Effects of Partial Blockage of Film Cooling Holes and Deposits on Film Cooling Effectiveness and Heat Transfer

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SCIES Project 04-01-SR115

Tom J. George, Program Manager, DOE/NETL
Richard Wenglarz, Manager of Research, SCIES

Project Awarded 08/01/04, 36 Months Duration
$445,306 Total Contract Value ($399,706 DOE)

Turbine Need: TBC Coat Down & Blockage

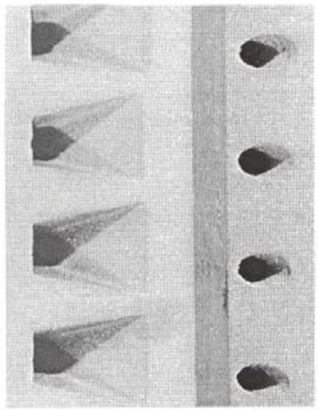


Figure 3. Baseline film holes formed by EDM (segment of 4 holes shown).

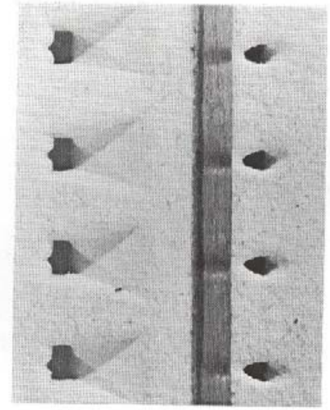


Figure 6. Round and diffusion shaped film holes after coatings have been applied.

Bunker (2000)

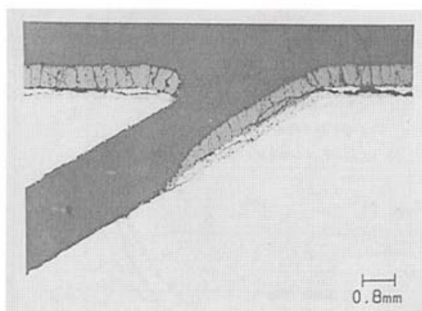


Figure 7. Micrograph through the centerline of coated round film hole.

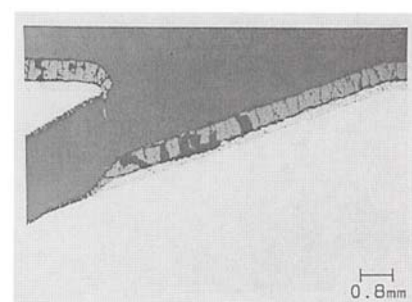


Figure 9. Micrograph of diffusion shaped film hole with blockage.

Project Objectives

- Investigate the effects of TBC coating and deposit partial blockage on film cooling performance – both adiabatic effectiveness and heat transfer coefficient
- Collaborative exploration of experiment and computation – essential for this type of study
- Assessment usefulness of CFD in design and analysis by comparing CFD with EFD/HT
- Explore innovative design concepts for film cooling

Scheduling: Experiment & Computation

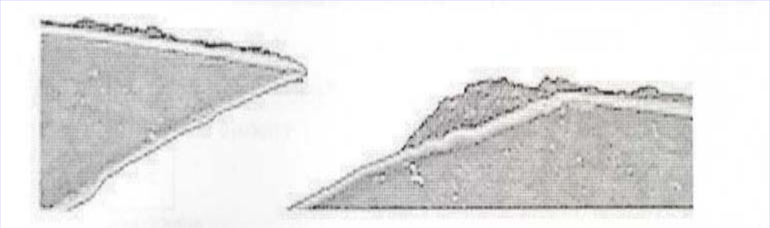
YEAR 1
Refine film cooling 3-temperature experimental systems
Fabrication of test section
Effectiveness (η) and heat transfer (h) measurements – baseline single hole, round and shaped
Effects of partial blockage in a film cooling hole – single round hole, η and h measurements
Effects of partial blockage in a film cooling hole – shaped holes, η and h measurements
YEAR 2
Effects of discrete deposits on film cooling rows
Effectiveness (η) and heat transfer (h) measurements – round hole and shaped holes with deposits, various flow conditions
Near-hole deposits roughness model development
YEAR 3
Down select most influencing factors for combined test
Integrated effects of passage blockage and deposits
Improved Film Cooling Design guidelines

YEAR 1
Validation and benchmarking
Procure geometry and flow conditions
RANS simulation for baseline round hole w/o surface roughness
RANS simulation for baseline round hole with surface roughness
YEAR 2
Simulate U Pitt Experiments
RANS simulation for baseline shaped hole w/o surface roughness
RANS simulation for baseline shaped with surface roughness
Develop Design Recommendations
YEAR 3
Complete detached eddy simulation
RANS simulation for multiple-row film holes
Recommend guidelines on best grids and turbulence models

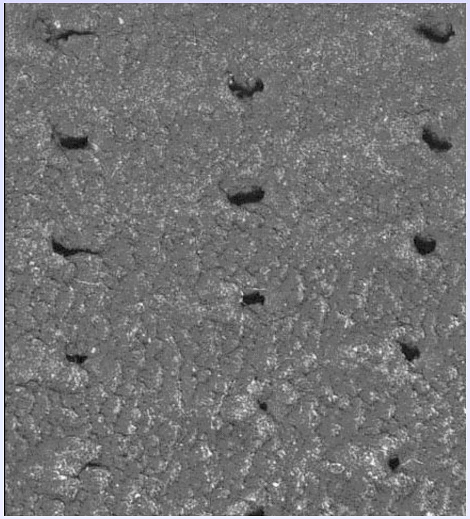
Accomplishments

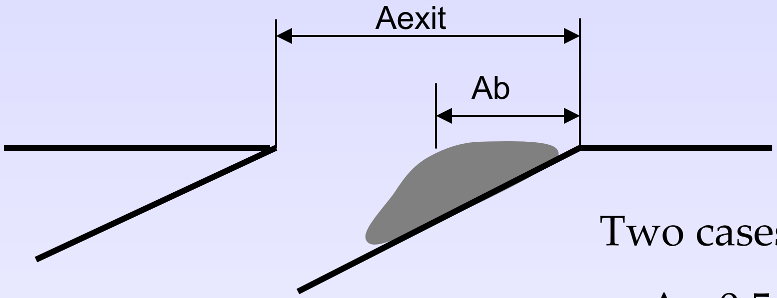
- Studied effects of TBC blockage & surface roughness on film cooling in 2-D
- Studied effects of TBC blockage in 3D
- Developed IR based film cooling measurement on simultaneous determination of film effectiveness and heat transfer coefficient
- Studied partial blockage effects on FC performance with round and shaped holes
- Developed and studied 3 new design concepts for film cooling to increase adiabatic effectiveness

Experiment Component: Deposit Blockage



Micrograph of typical deposits in a film cooling hole (Bogard et. al, 1998)





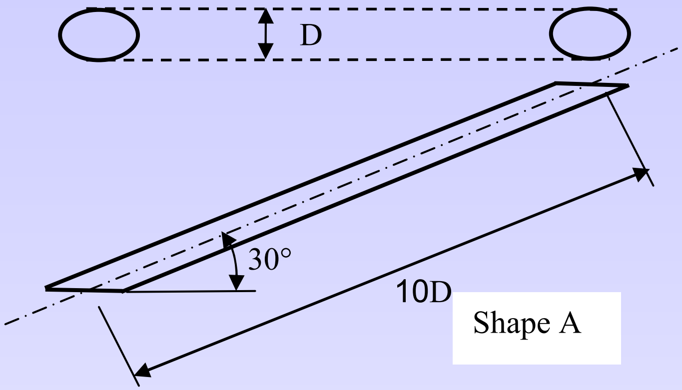
Blockage model

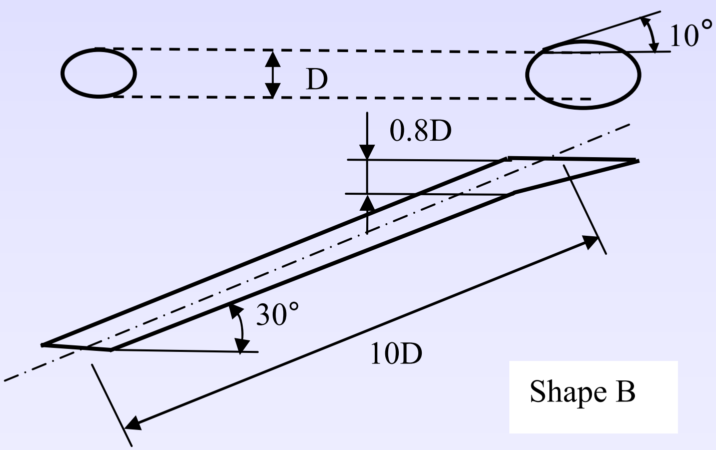
Two cases:

A_b=0.5A_{exit}

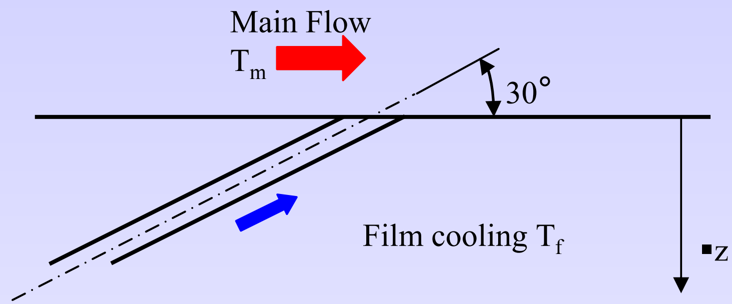
A_b=0.75A_{exit}

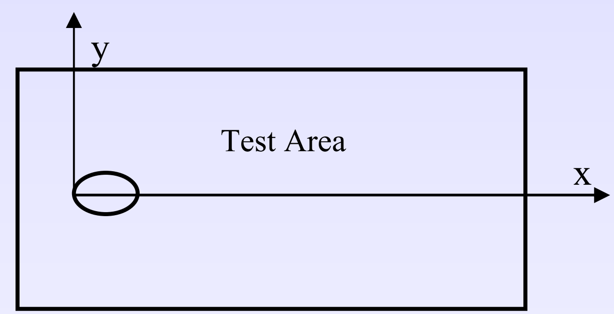
Film Hole Configurations





D= 6.4 mm





Film Cooling: Three-Temperature Convection

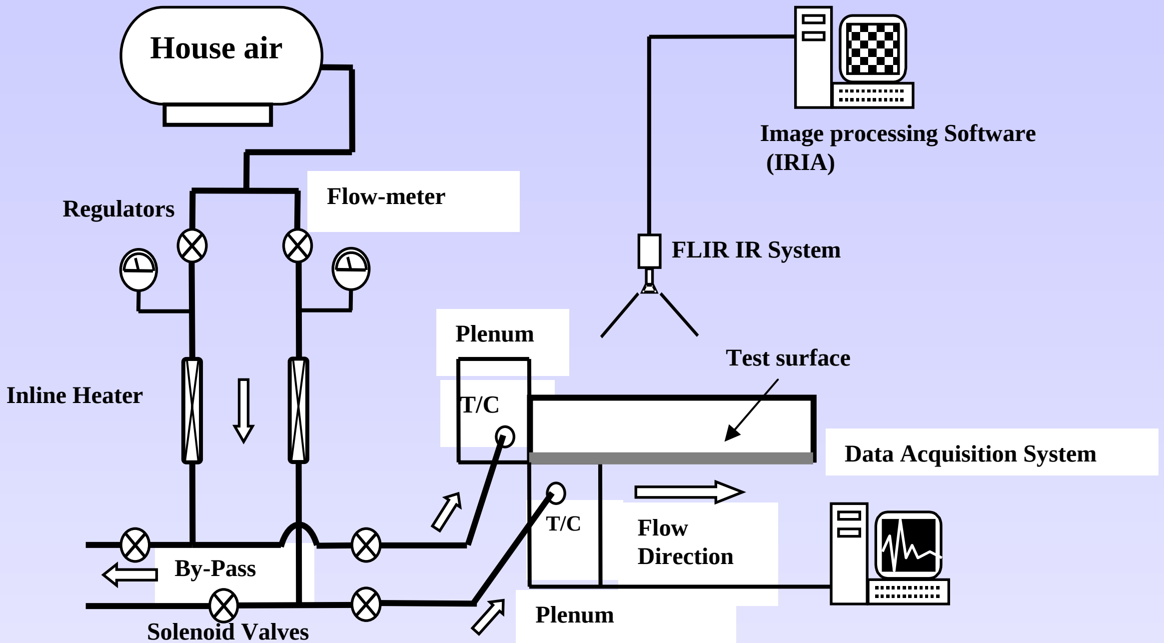
- Heat Transfer Coefficient: $$q = h(T_{aw} - T_w)$$
- Film Effectiveness: $$\eta = \frac{T_{aw} - T_m}{T_c - T_m}$$
- Both h and η are unknown and can be determined simultaneously using a transient method

$$\frac{T_w - T_i}{T_{aw} - T_i} = 1 - \exp\left[\frac{h^2 \alpha \tau}{k^2}\right] erfc\left[\frac{h\sqrt{\alpha \tau}}{k}\right]$$

- Heat Flux Ratio – Film Protected vs. Unprotected:

$$q / q_o = (h / h_o)(1 - \eta / \varphi), \qquad \varphi = \frac{T_w - T_m}{T_c - T_m} \approx 0.6$$

Test Section and Conditions



M = 0.48, 0.95, 1.69

Density ratio ~1

Re_{Dh}= 29,200, Re_D= 992, 1980, 3740

Freestream turbulence ~ 2%

Test Section Photos

Top view with IR transmitted window

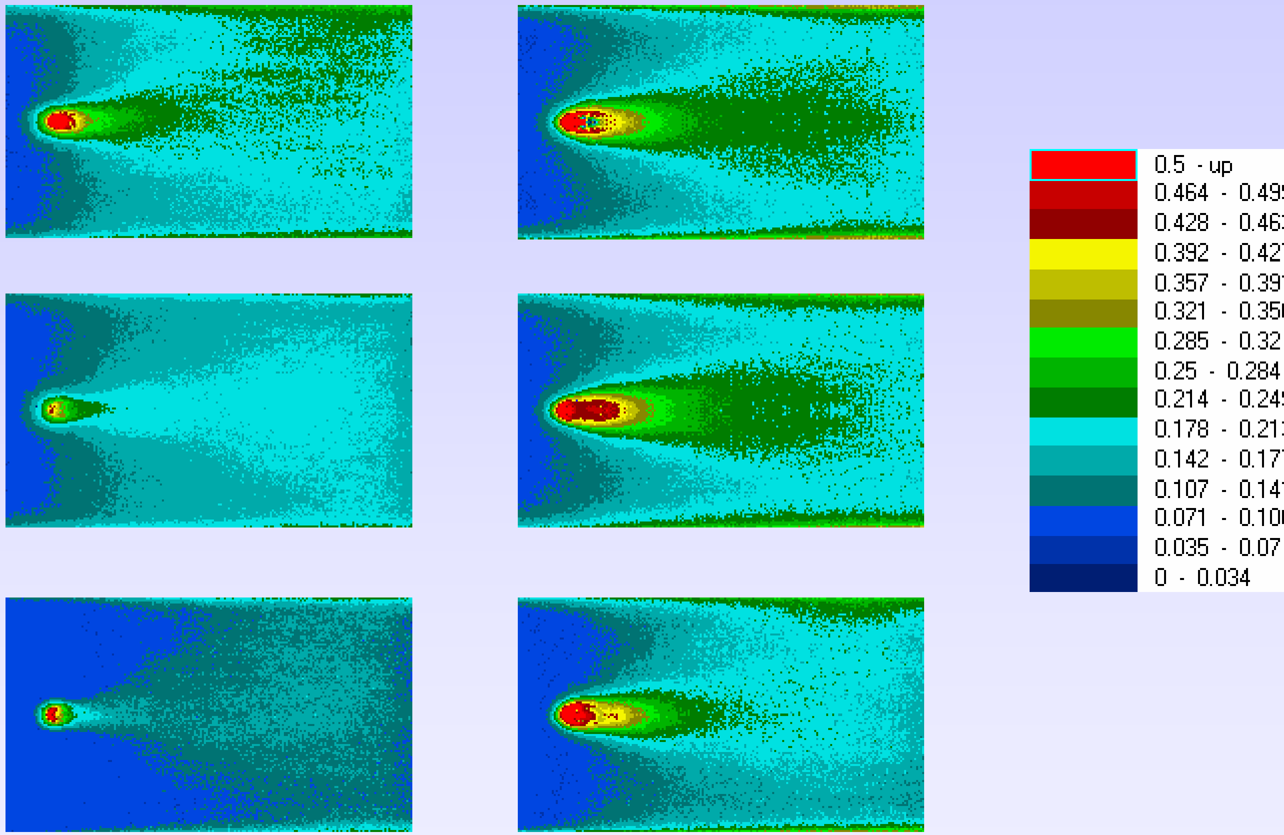
Film Cooling Effectiveness Distribution: M=1.69

Circular round hole | Shaped hole

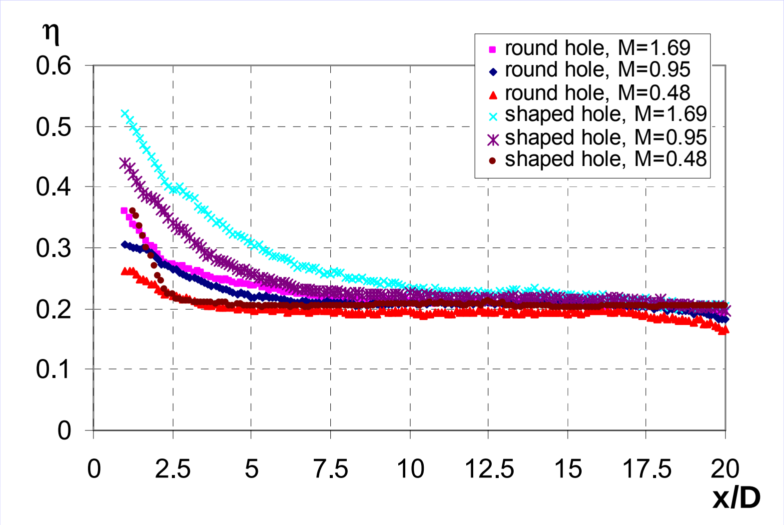
No blockage

0.5 blockage

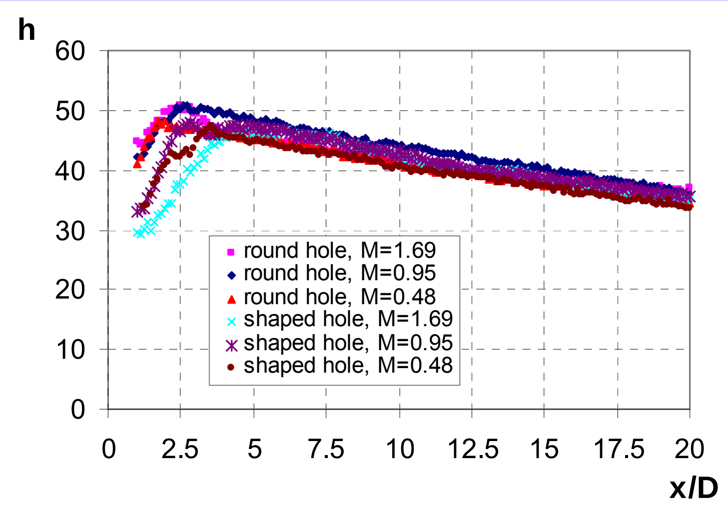
0.75 blockage



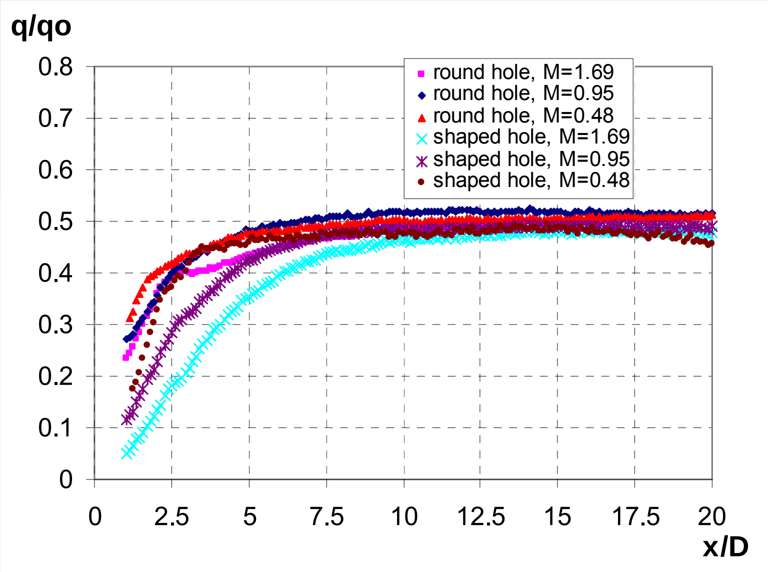
No Blockage



η
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2.5
5
7.5
10
12.5
15
17.5
20
x/D
round hole, M=1.69
round hole, M=0.95
round hole, M=0.48
shaped hole, M=1.69
shaped hole, M=0.95
shaped hole, M=0.48

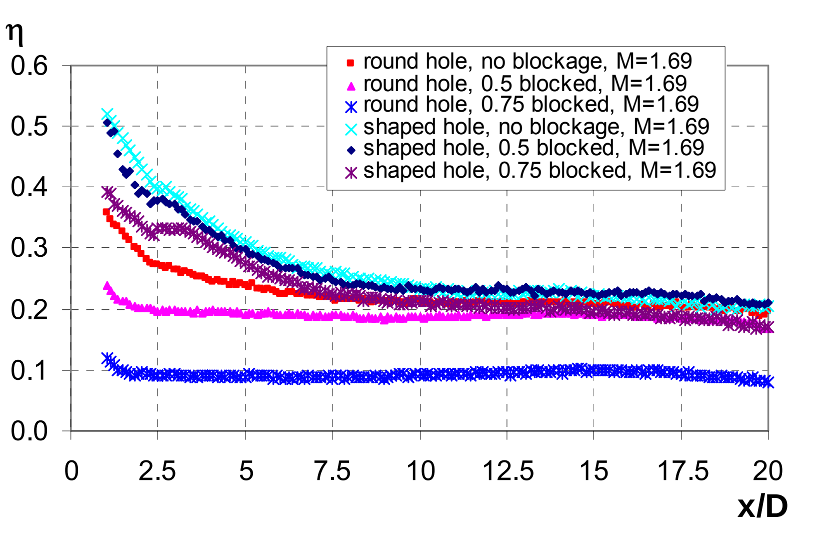


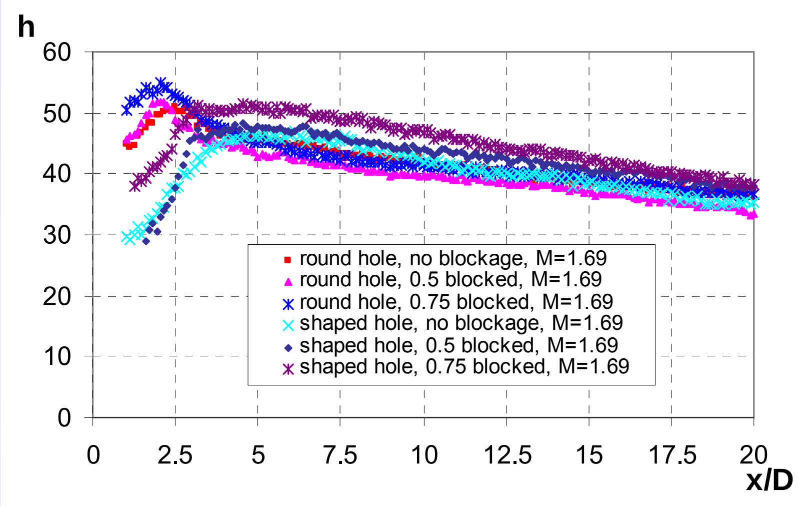
h
60
50
40
30
20
10
0
0
2.5
5
7.5
10
12.5
15
17.5
20
x/D
round hole, M=1.69
round hole, M=0.95
round hole, M=0.48
shaped hole, M=1.69
shaped hole, M=0.95
shaped hole, M=0.48

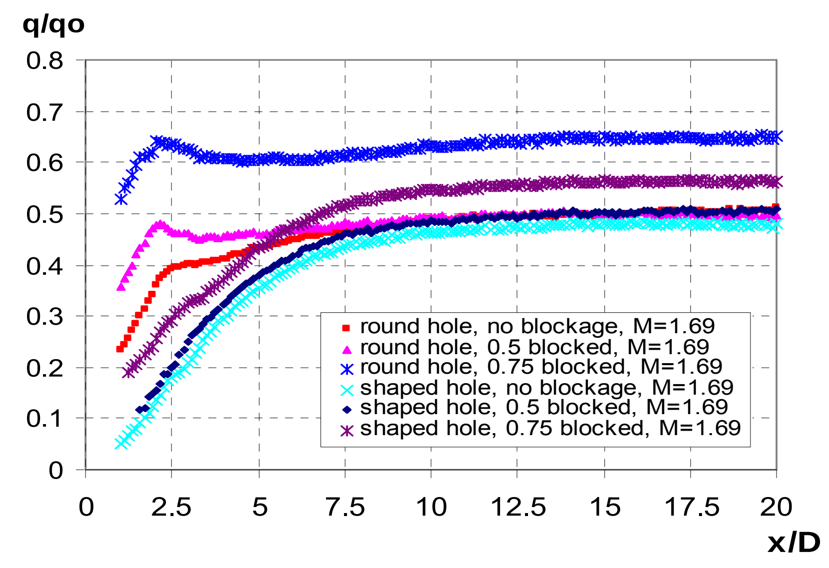


q/qo
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2.5
5
7.5
10
12.5
15
17.5
20
x/D
round hole, M=1.69
round hole, M=0.95
round hole, M=0.48
shaped hole, M=1.69
shaped hole, M=0.95
shaped hole, M=0.48

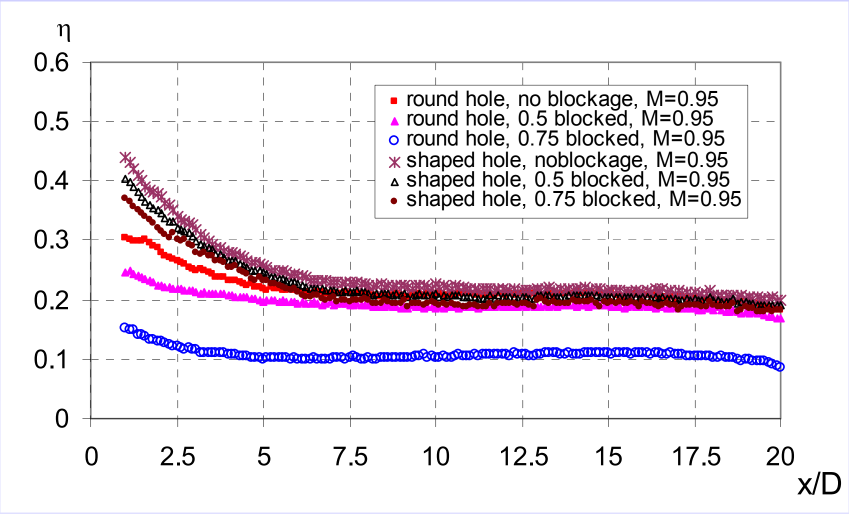
With Blockage: M = 1.69

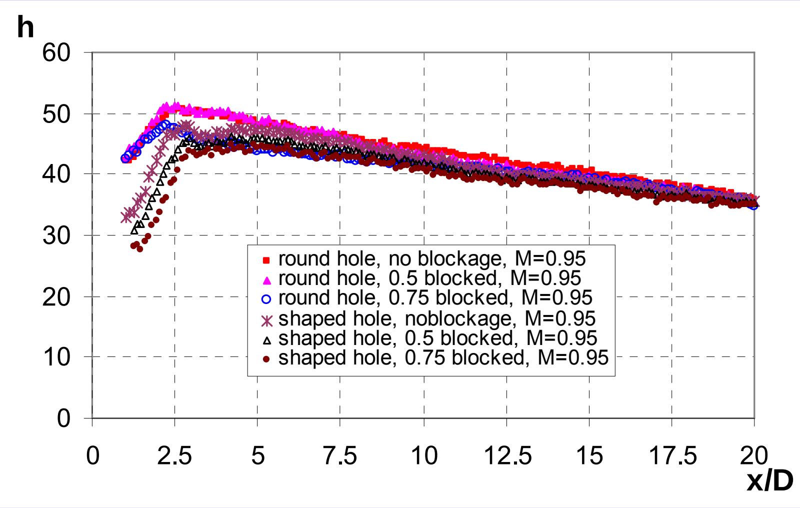


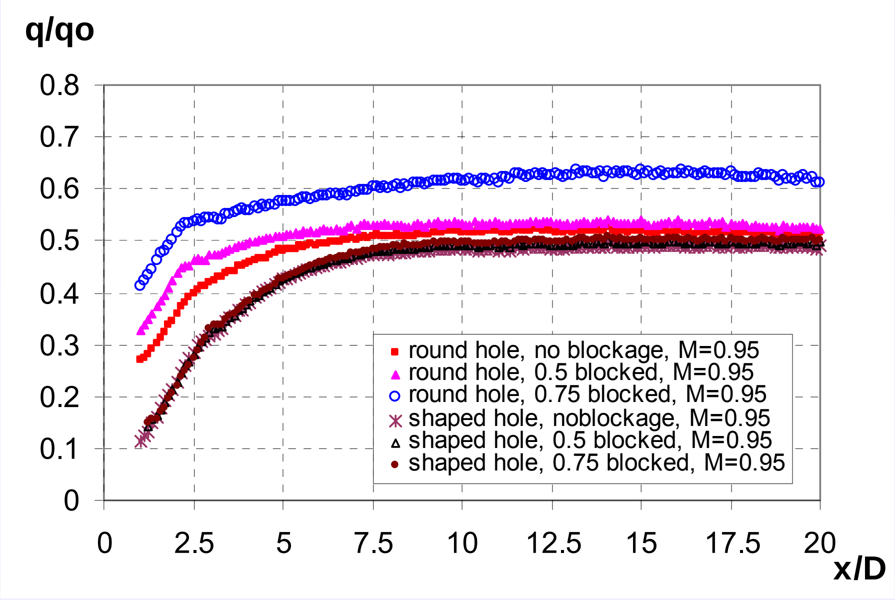




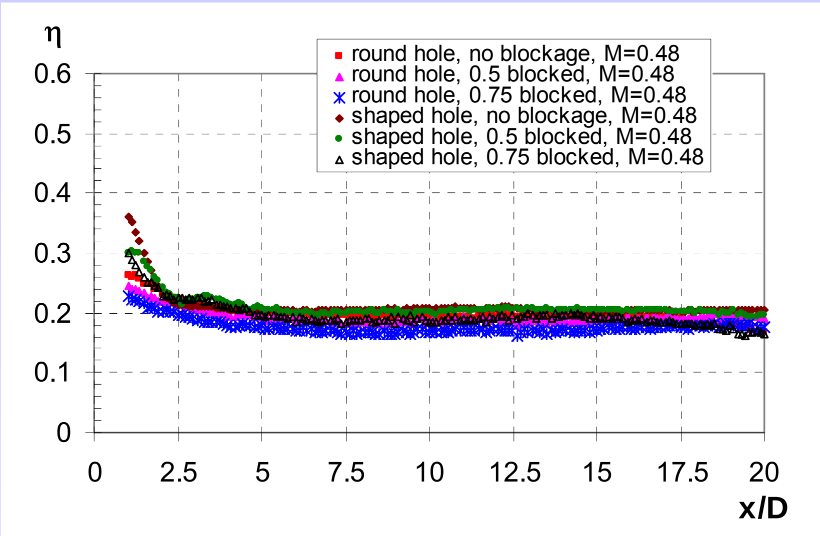
With Blockage: M = 0.95

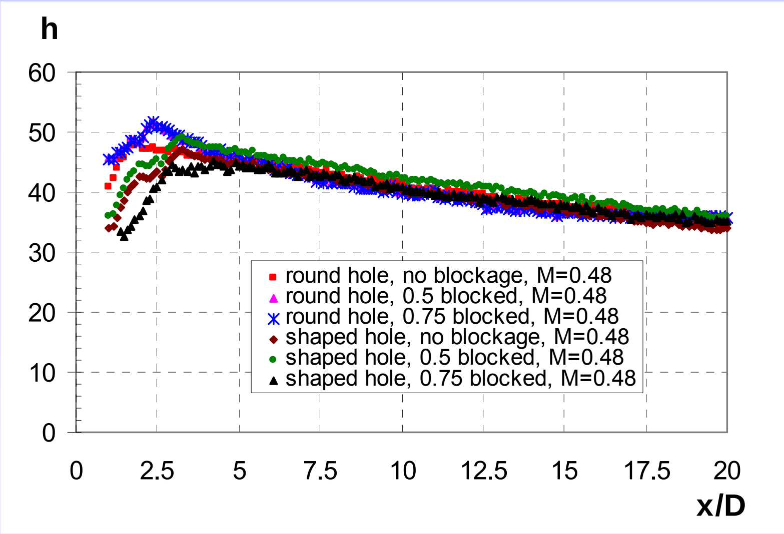


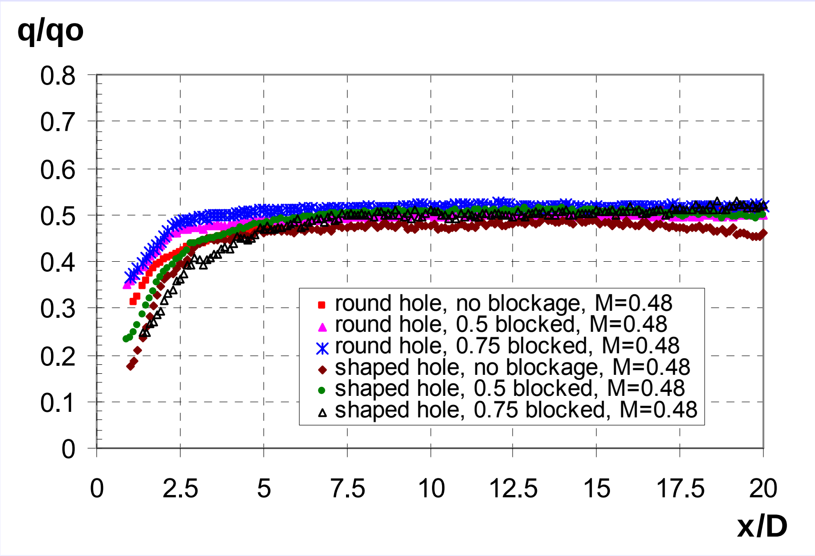




With Blockage: M = 0.48







Summary from Experiment

- Deposit simulated blockage consistently reduces the levels of film effectiveness, at least for the present test range and hole shapes
- Heat transfer coefficient h is a strong function of local surface condition in the near hole region; h sufficiently downstream appears to be insensitive to blockage
- Both η and h contribute significantly to the overall heat transfer reduction. q/q_o is generally low immediately downstream to film hole due to combined effect of high η and low h
- Future work will also focus on CFD-led film cooling design innovation

UTSR Peer Review Workshop III

18-20 October 2005

Effects of Coating Blockage and Deposits on Film-Cooling Effectiveness and Heat Transfer

CFD Component:

Tom Shih

Iowa State University

Minking Chyu

U. of Pittsburgh

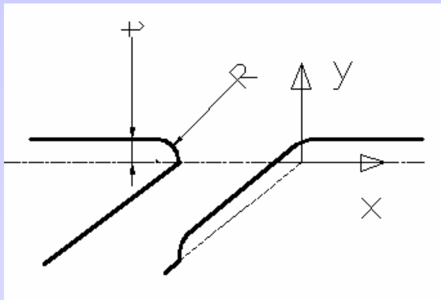
Objectives of CFD Component

- Assess usefulness of CFD in design and analysis by comparing CFD **with EFD/HT**.
- Assess effects of TBC blockage and surface roughness on film cooling **with EFD/HT**.
- Explore FC design concepts **with EFD/HT**.

Accomplishments

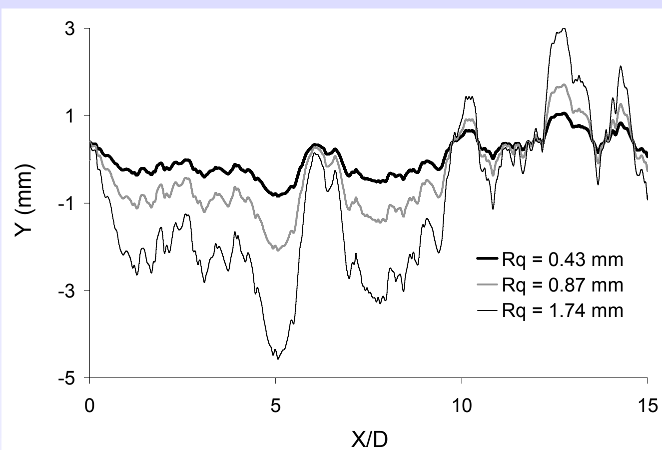
- Studied effects of TBC blockage & surface roughness on film cooling in 2-D.
- Studied effects of TBC blockage in 3-D.
- Developed & studied 3 new design concepts for film cooling to increase adiabatic effectiveness.

Effects of TBC Blockage and Roughness



t = 6.35, 9.525 mm
R = 6.35, 9.525 mm

TBC configurations studied (0.5D, 0.75D)



Surface roughness studied (3 cases)

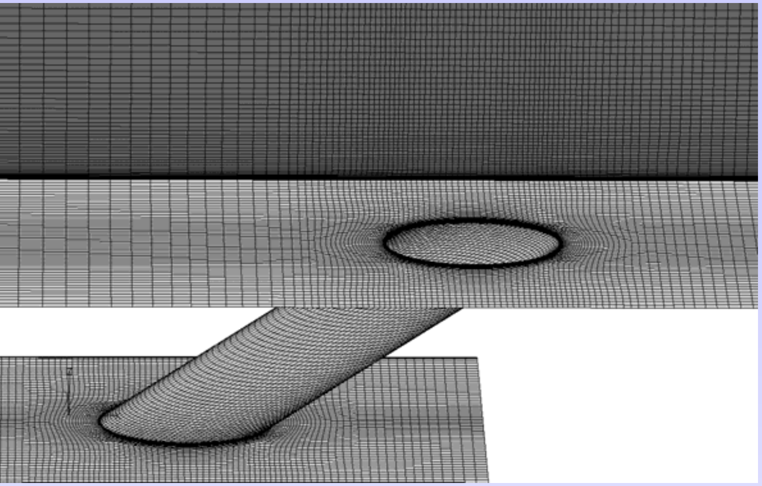
2-D cases (treat hole as slot)

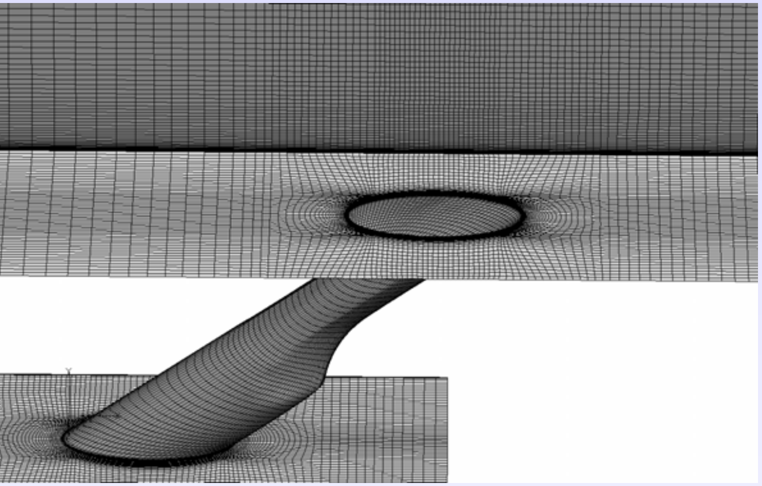
- no coating, no roughness
- with coating
- with coating & roughness

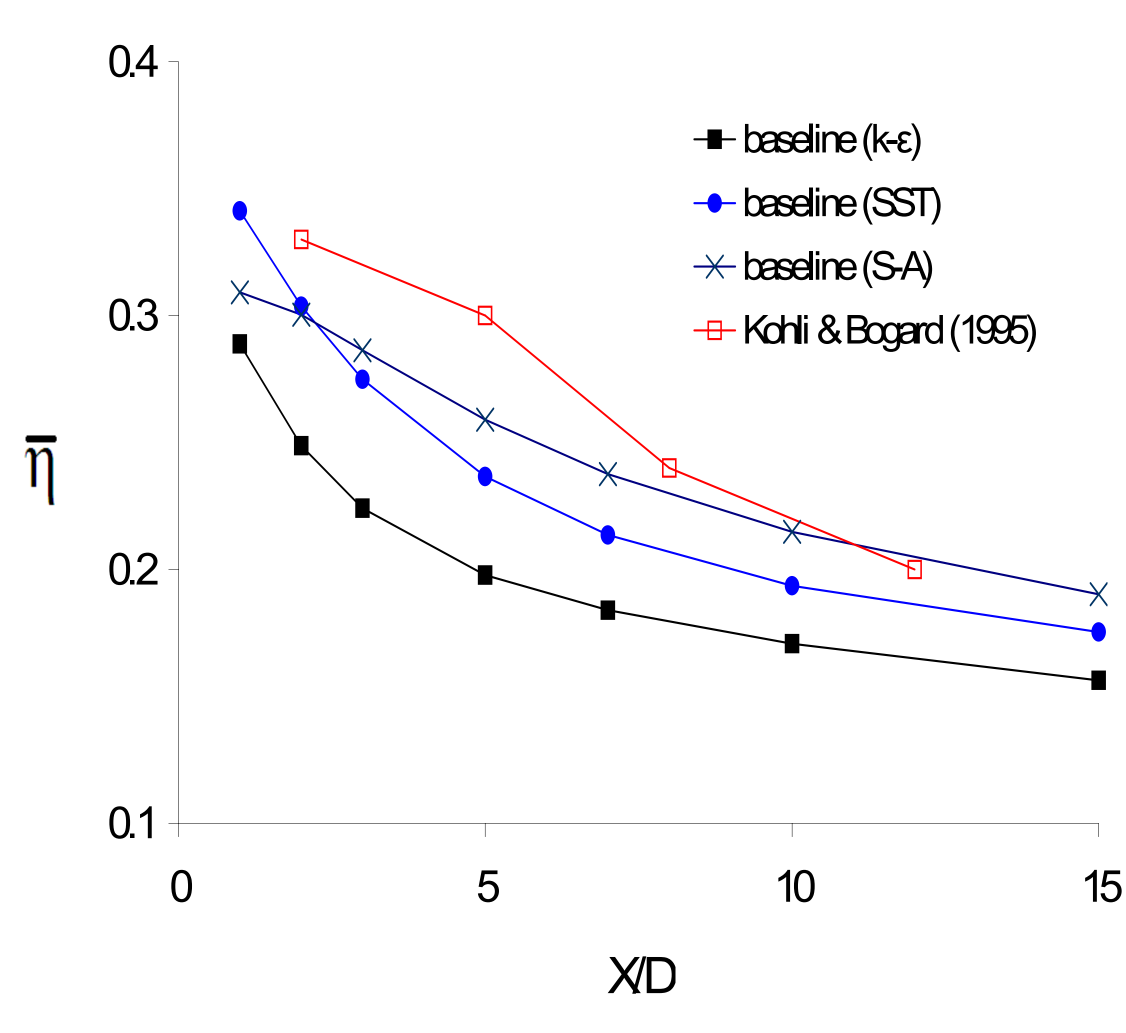
3-D cases (1 row of holes)

- no coating, no roughness
- with coating

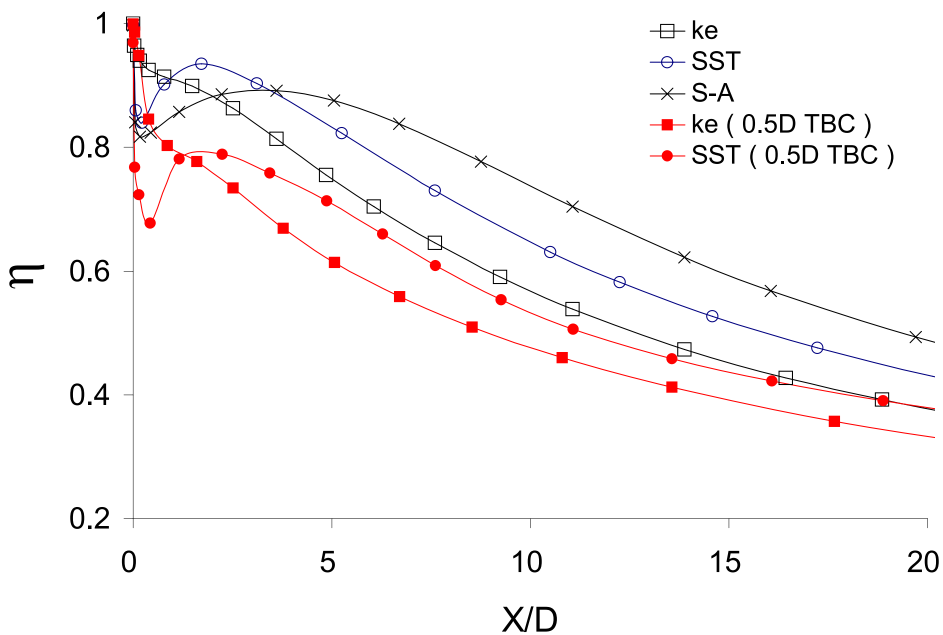
Effects of TBC Blockage

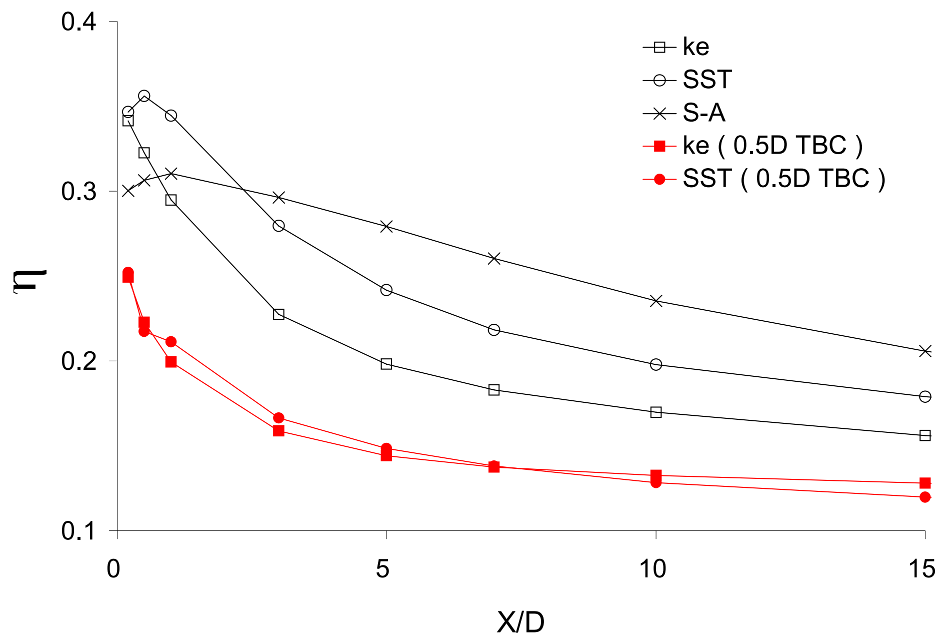


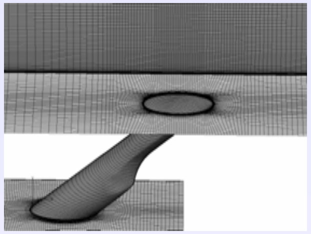




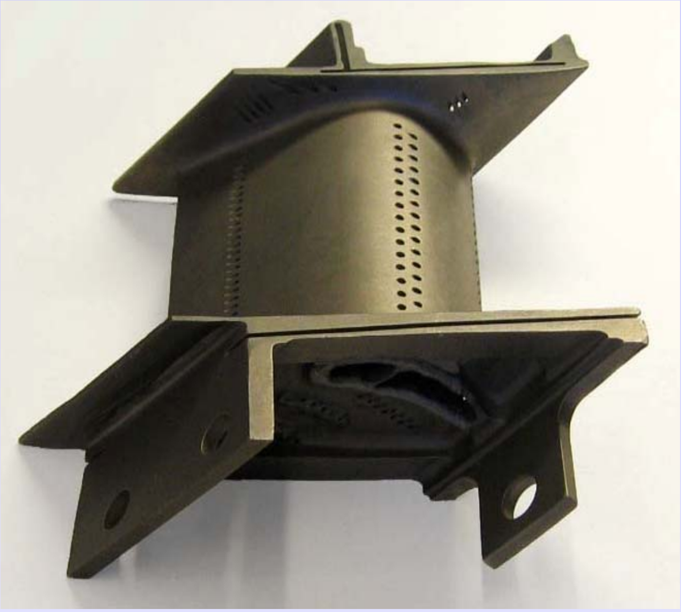
Effects of TBC Blockage: 3-D CFD Study

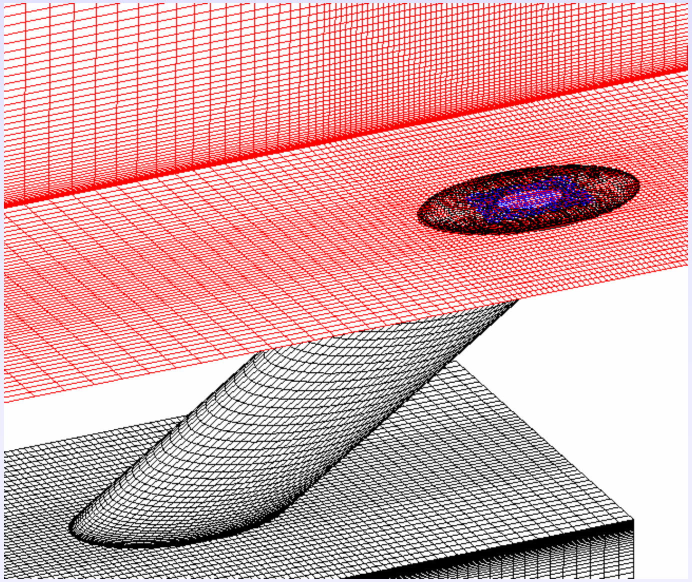






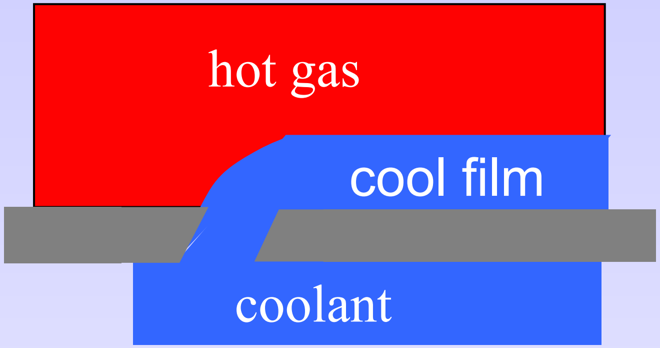
CFD Design Exploration





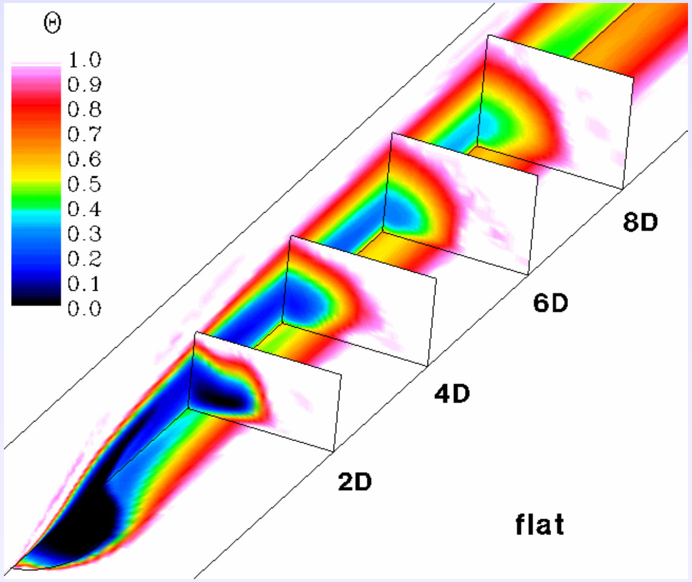
Goal:

form a film between hot gas and metal

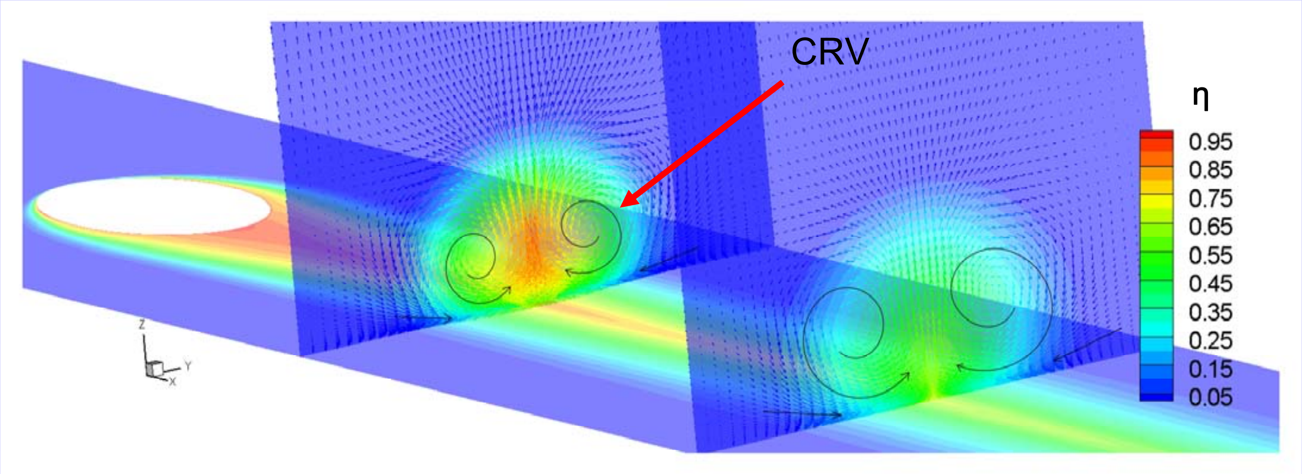


But,

Cooling jets always lift off

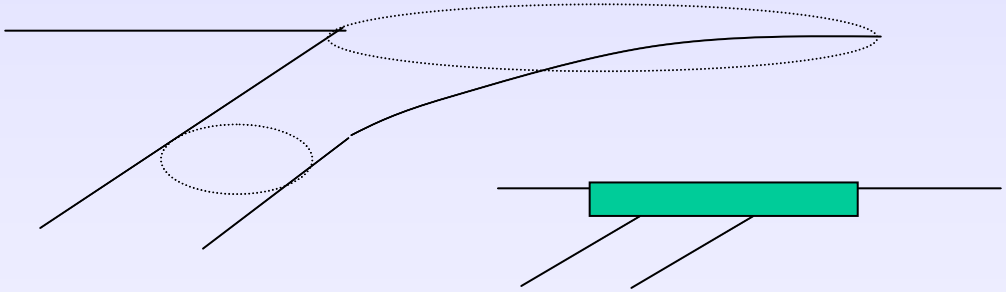


How to minimize hot gas entrainment?



Previous
Design Concepts

Slots
Shape Holes
Tabs about Holes
Trench (Bunker)

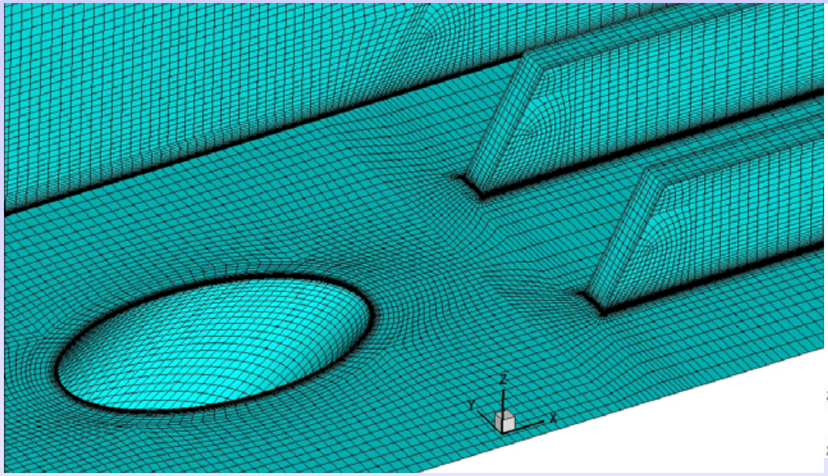


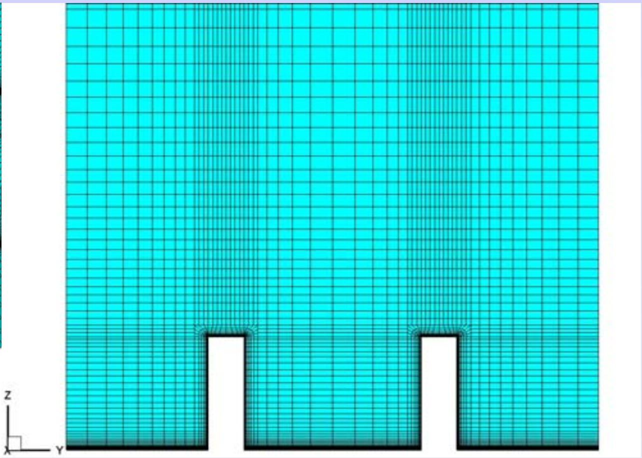
Developed Three New Design Concepts
Disclosures Submitted

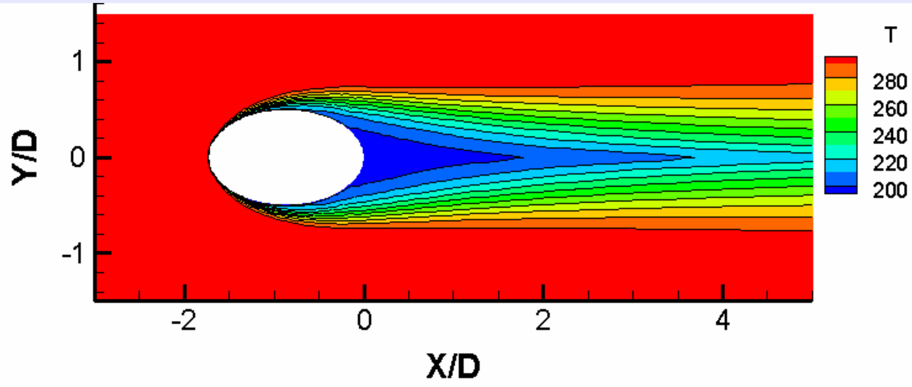
- Flow-Aligned Blockers
- Upstream Ramp
- Momentum Preserving Shape Holes

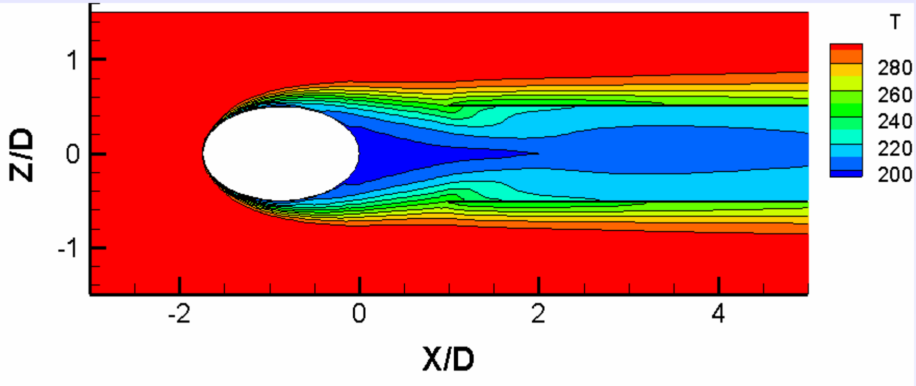
New Design Concept 1: Flow-Aligned Blockers

Shih, Na, & Chyu (2006): **blocker** (disclosure submitted)



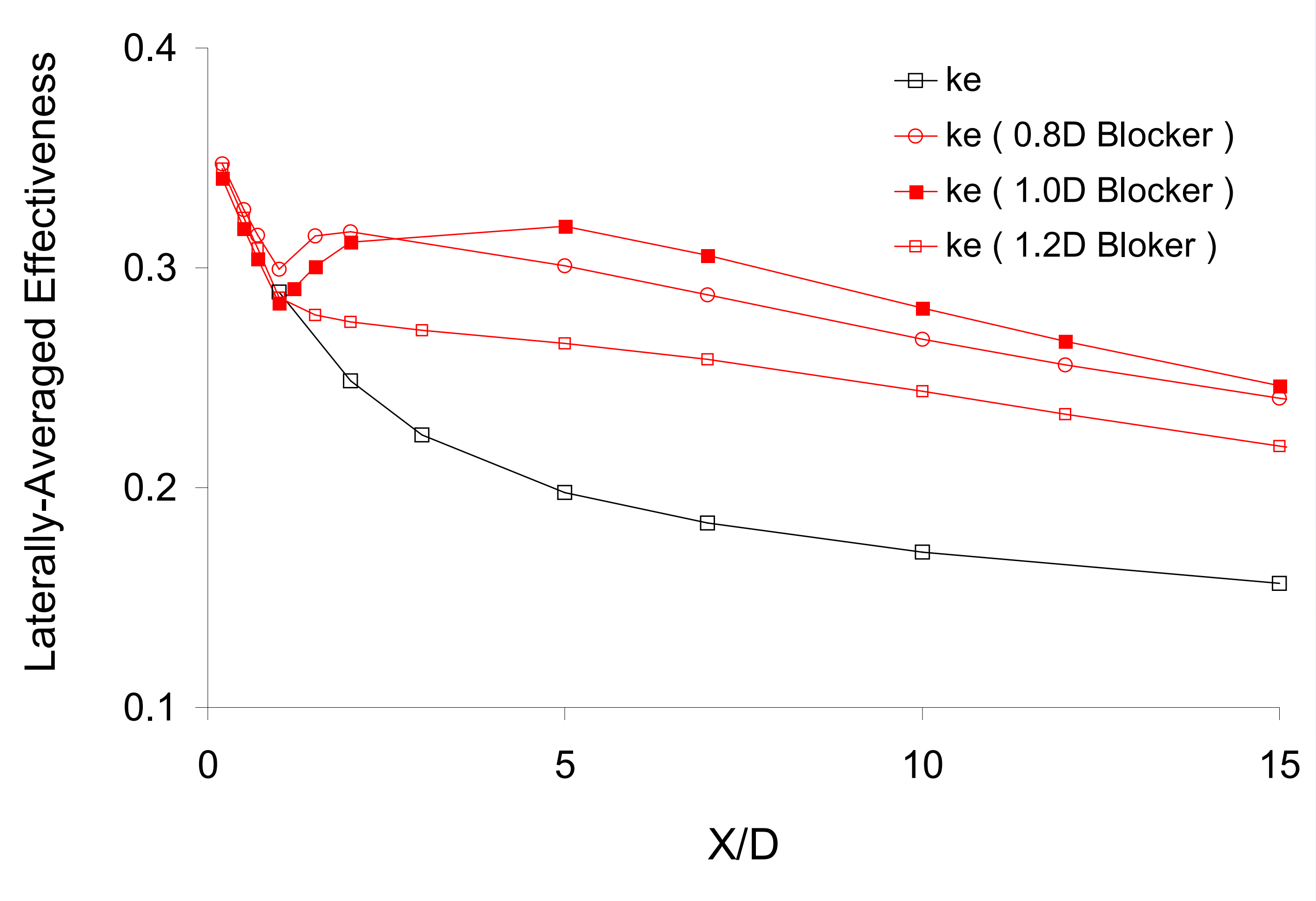






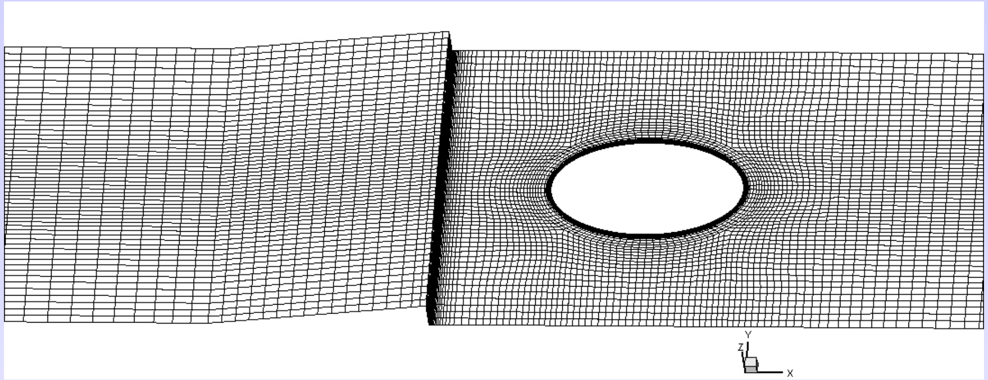
Flow-Aligned Blockers

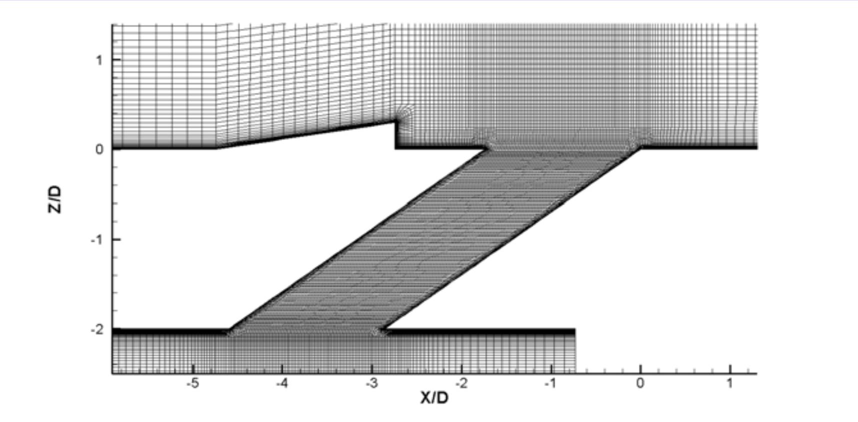
Shih, Na, & Chyu (2006): **blocker** (disclosure submitted)

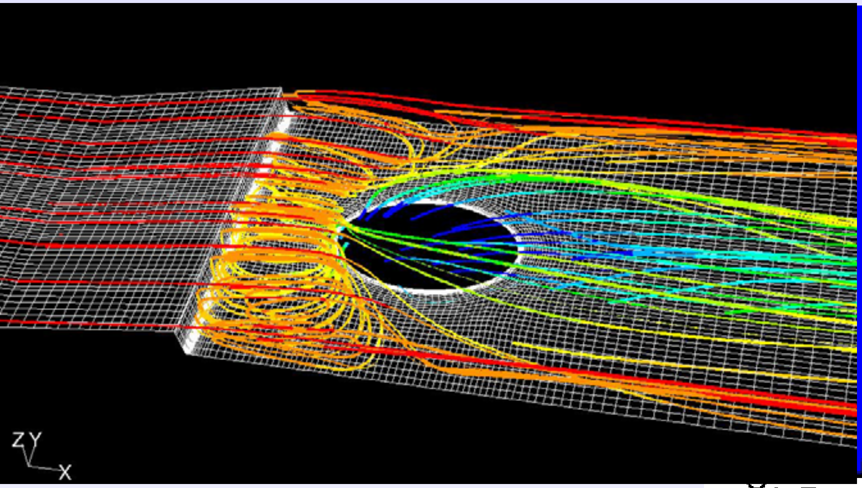


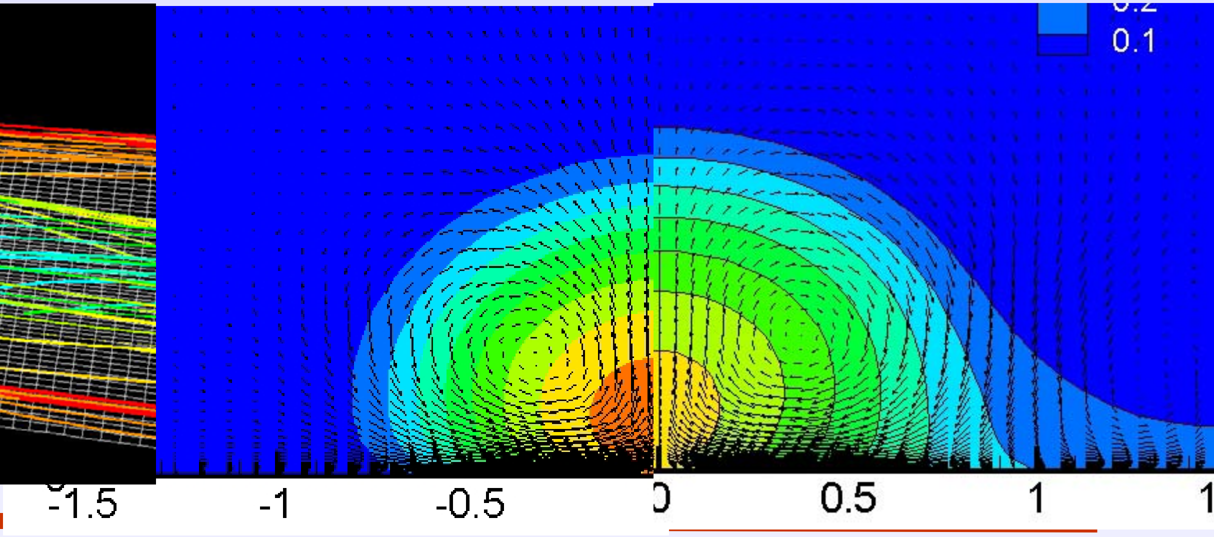
New Design Concept 2: Upstream Ramp

Shih & Na (2006): **ramp** (disclosure submitted)

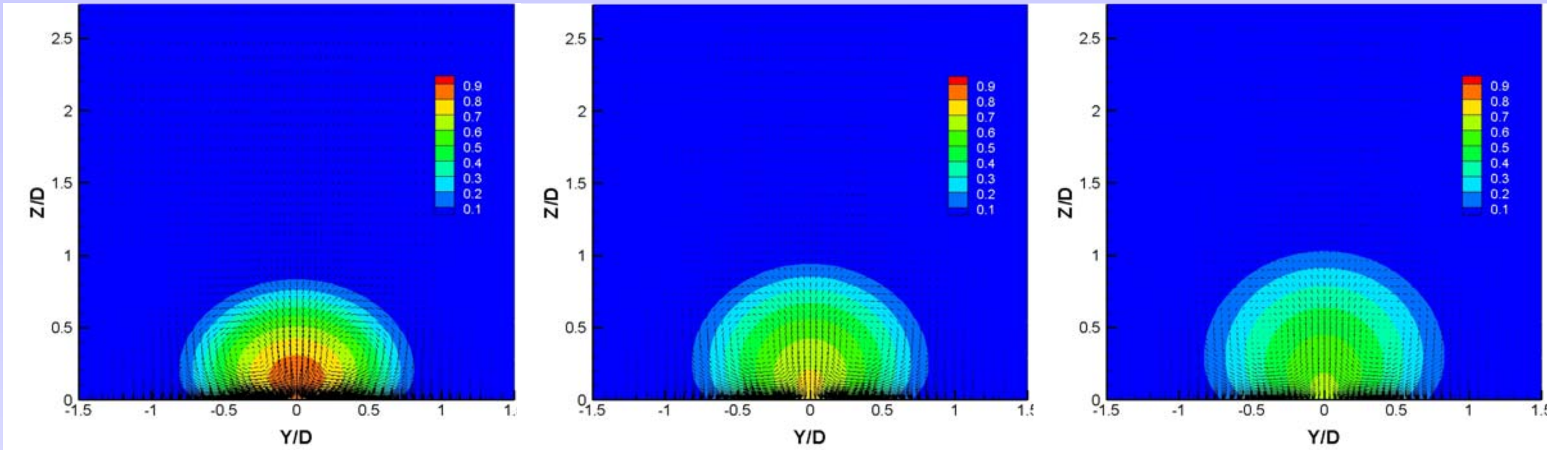




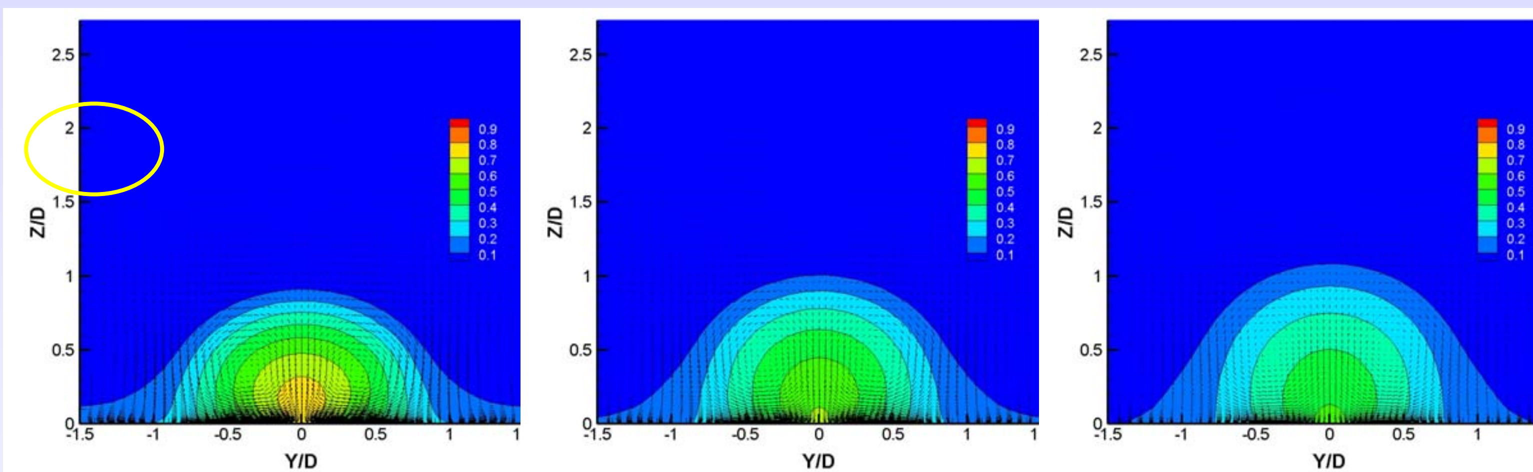




baseline

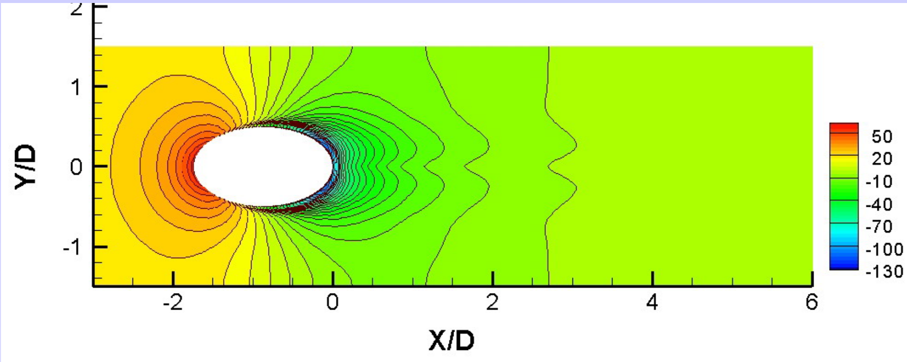


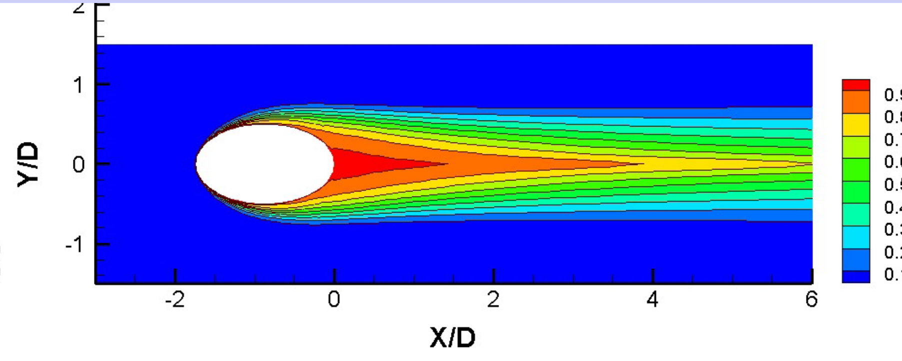
ramp



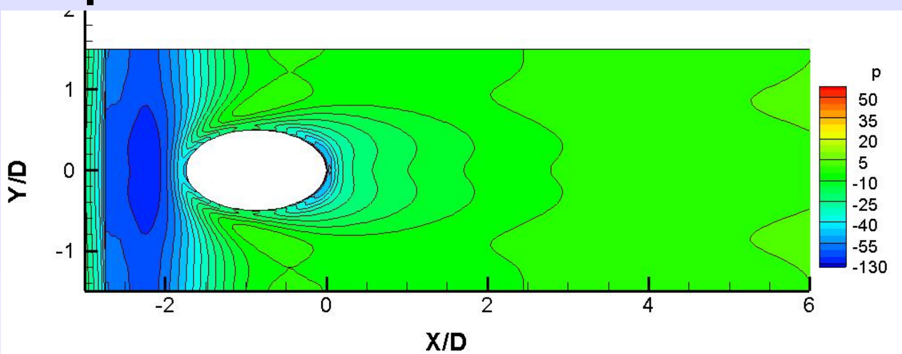
X=3D **X=5D** **X=7D**

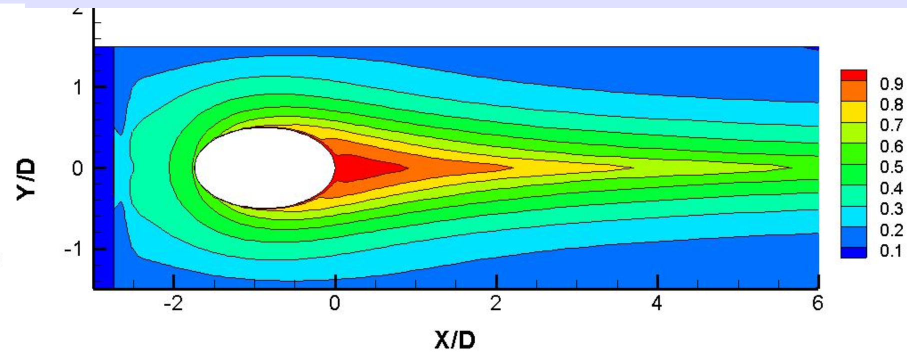
baseline





ramp

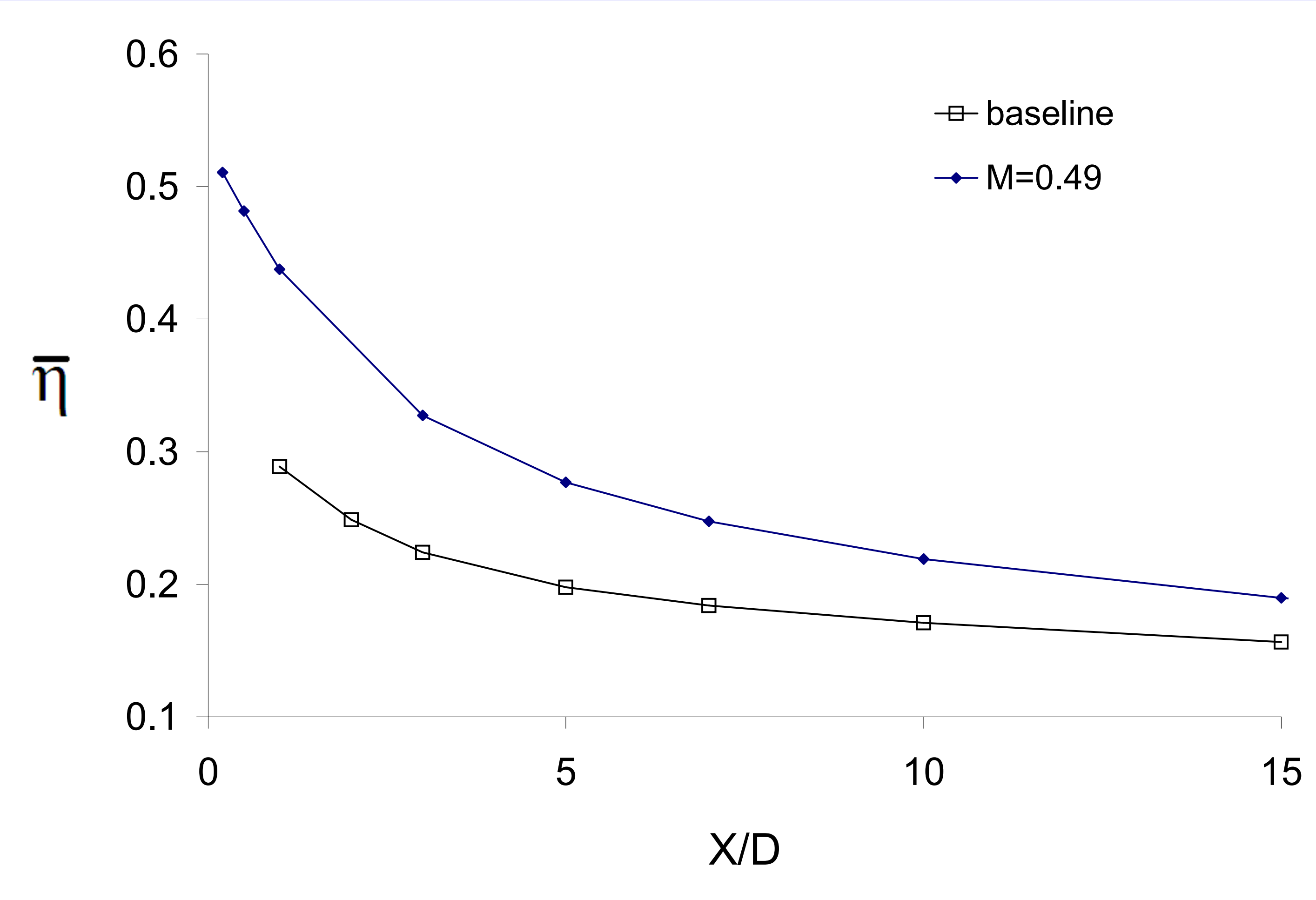




Pressure **Effectiveness**

Upstream Ramp

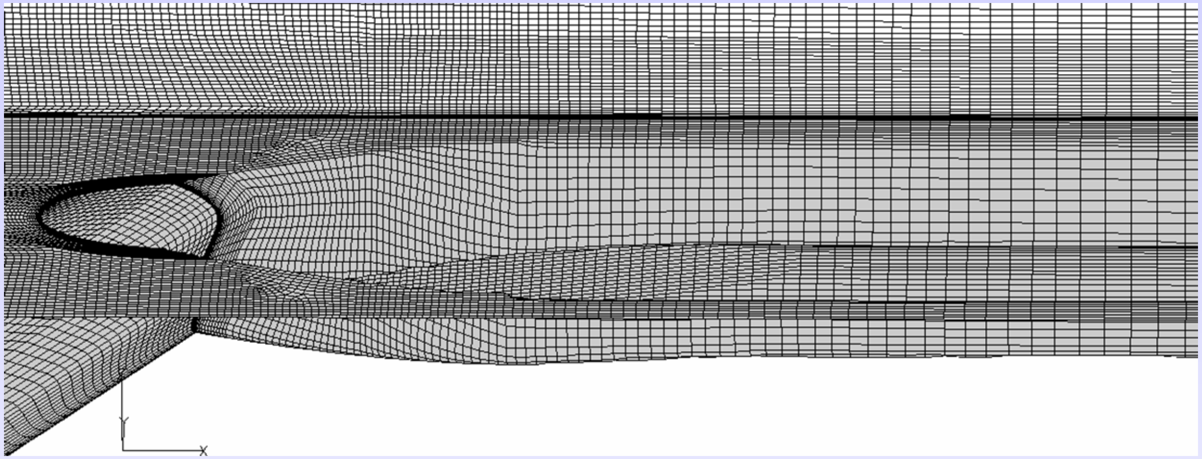
Shih & Na (2005, 2006): **ramp** (patent pending)



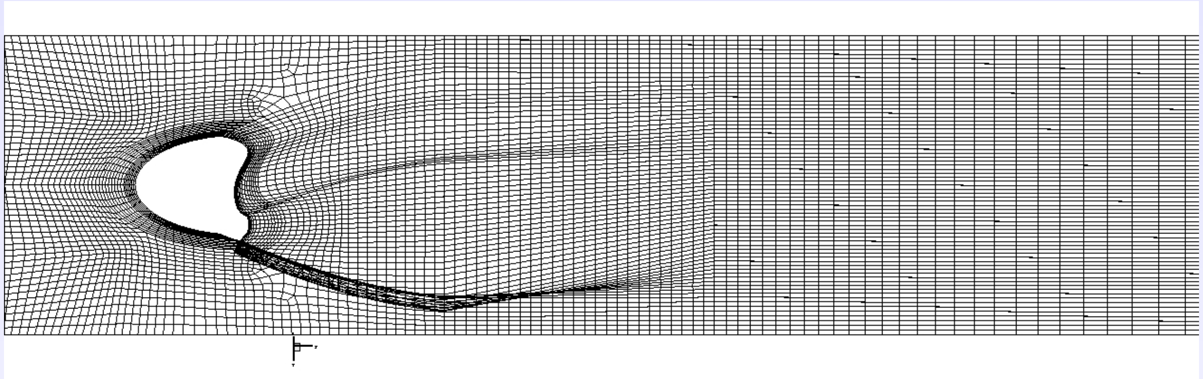
New Design Concept 3: Momentum-Preserving Shaped Holes

Shih, Na, & Chyu (2006): **momentum-preserving shaped holes** (disclosure submitted)

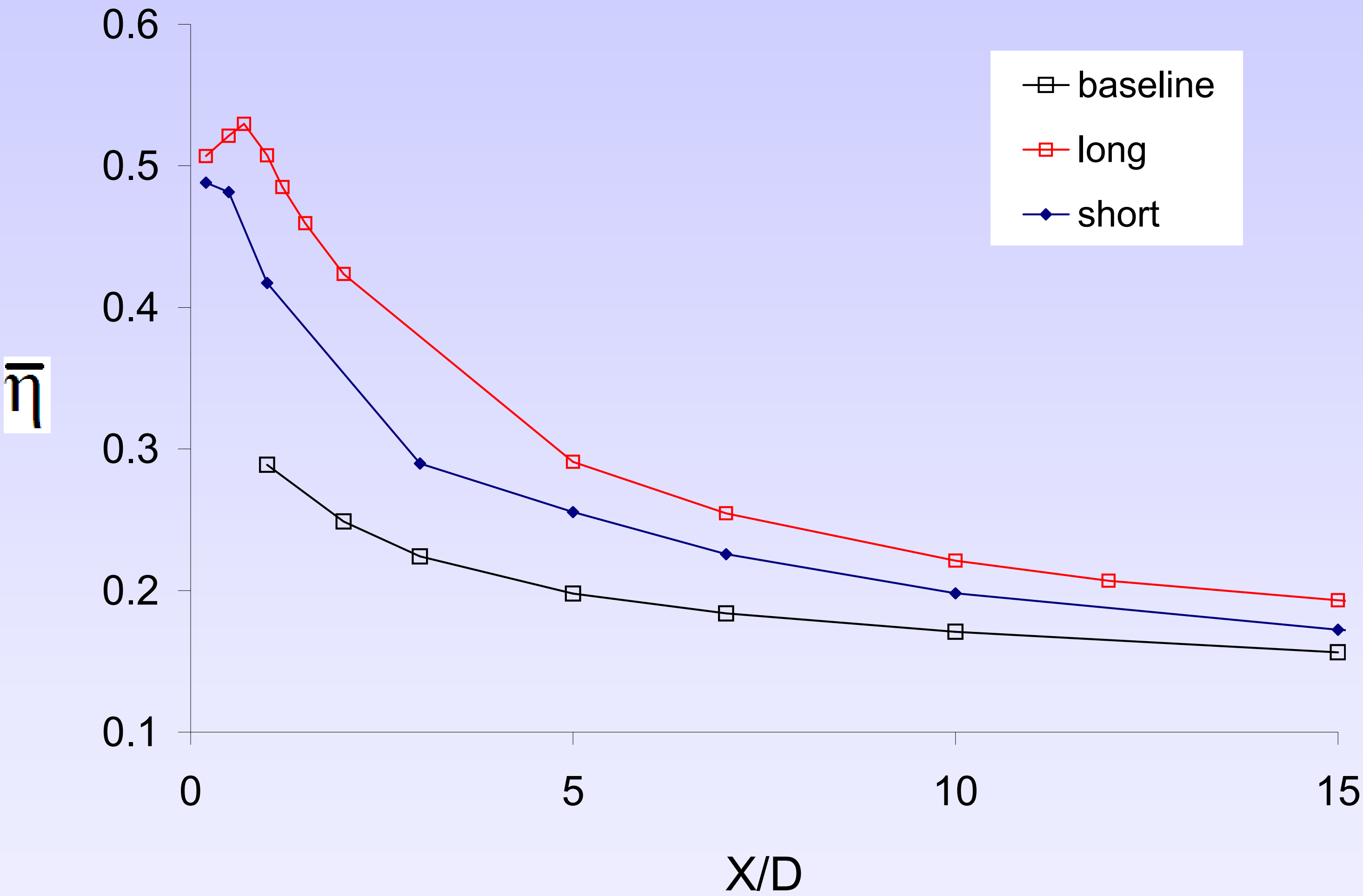
long



short



Momentum-Preserving Shaped Holes



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Summary of CFD Component

- Studied effects of TBC blockage and surface roughness in 2-D (slots).
- Studied effects of TBC blockage in 3-D.
- The 3 new design concepts developed for film cooling appear to be quite promising.

Future Plan

- Examine rounded vs sharp edges for the 3 new design concepts.
- Validate CFD by EFD/HT data.

Questions?

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