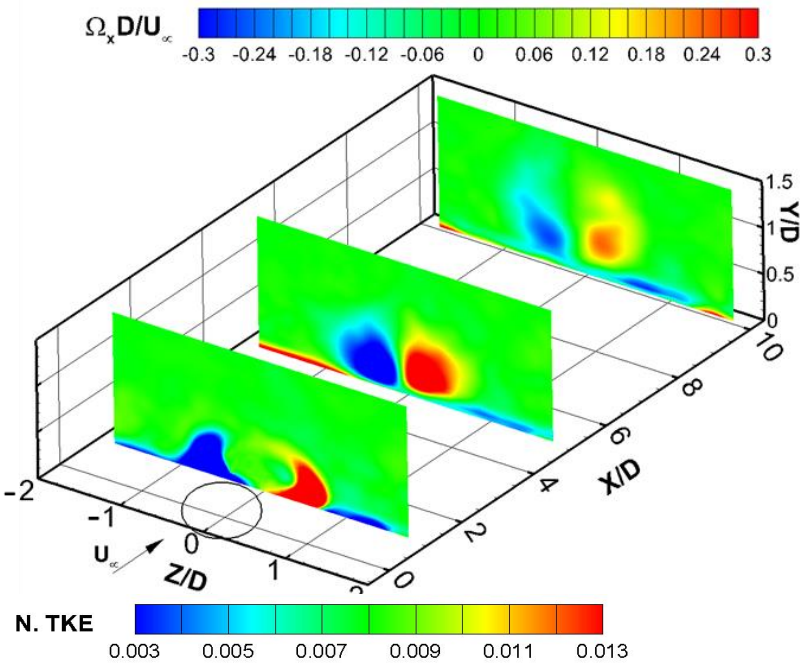


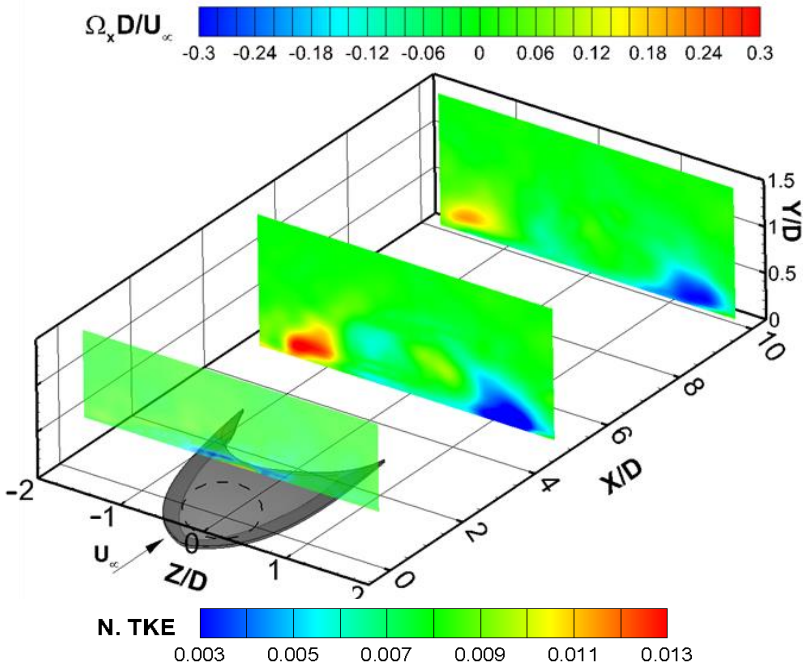
Circular hole, x/D=5

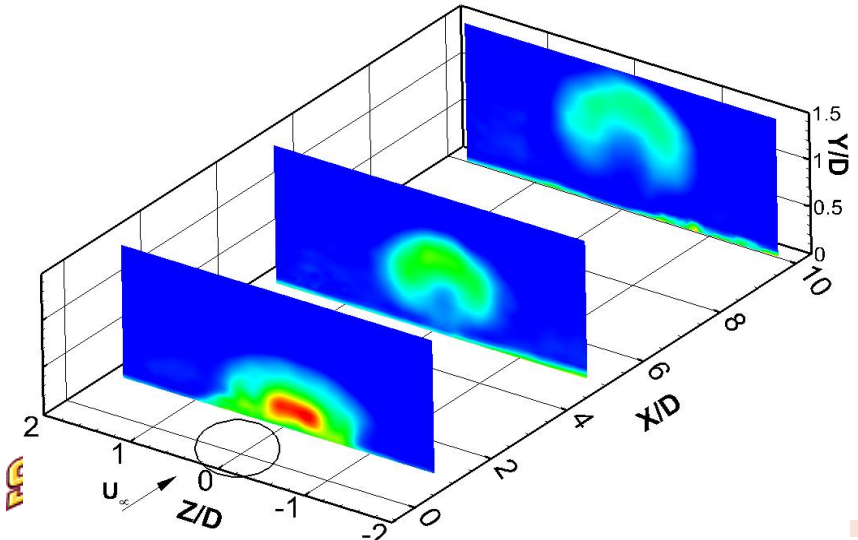


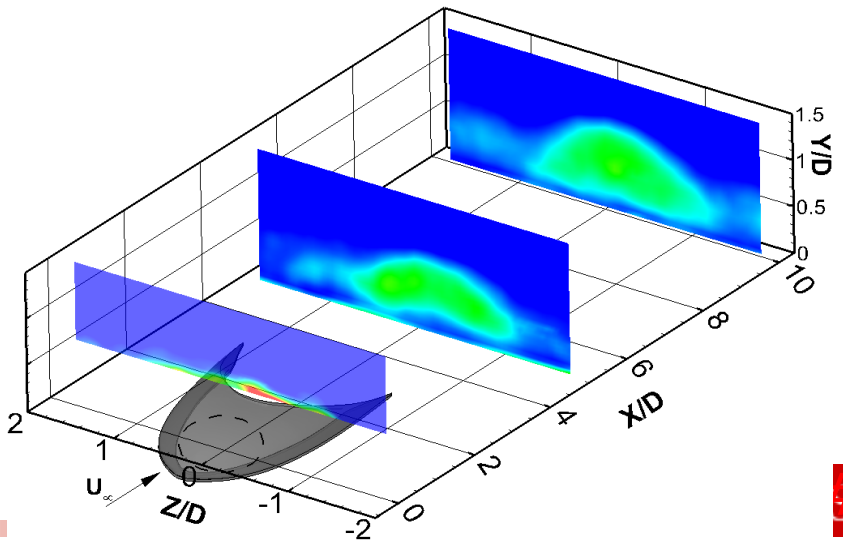
BDSIC, x/D=5

Stereo PIV Measurement (2D3C) [M=0.9]









Aerodynamic loss

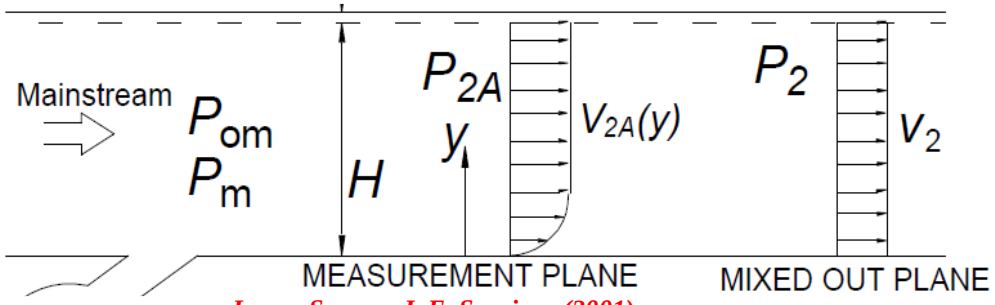
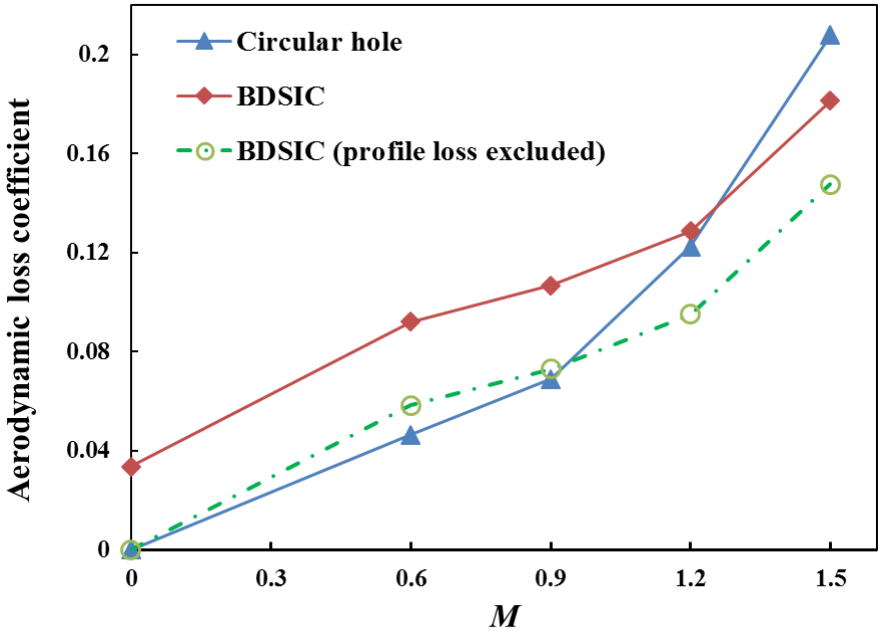
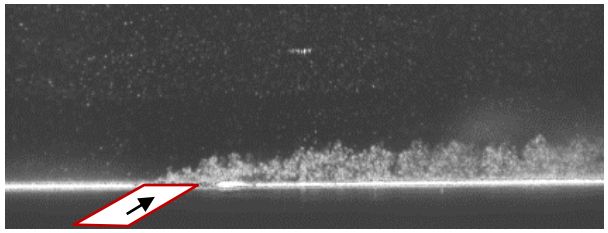


Image Source: J. E. Sargison (2001).

$$Loss = 1 - \frac{0.5\rho v_2^3 A}{\frac{\dot{m}_m}{\rho_m}\left(P_{om} - P_2\right) + \frac{\dot{m}_c}{\rho_c}\left(P_{oc} - P_2\right)}$$

- ***CV (-2D<x<10D, 0<y<2.5D, and-3D<z<3D);***
- ***Air served as coolant.***

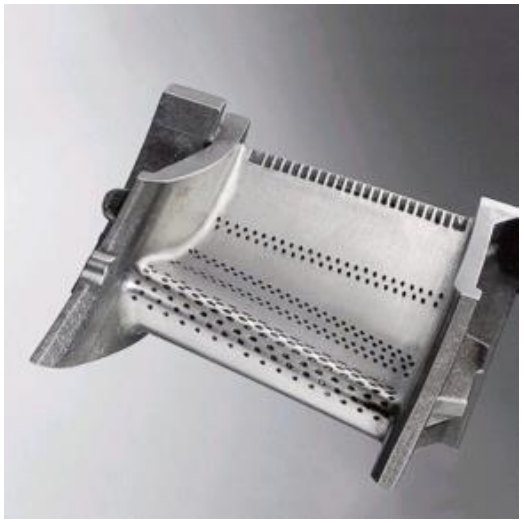


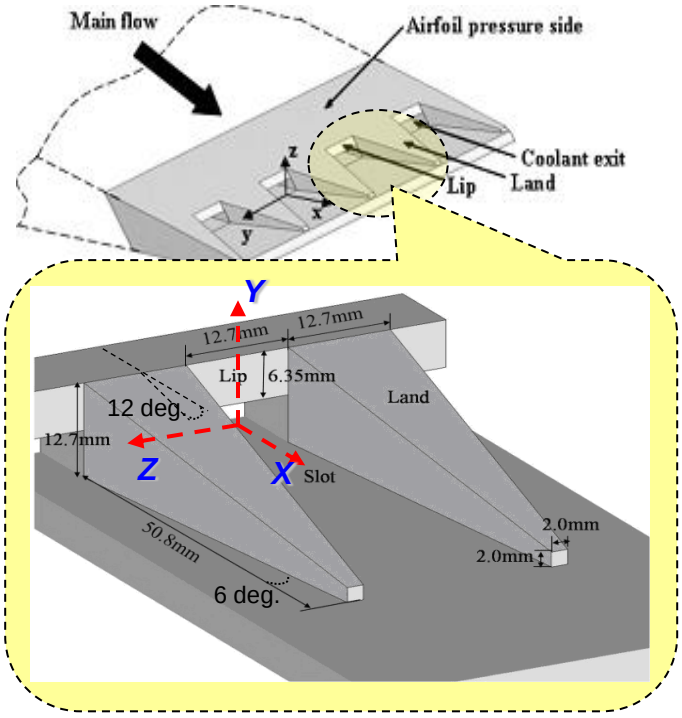


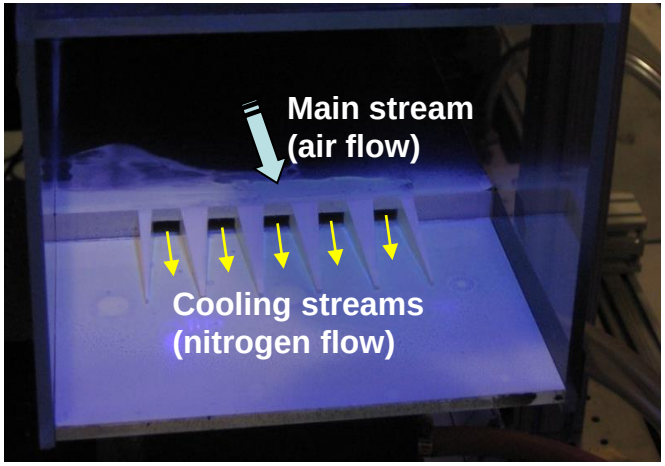
- ***Boundary layer mixing is the primary loss for low M.***
- ***The circular jet took off and penetrated into the mainstream at high M.***
- ***The BDSIC does help alleviate the turbulent mixing between jet and mainstream at relative high M.***

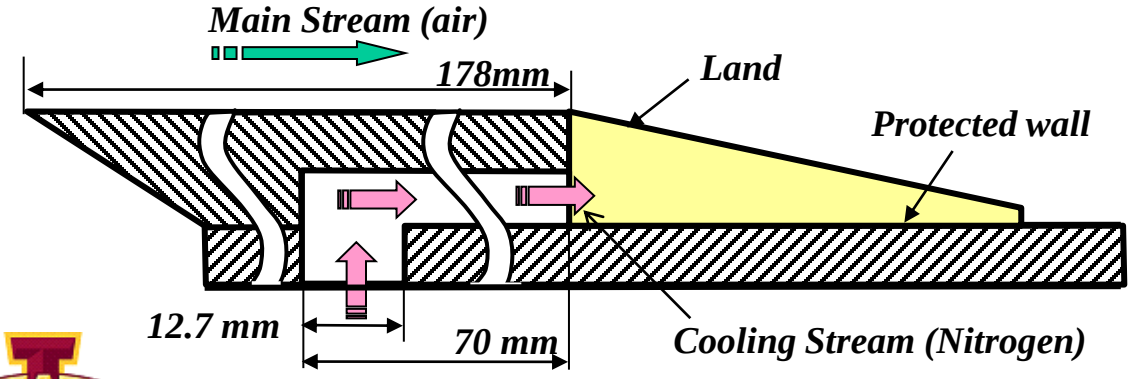
Sargison, J.E., "Development of a Novel Film Cooling Hole Geometry" ,University of Oxford, 2001.

Trailing Edge Cooling: Test Model and Flow Conditions

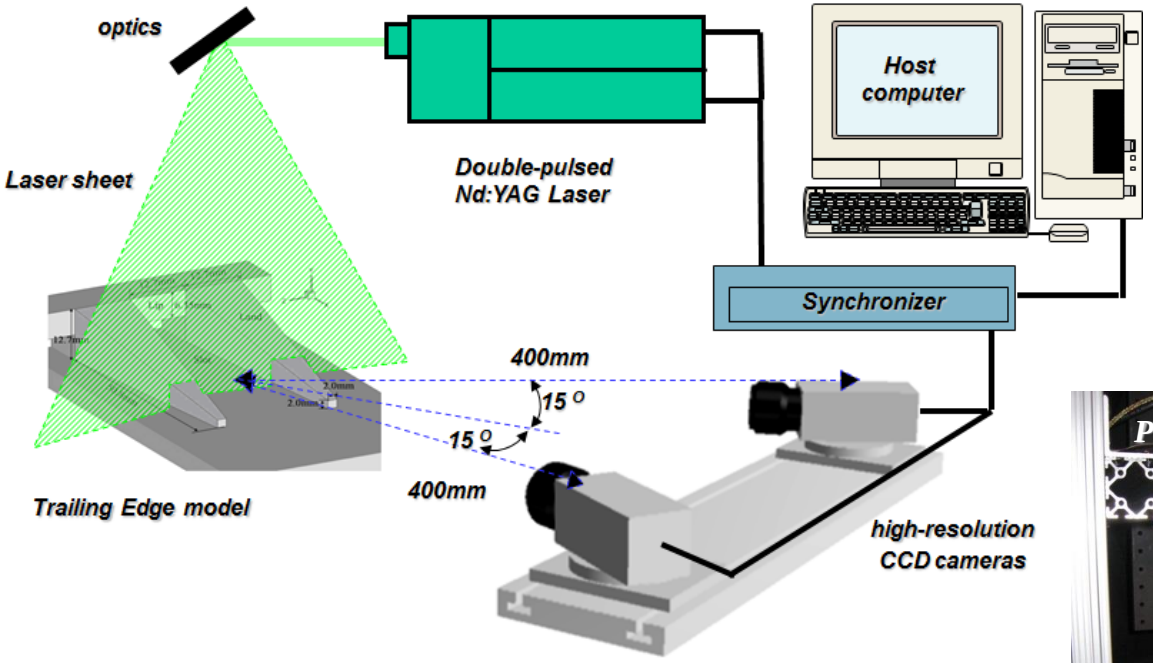




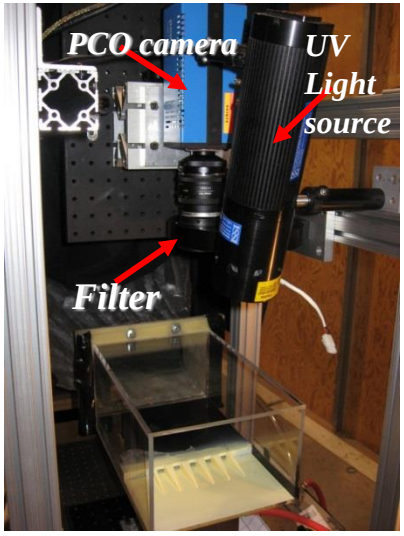


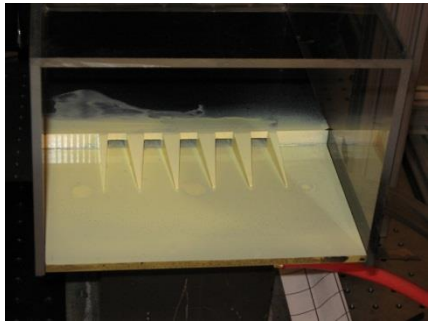


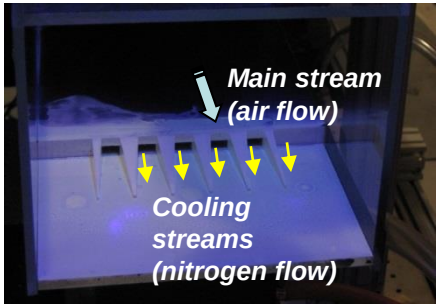
Experimental Setup: Stereo PIV and PSP Measurements



Experimental Setup for SPIV measurements





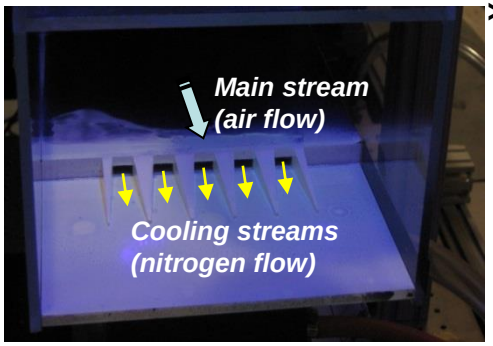


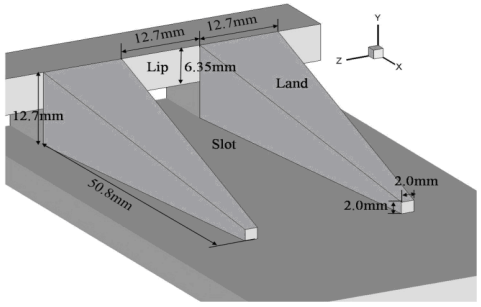
Experimental Setup for PSP measurements

Test conditions:

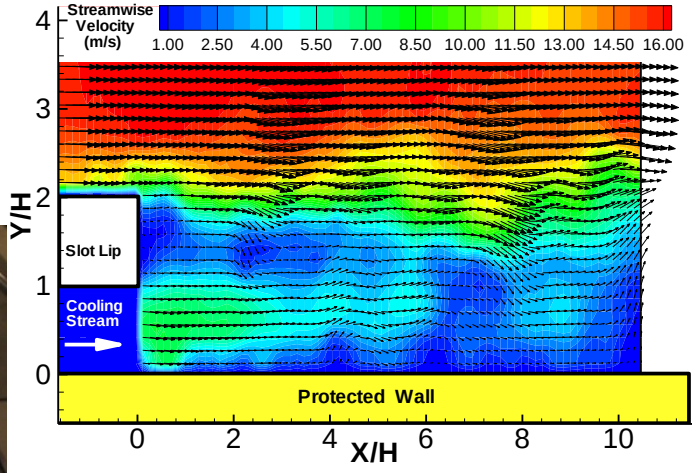
- *Flow velocity of main stream:* V_0*=16.2m/s*
- *Blowing ratio :* *M = 0 ~1.6.*
- Re_m*= 190K based on model length.*
- Re_s *= 2,800~10,500 based on tip thickness*
- *Turbulence intensity for main stream: < 1.0%*
- *Turbulence intensity for coolant streams: ~5.0 %.*

PIV measurement Results in the Cross Plane Along Flow Direction



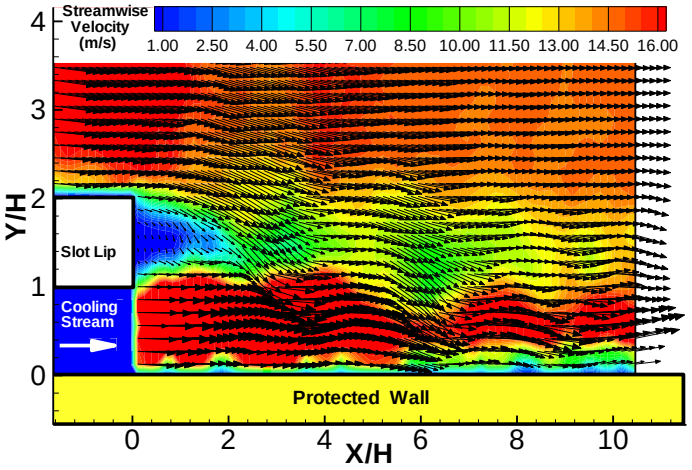


Blowing ratio M=0.45

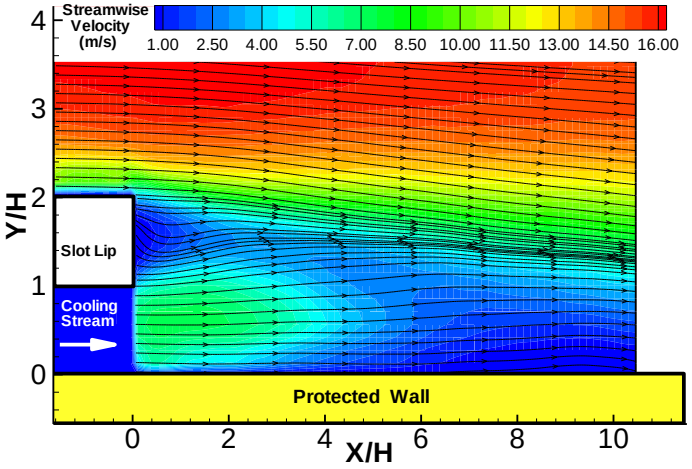


Instantaneous velocity distributions

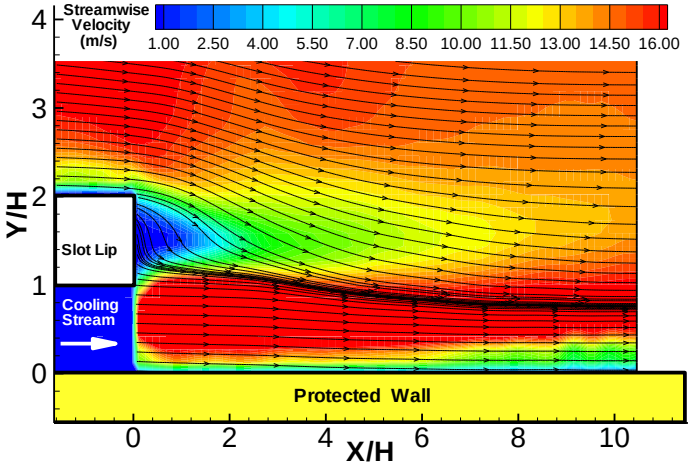
Blowing ratio, M=1.60



Instantaneous velocity distributions

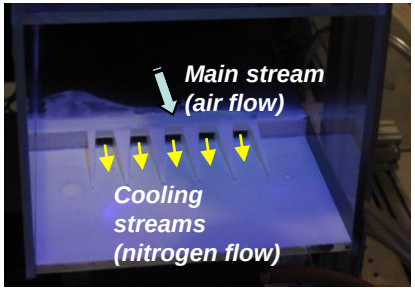


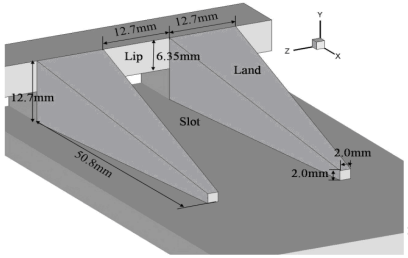
Time-averaged velocity distribution

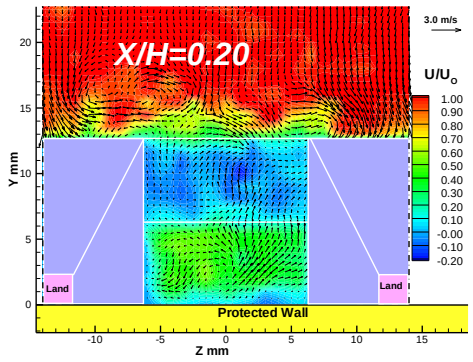


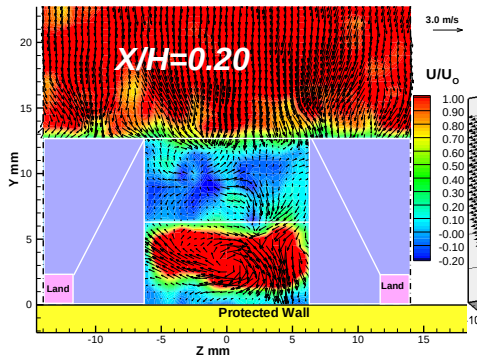
Time-averaged velocity distribution

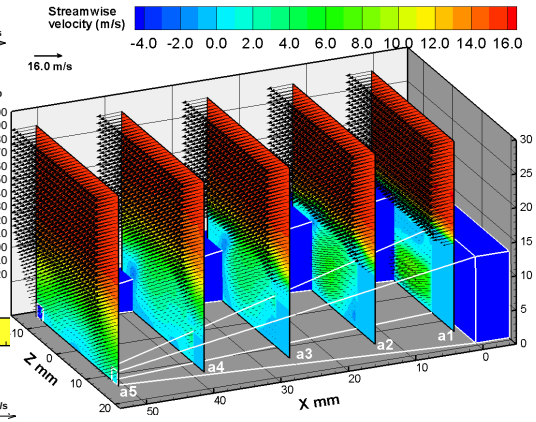
Stereoscopic PIV measurement Results



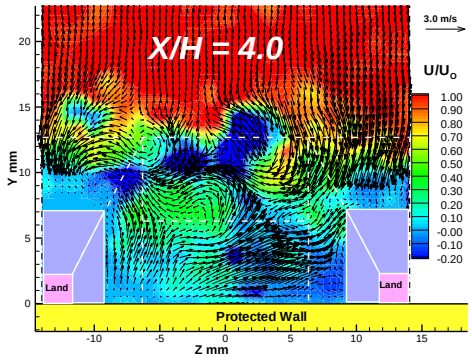


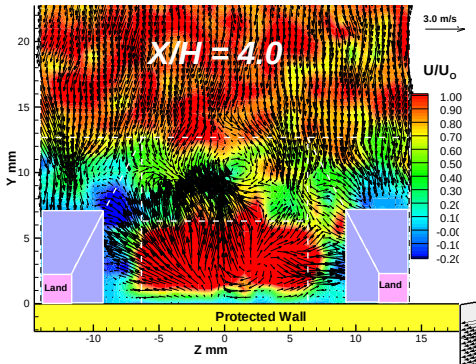


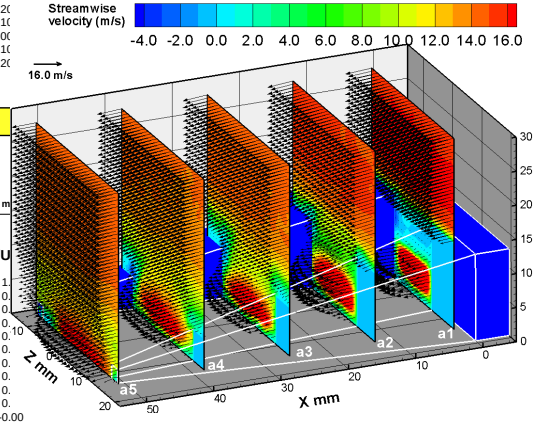




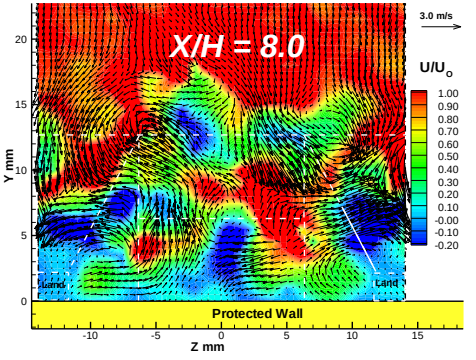
Blowing ratio, M = 0.45

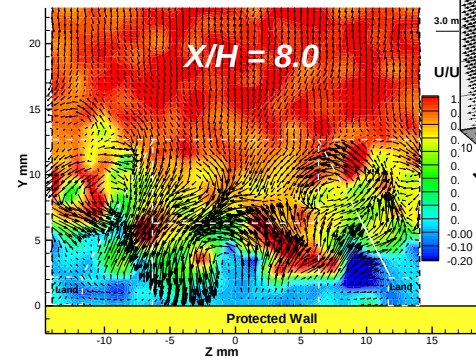






Blowing ratio, M = 1.60





Blowing ratio, M = 0.45

Blowing ratio, M = 1.60

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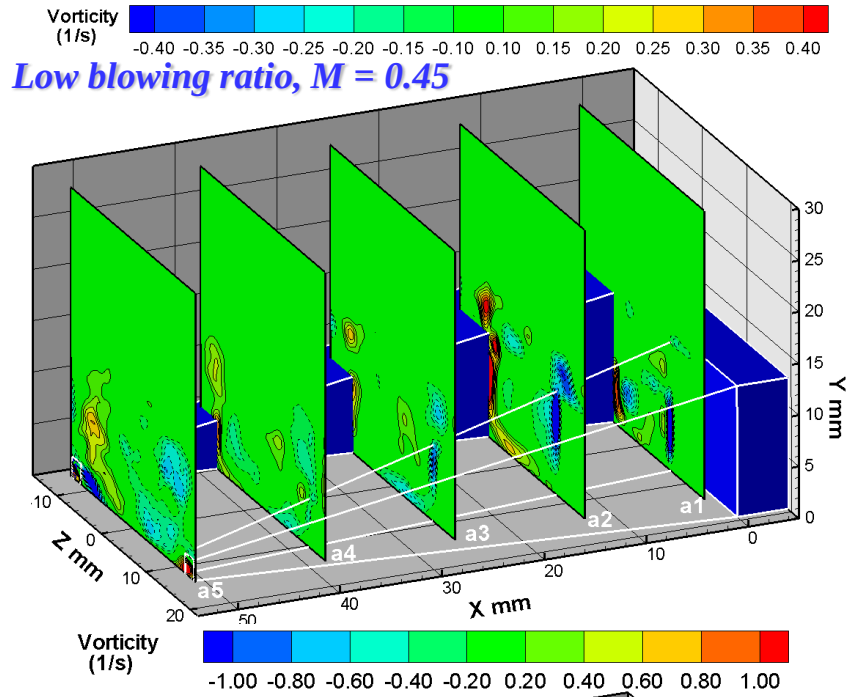
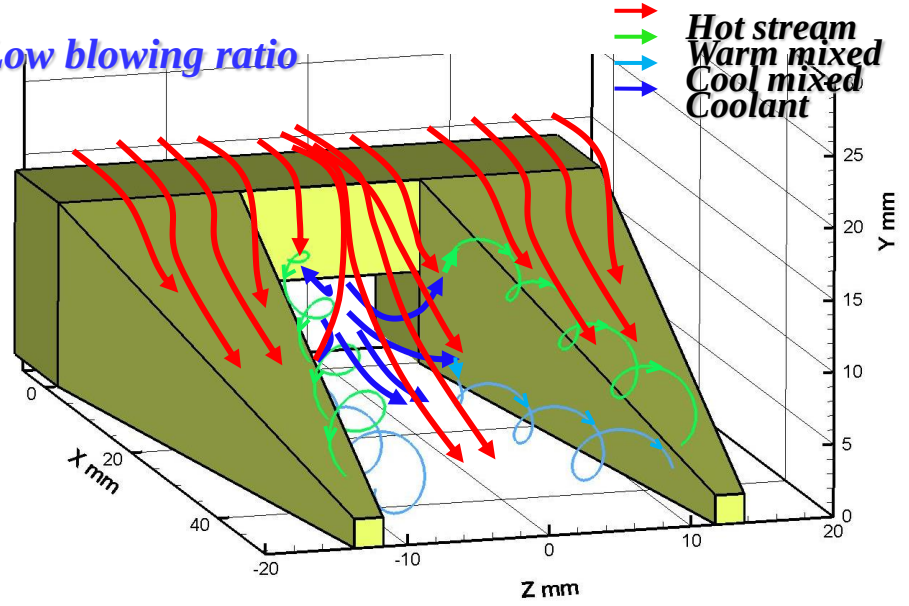
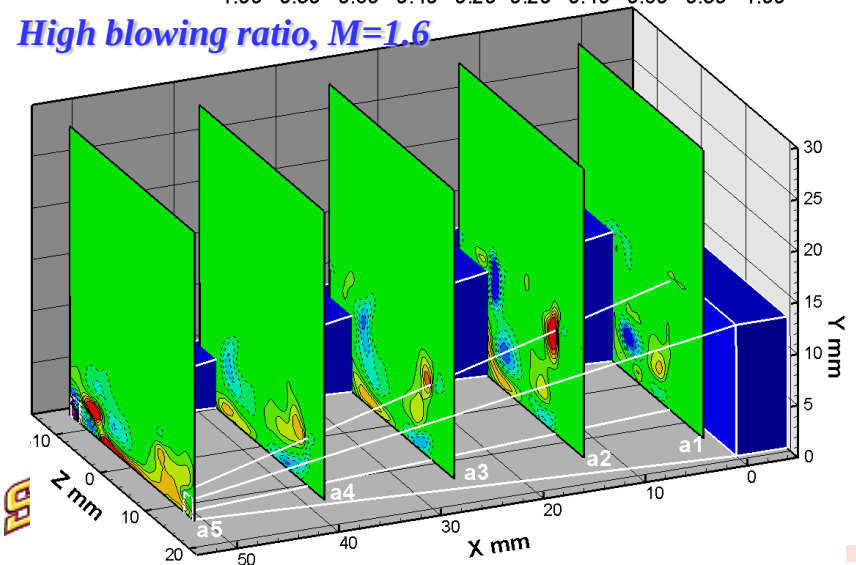
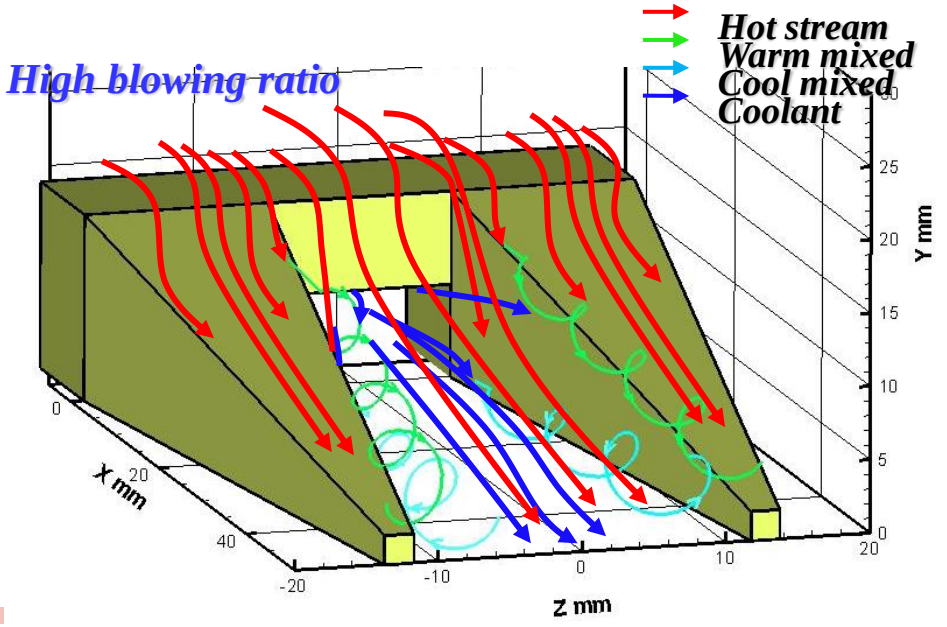
Flow Patterns of the Slot Jets near the Trailing Edge of a Turbine Blade



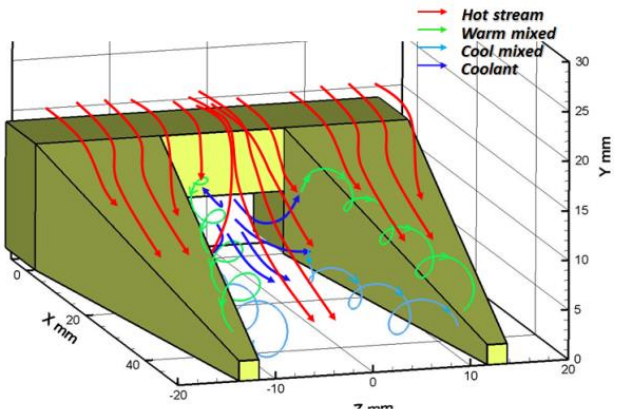


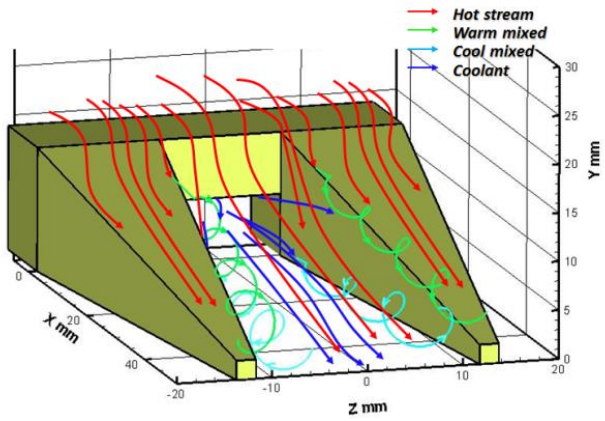




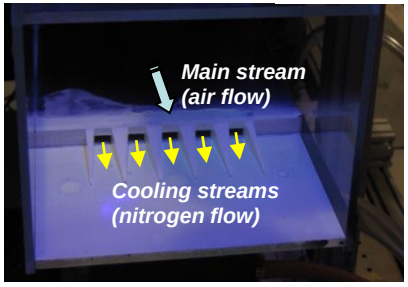
PSP Measurement Results – Blow Ratio, M = 1.60

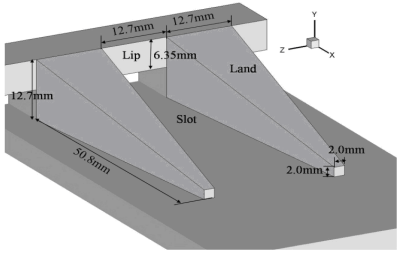
At a lower blowing ratio, M < 1.0

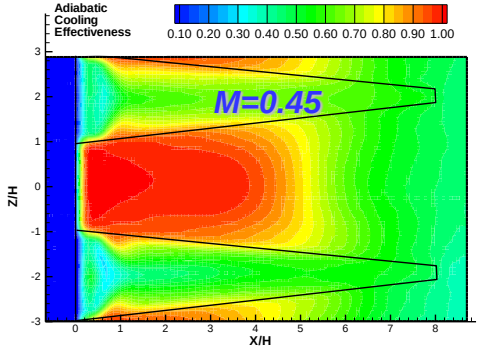


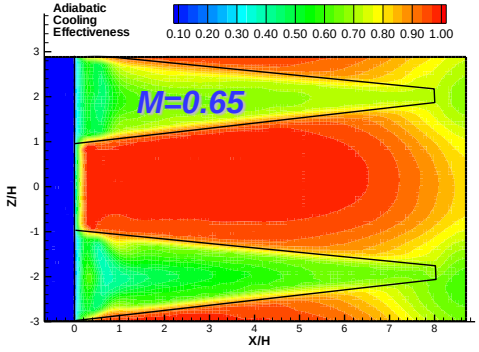


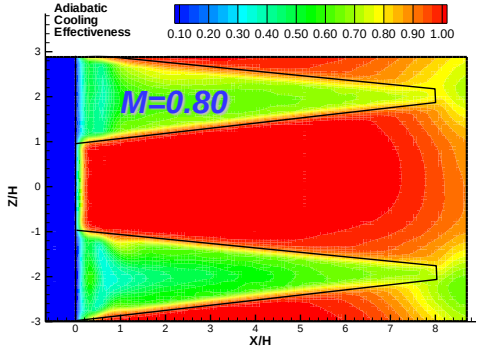
At a higher blowing ratio, M > 1.0

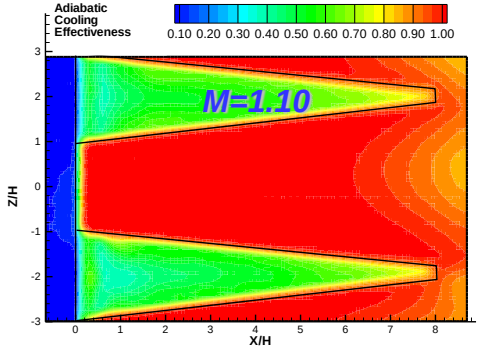


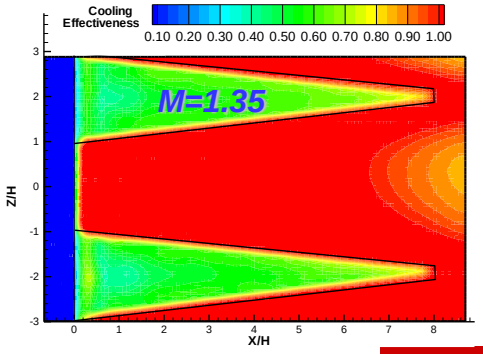


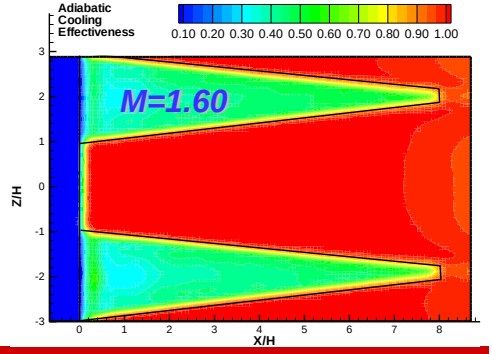












(Yang and Hu, AIAA J. of Power and Propulsion, Vol.27, No.3, pp700-709, 2011)

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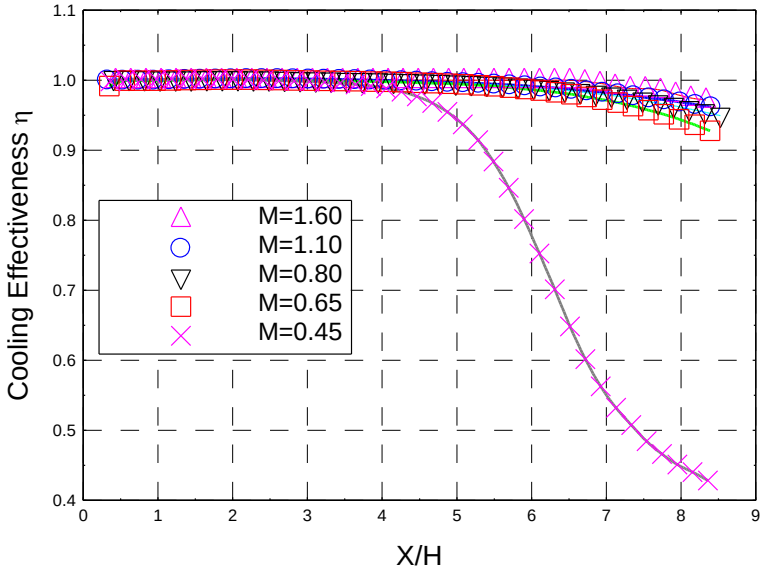
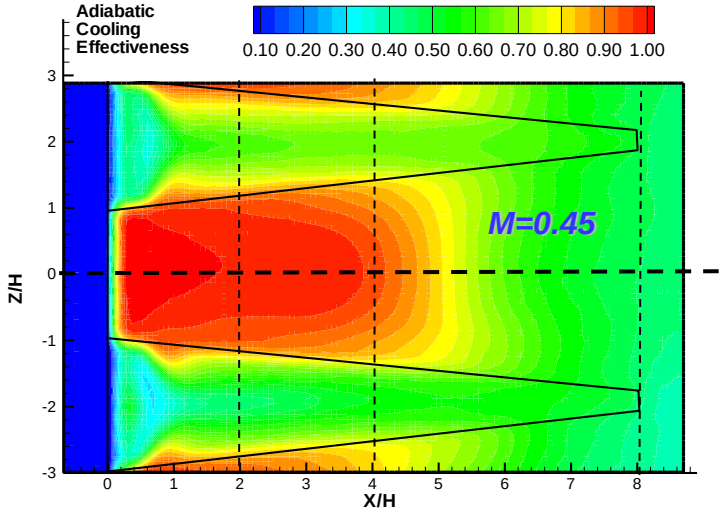
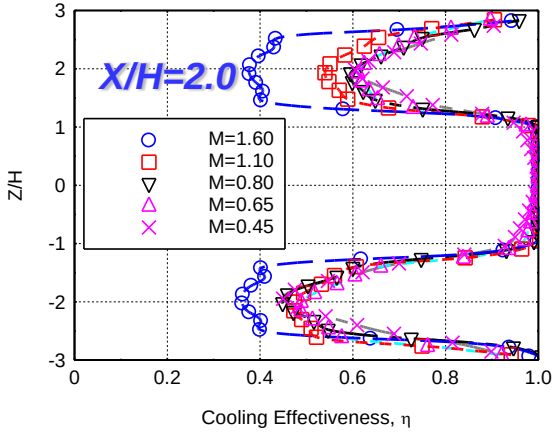
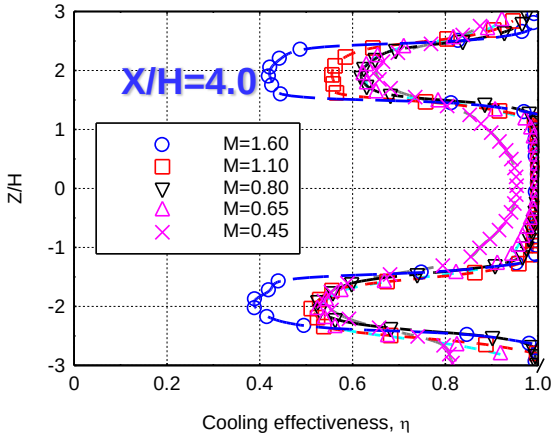
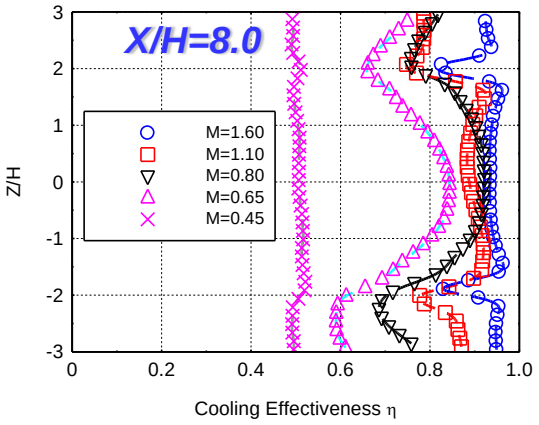
Cooling Effectiveness Measurements by using PSP technique











(Yang and Hu, AIAA J. of Power and Propulsion, Vol.27, No.3, pp700-709, 2011)

Internal Cooling of Turbine Blades

***Internal heat transfer*:**

- ***Impinging cooling along the leading edge and trailing edge***
- ***Rib turbulator in the middle range to enhance force convective heat transfer***
- ***Near trailing edge utilizing pin-fin cooling***

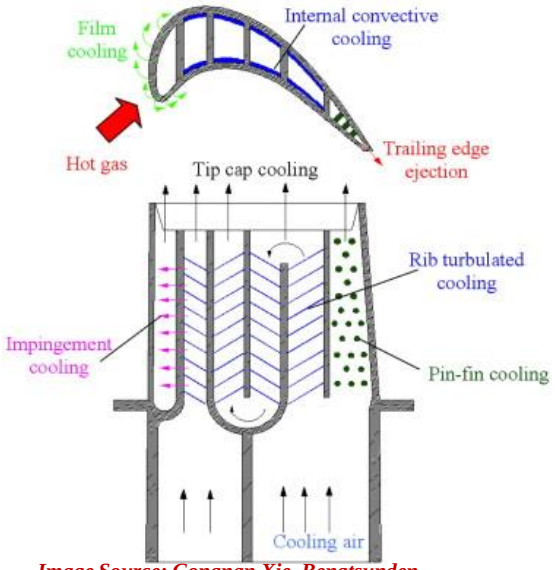


Image Source: Gongnan Xie, Bengtsunden

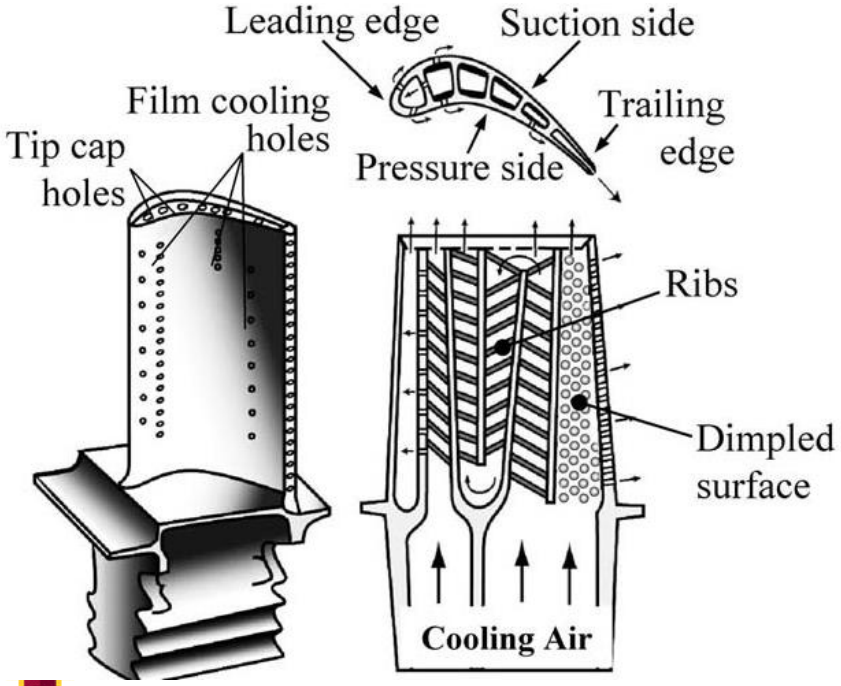


Image Source: Murata Lab

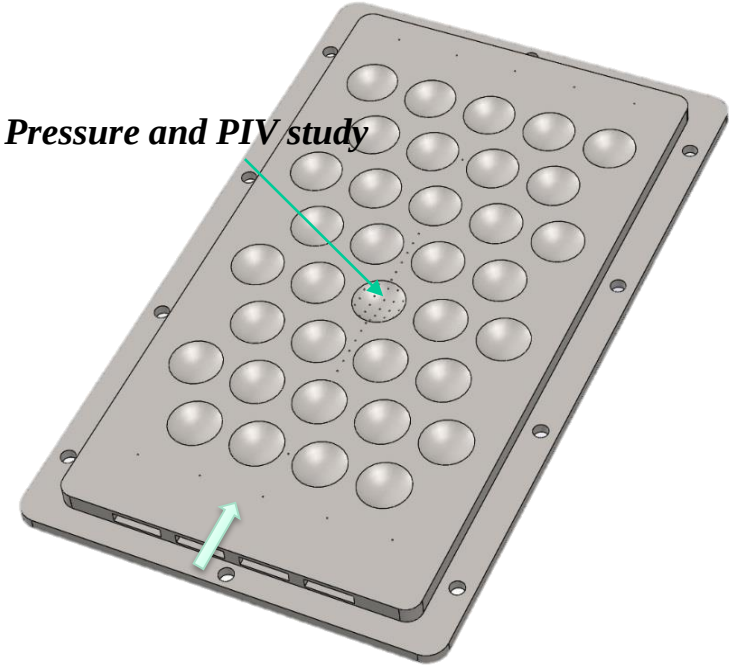
What about replacing the cylinder pin with dimples?

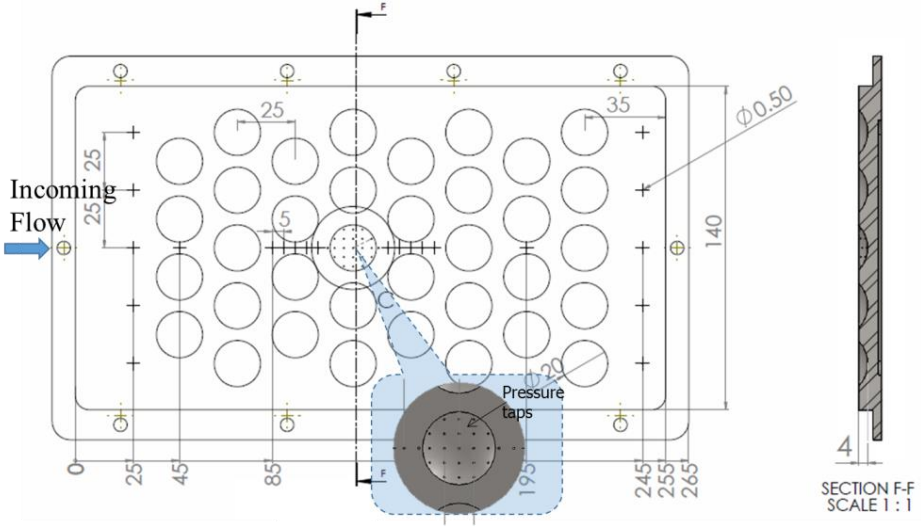
Dimples

- ***Modest heat transfer enhancement***
- ***Lower pressure loss penalty than fins***

Experimental Setup

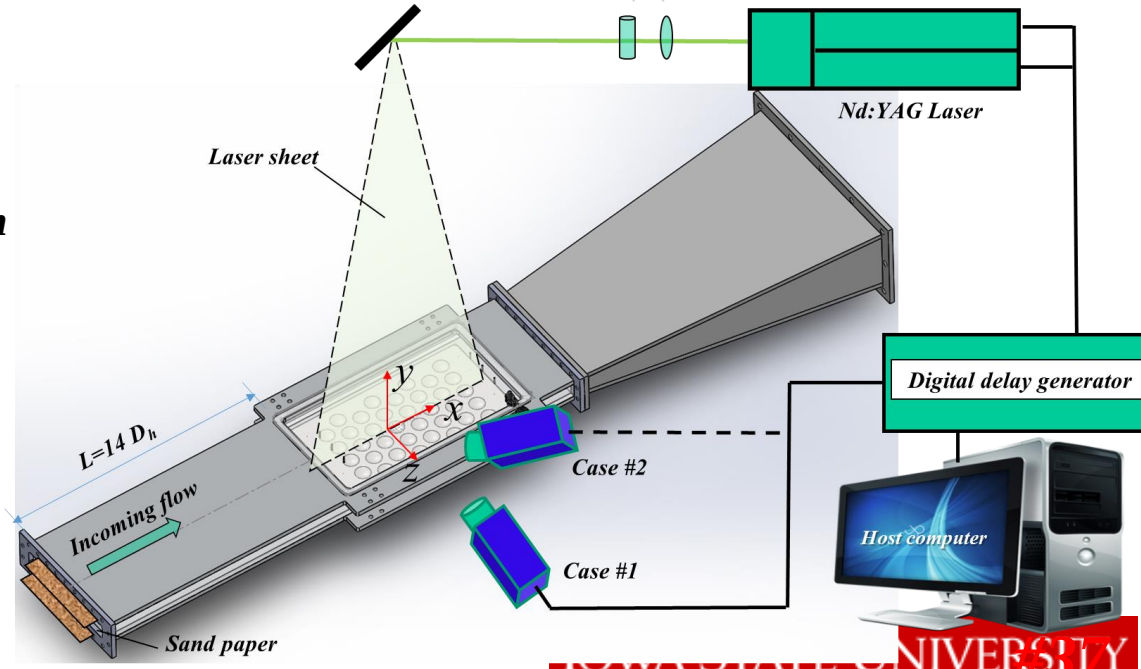
Pressure and PIV study





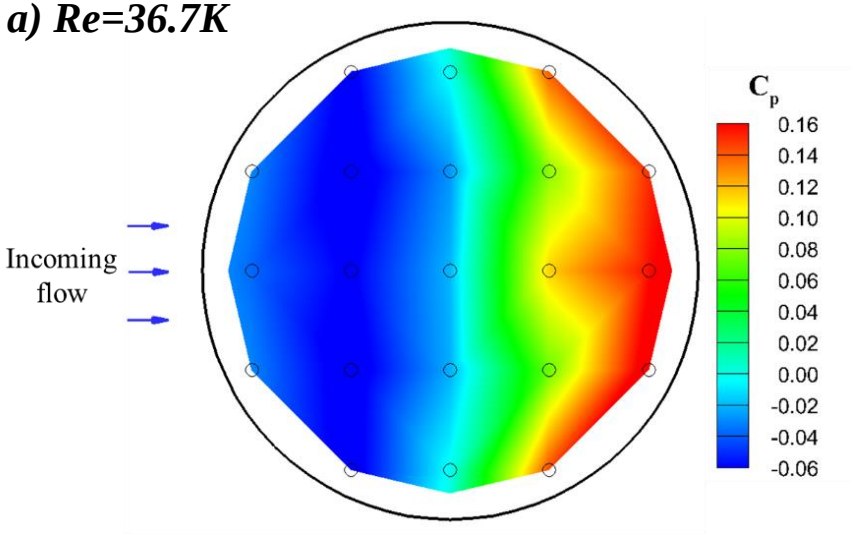
Hydraulic diameter: D_h=35.36mm

1. *Dimple diameter D=20 mm*
2. *Dimple depth h = 4 mm*
3. *21 pressure taps inside dimple*
4. *Channel height H=20 mm*
5. *H/D=1*
6. *h/D=0.2*

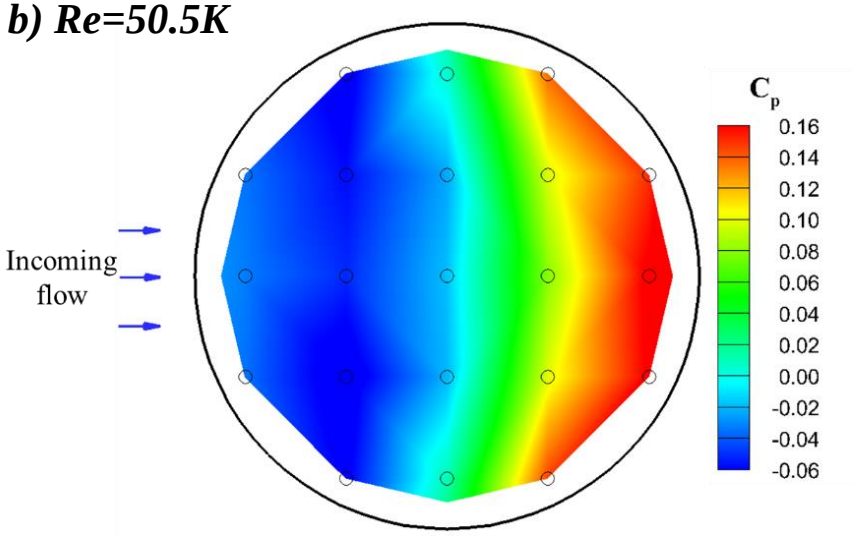


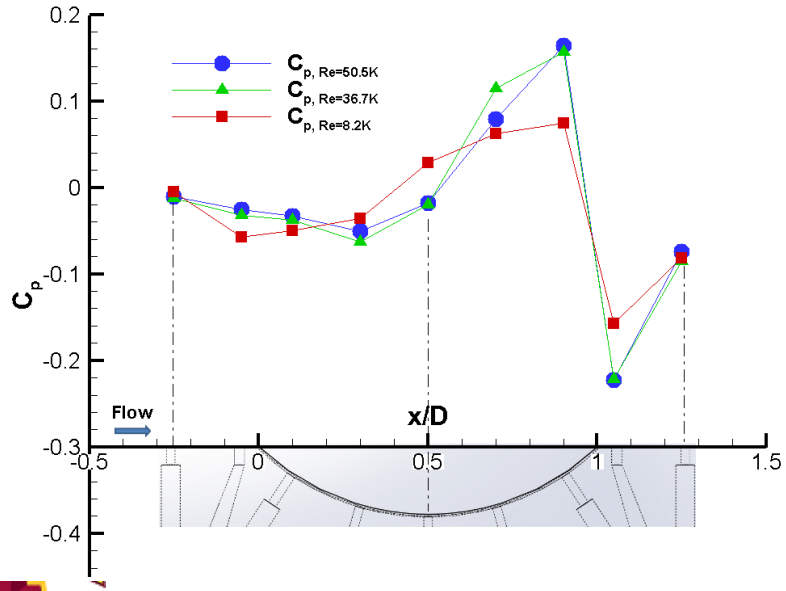
Pressure Distribution inside Dimple

a) Re=36.7K



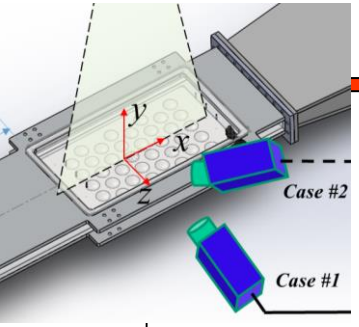
b) Re=50.5K

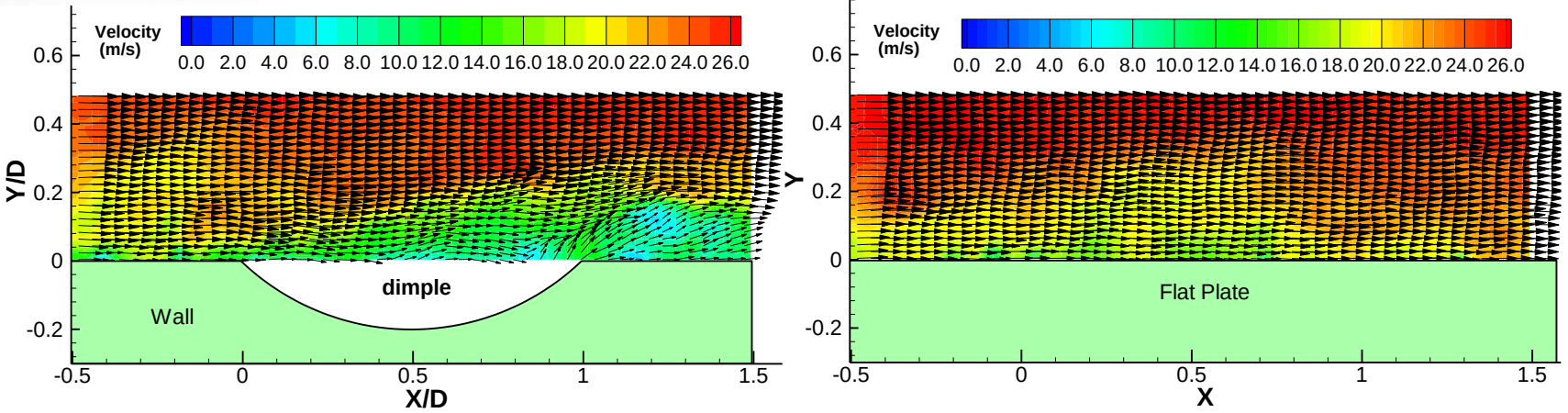




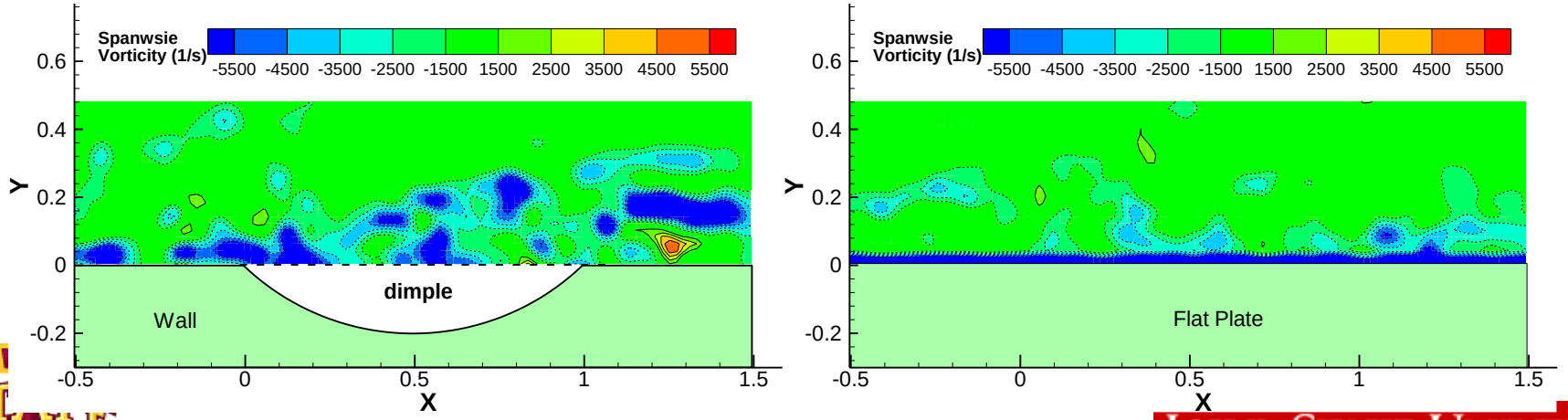
- *Similar pressure distribution for tested cases*
- *Separation at the front, impinging at the back of dimple*
- *Insensitive to Reynolds number*

PIV Measurement Results (Re=50.5K)



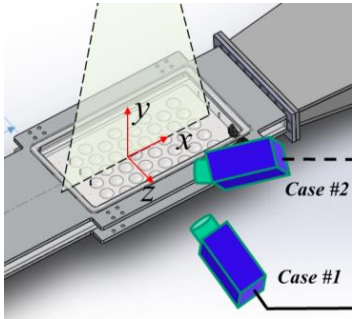


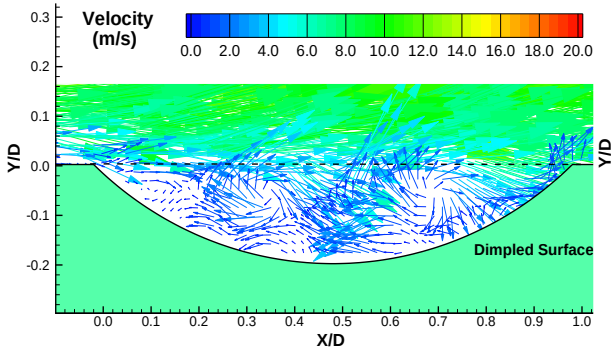
(a). Instantaneous velocity field



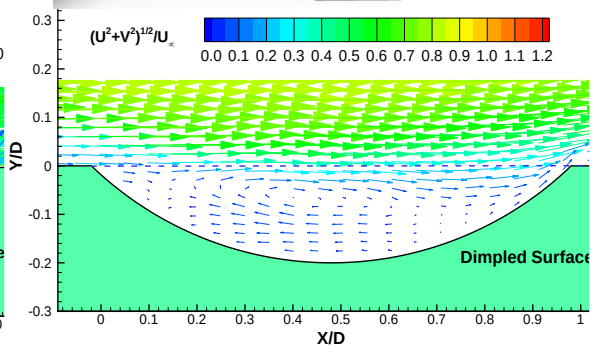
(b). Instantaneous vorticity distributions

❑ PIV Measurement Results(Inside the dimple, Re=36.7K)

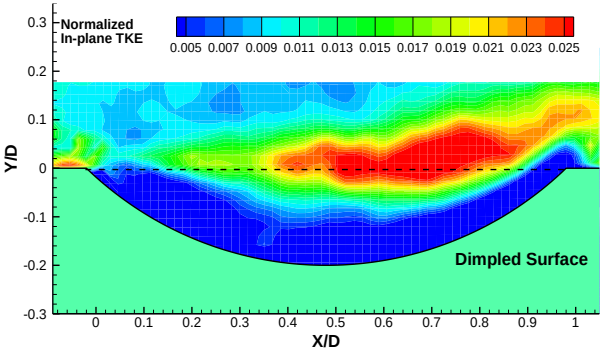




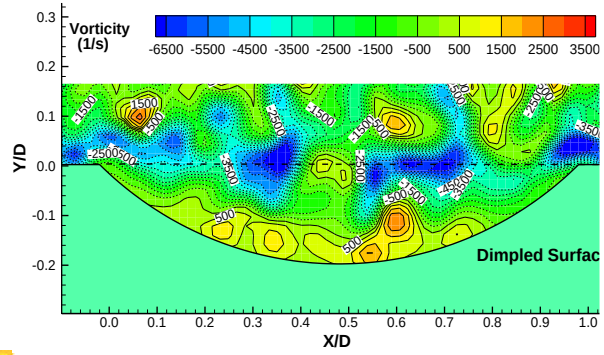
(a). Instantaneous velocity



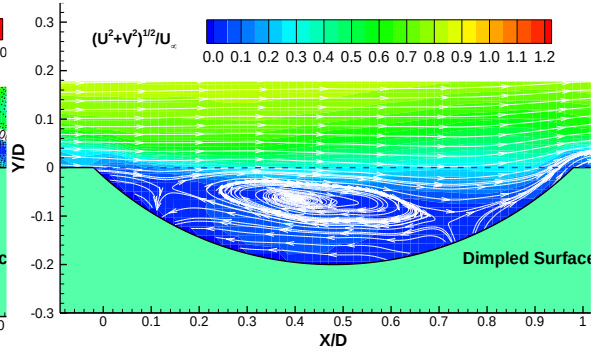
(c). Ensembles-averaged velocity



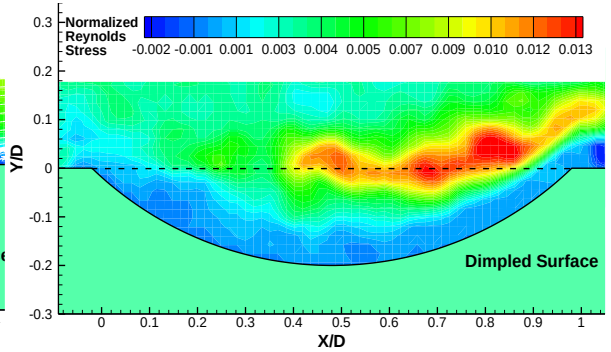
(e). In-plane TKE



(b). Instantaneous vorticity



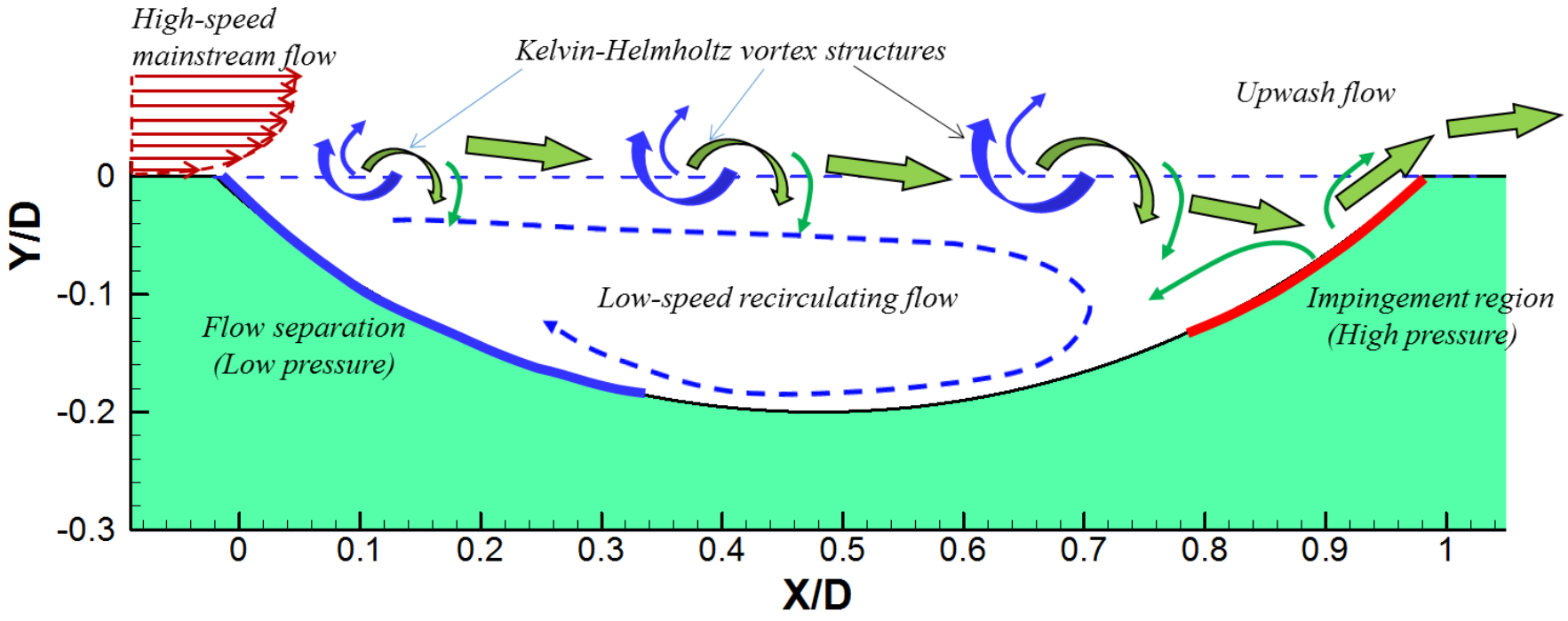
(d). Streamlines of the mean flow



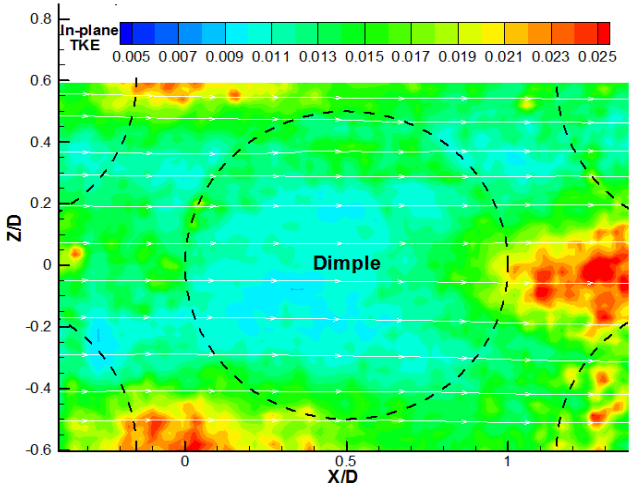
(f). N. Reynolds stress

Similar results for different Reynolds numbers

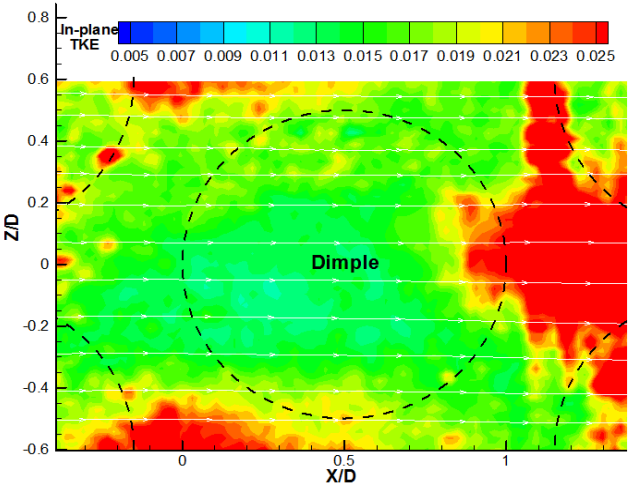
Results and Discussion



PIV Measurement Results

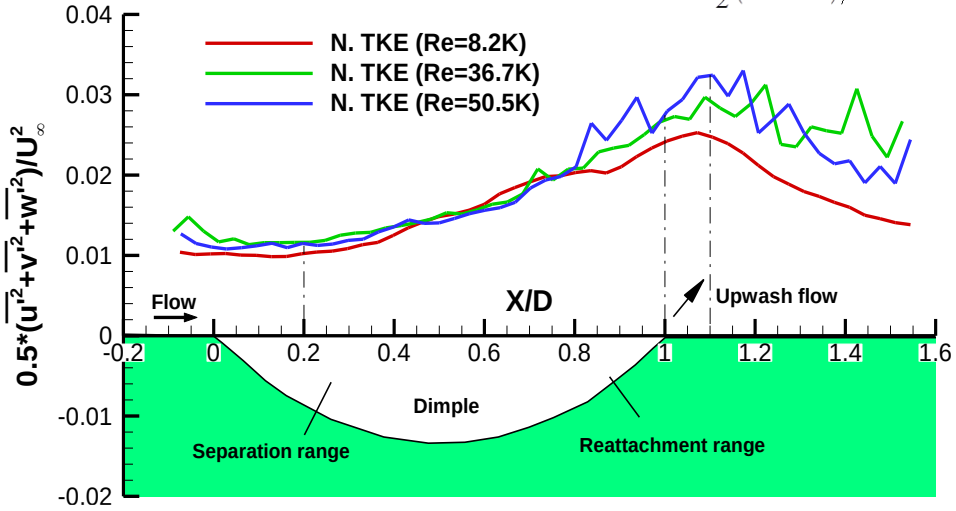


(a) Re= 36.7K

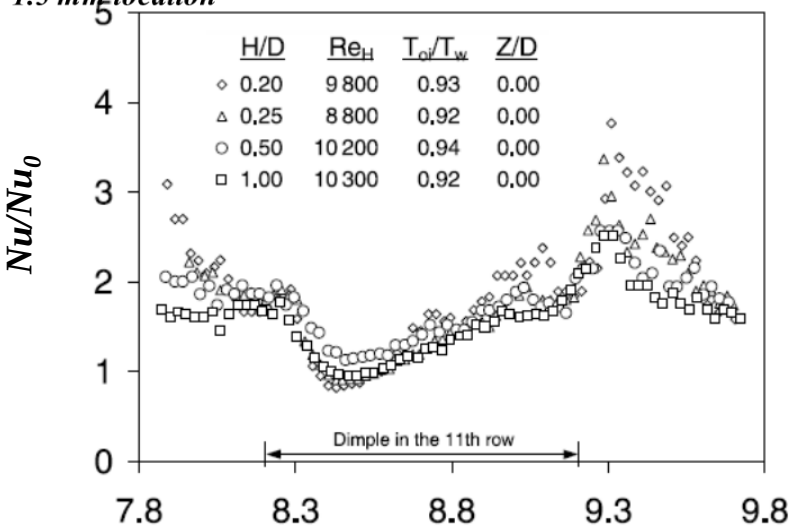


(b) Re= 50.5K

In-plain TKE $\frac{1}{2}\left(\overline{u'^2}+\overline{w'^2}\right)/U_\infty^2$ ***at y=1.5 mm location***



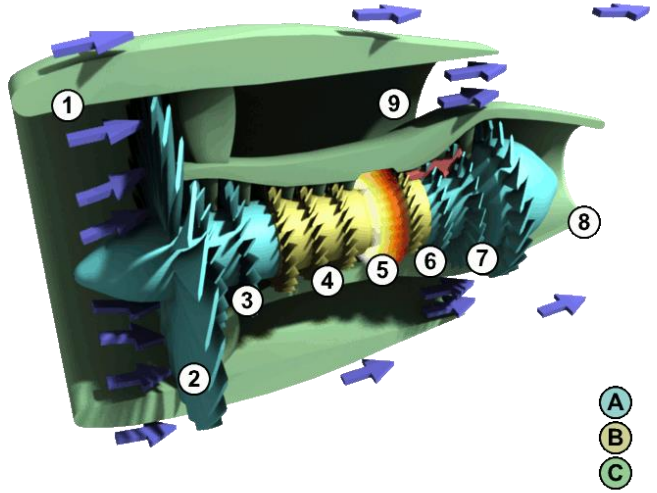
(a) Measured TKE profiles of the present study



(b) ***L***ocal *Nu* distribution (***Mahmood et al. (2002)***)

Mahmood, G., and Ligrani, P., International Journal of Heat and mass transfer, vol. 45, 2002, pp. 2011–2020.

Thank You Very Much for Your Time!
Questions?



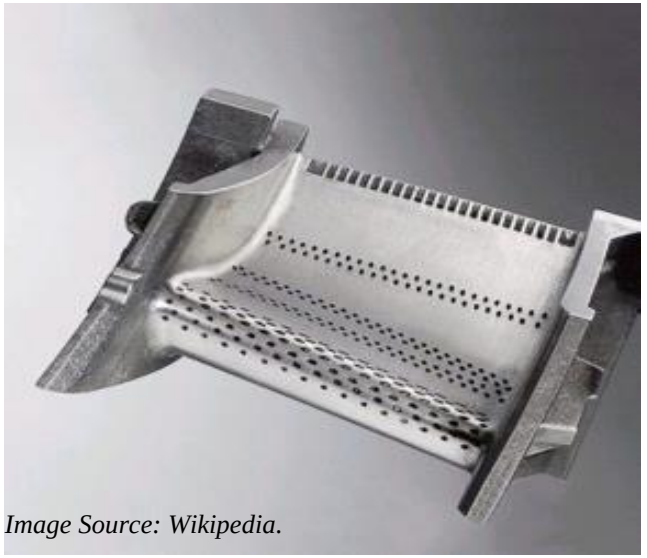


Image Source: Wikipedia.