Experimental and Numerical Study of Liner Film Cooling and Combustor Swirl Flow Interaction

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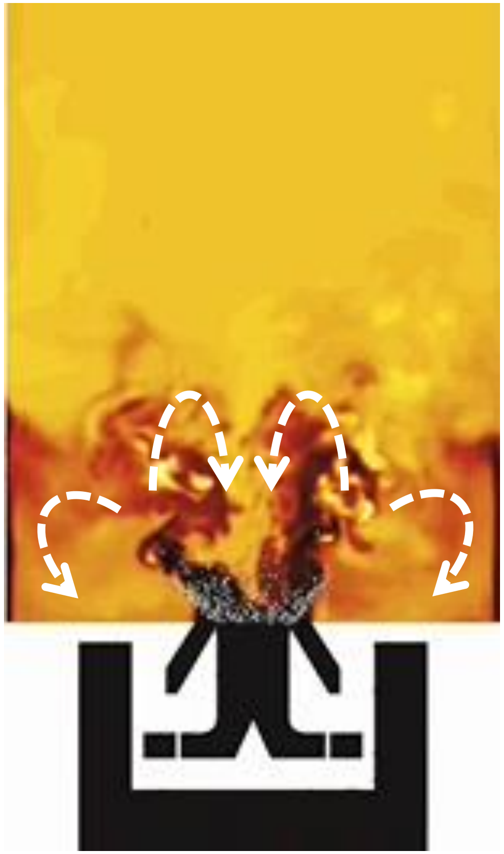
Outline

- Aim and motivation
- Experimental setup
- Experimental results – Flowfield
- Numerical setup
- Numerical results – Flowfield
- Experimental results – Heat Transfer
- Conclusions

Aim and motivation of this work

Swirl stabilized flames

- Development of modern gas turbine combustors
  - Reduction of NOx and soot pollutant emissions
    - Adoption of lean burn concept
    - Ground-based and aero-engine GTs
  - Other challenging requirements:
    - High combustion efficiency and compact size combustors
    - Reliable ignition, combustion dynamics
- Highly swirled flows for flame stabilization and anchoring
  - Large low speed regions produced by the onset of inner and outer recirculations
    - Continuous supply of high temperature gases to incoming fresh mixture
      - Strong velocity gradients and flow unsteadiness
        - » Greatly enhance freestream turbulence and then overall reaction and mixing rates



S. Puggelli, D. Bertini, L. Mazzei and A. Andreini, **Assessment of Scale-Resolved Computational Fluid Dynamics Methods for the Investigation of Lean Burn Spray Flames.** J. Eng. Gas Turbines Power 139(2), 2016

Aim and motivation (continued)

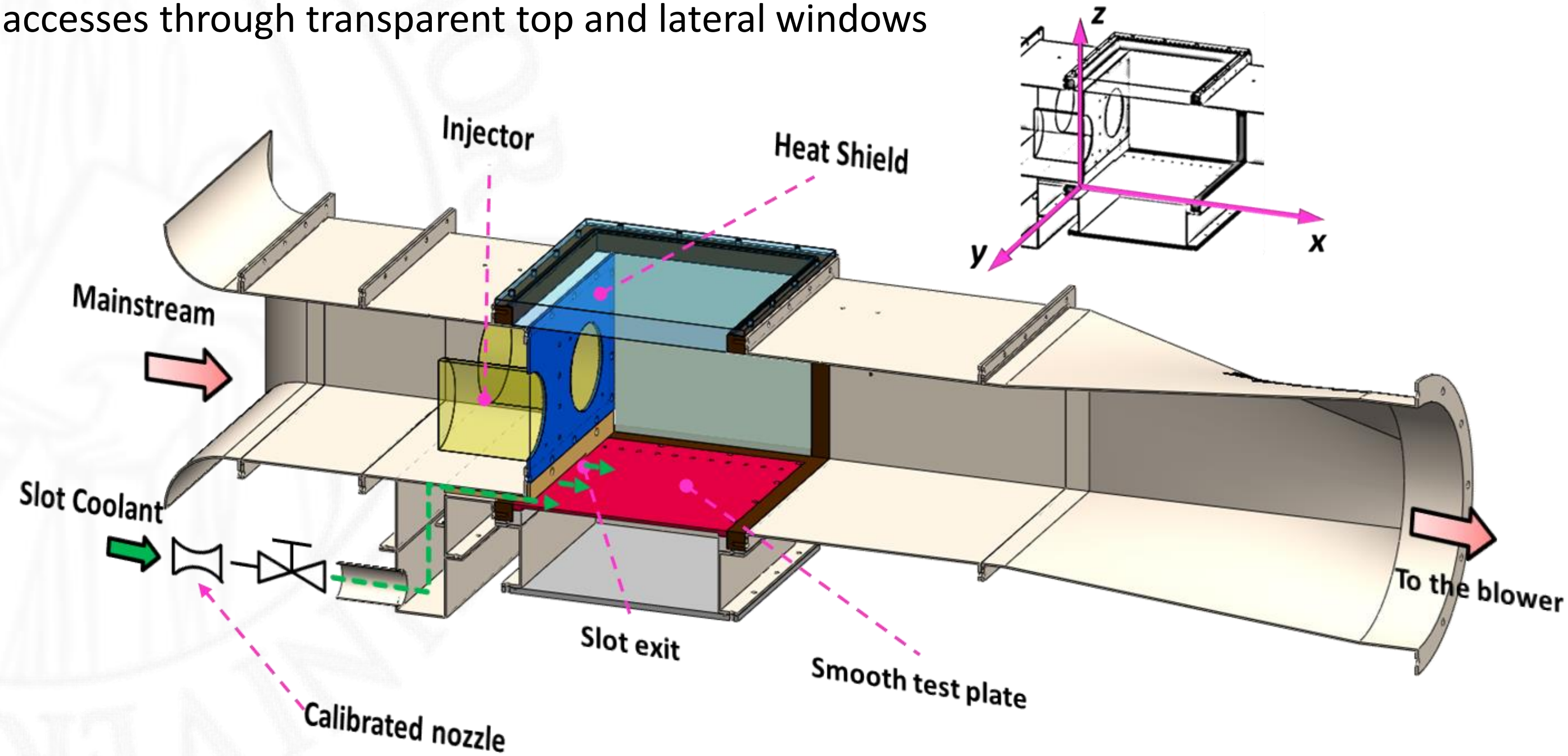
Investigate the role of increasing slot film blowing ratio on the liner heat transfer coefficient under realistic swirling flow conditions

- Generic axial swirlers installed in a linear three-sector rig
- Dedicated measurements of flow field (by PIV system) and Heat Transfer Coefficient (by a TLC thermography)
  - Description and understanding of basic mechanisms involved
- Scale-resolving simulations to support flow field description
  - Validation with experimental data

Experimental Setup

Planar three-sector combustion chamber

- Open Loop suction type wind tunnel (**scaled ambient conditions**)
- Slot cooling system fed by dedicated plenum chamber (slot lateral extension: 2 swirler pitchs)
- Smooth test plate representing the inner liner
- Wide optical accesses through transparent top and lateral windows



Measurement Techniques

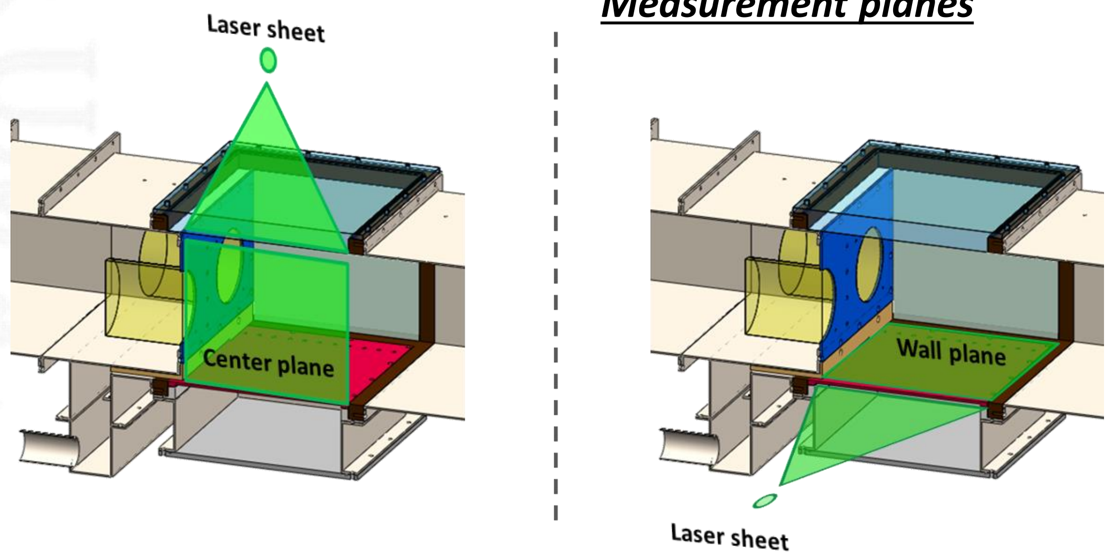
Flow field investigation: Standard 2D Particle Image Velocimetry (PIV)

- Two different planes investigated: Center plane and Wall plane
- Several camera-laser positions to cover the investigation areas

- Dantec Dynamic 2D PIV system
  - 120mJ New Wave Nd:YAG pulsed laser 532nm
  - Phantom Miro 320S camera
  - Olive oil particles as seeding
- Settings
  - Time delay: 10 µs
  - Laser sheet thickness: 1mm

- Data post processing
  - Adaptive grid iterative method
  - Peak-height validation and moving-average validation

Measurement planes



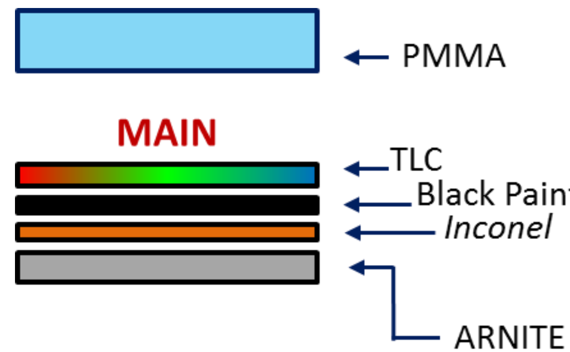
Measurement Techniques

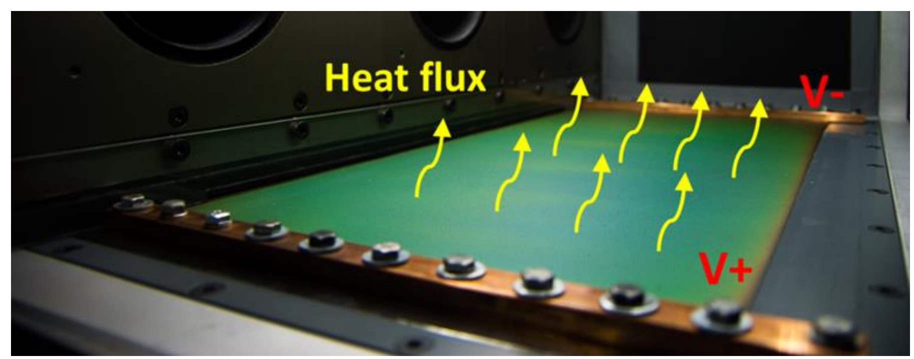
Heat transfer coefficient measurements

- Steady state technique with isothermal flows conditions
- Surface heat flux
  - Inconel heating foil 25.4 µm
    - Two copper bus bars on lateral sides
- Wall temperature measurement
  - TLC wide band 30-50°C

$$HTC = \frac{q_{conv}}{T_w - T_{aw}}$$

- Data post-processing exploiting a 3D thermoelectric FEM analysis





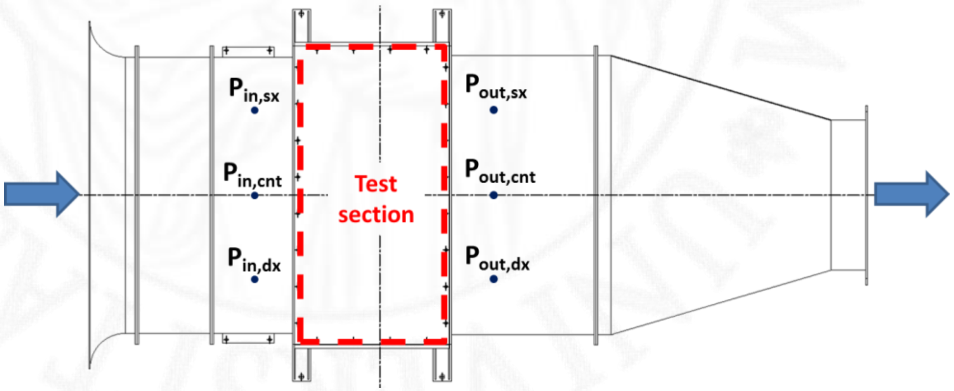
Test conditions

- Rig inlet air at ambient pressure and temperature
- Mainstream: Pressure drop across the injectors and Reynolds of the main-flow
  - Reynolds number estimated using the cross sectional area of hydraulic diameter of test section

$$\frac{\Delta P}{P} = \frac{P_{in} - P_{out}}{P_{in}} \qquad Re_{main} = \frac{m_{main} \cdot d_h}{A_{main} \cdot \mu_{air}}$$

- Slot cooling system: Coolant flow parameter and Reynolds number
  - Reynolds number estimated using the height of the slot exit

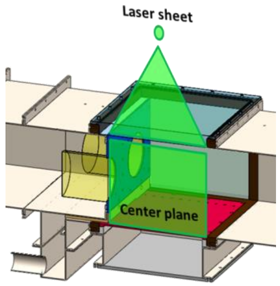
$$W = \frac{m_{slot}}{m_{main}} \cdot \frac{3}{2} \qquad Re_{slot} = \frac{\dot{m}_{slot} \cdot h}{A_{slot} \cdot \mu_{air}}$$

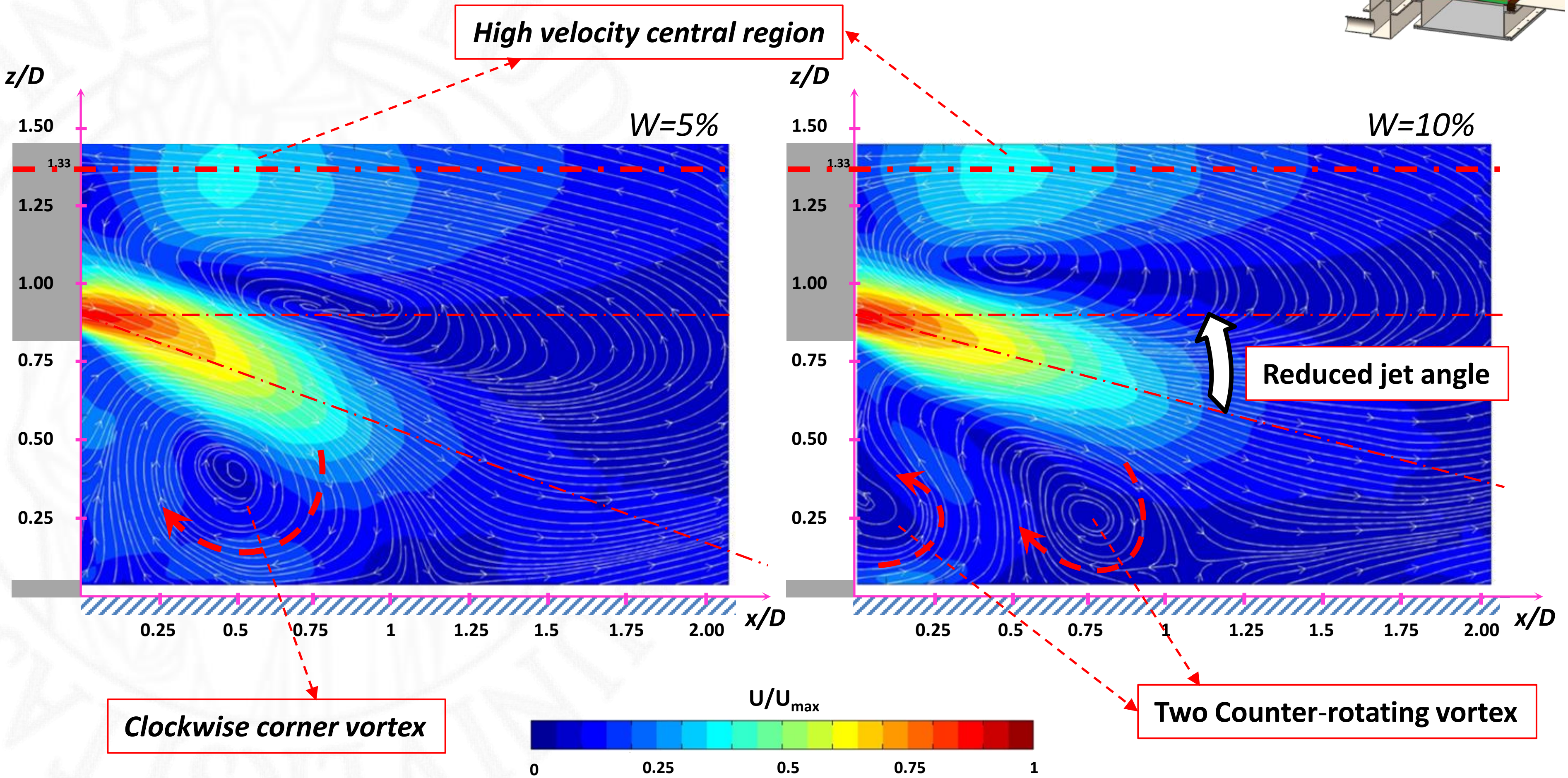


	PIV	HTC
T_{main} [K]	295	295
ΔP/P [%]	5	5
W [%]	5 ; 10	0; 5; 6; 7.5; 8.5; 10
Re_{main}	124000	124000
Re_{slot}	5200 – 8200	0 – 8200

Experimental results - Flow field

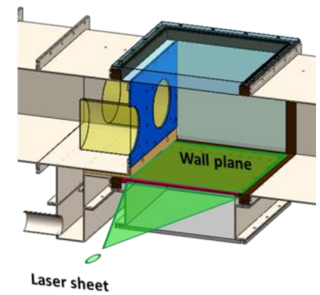
PIV results on Center Plane varying slot coolant flow

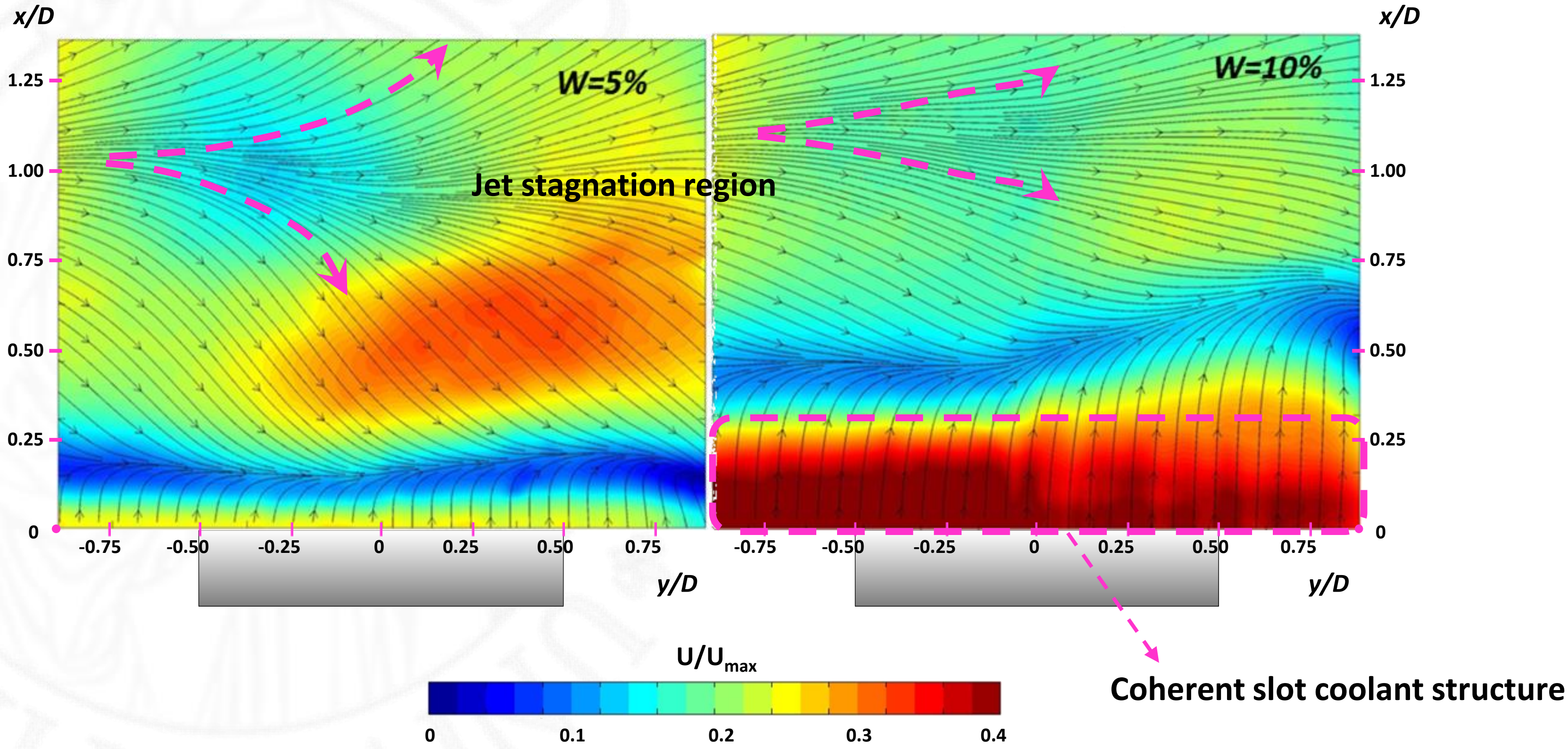




Experimental results - Flow field

PIV results on Wall Plane varying slot coolant flow

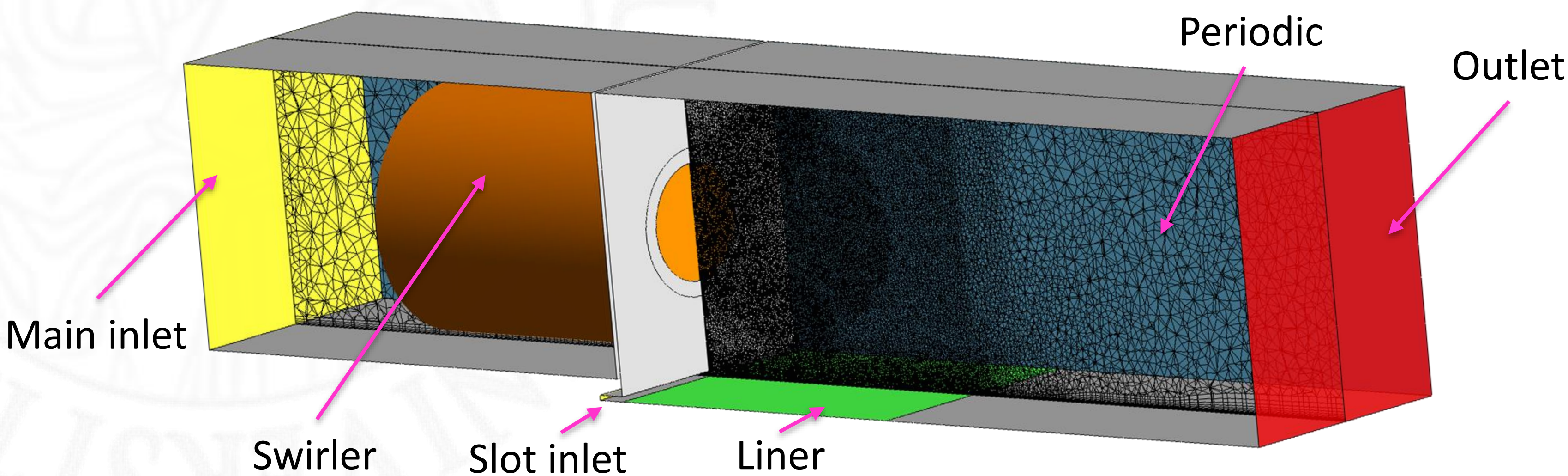




Numerical Details

Setup

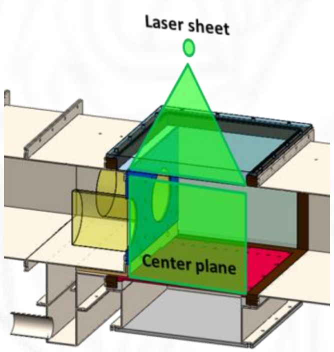
- Code: ANSYS Fluent v16.2
  - SAS - Scale-Adaptive Simulation
  - Pressure: 2nd order
  - Momentum: Bounded Central Difference
  - Other equations: 2nd order upwind
  - Time: bounded 2nd implicit
  - Time step: 7.5e-6 s (CFL < 1)
- Boundary conditions
  - Prescribed inlet mass-flow
    - Main and Slot entrances
  - Outlet: static-pressure
  - Lateral surfaces: periodicity
  - Walls: smooth, no slip, adiabatic
- Mesh: ANSYS Meshing
  - Tetrahedrons + 15 prisms ($y^+ \approx 1$)
  - 45 elements at the swirler exit
  - Roughly 14.25Me, 3.43Mn

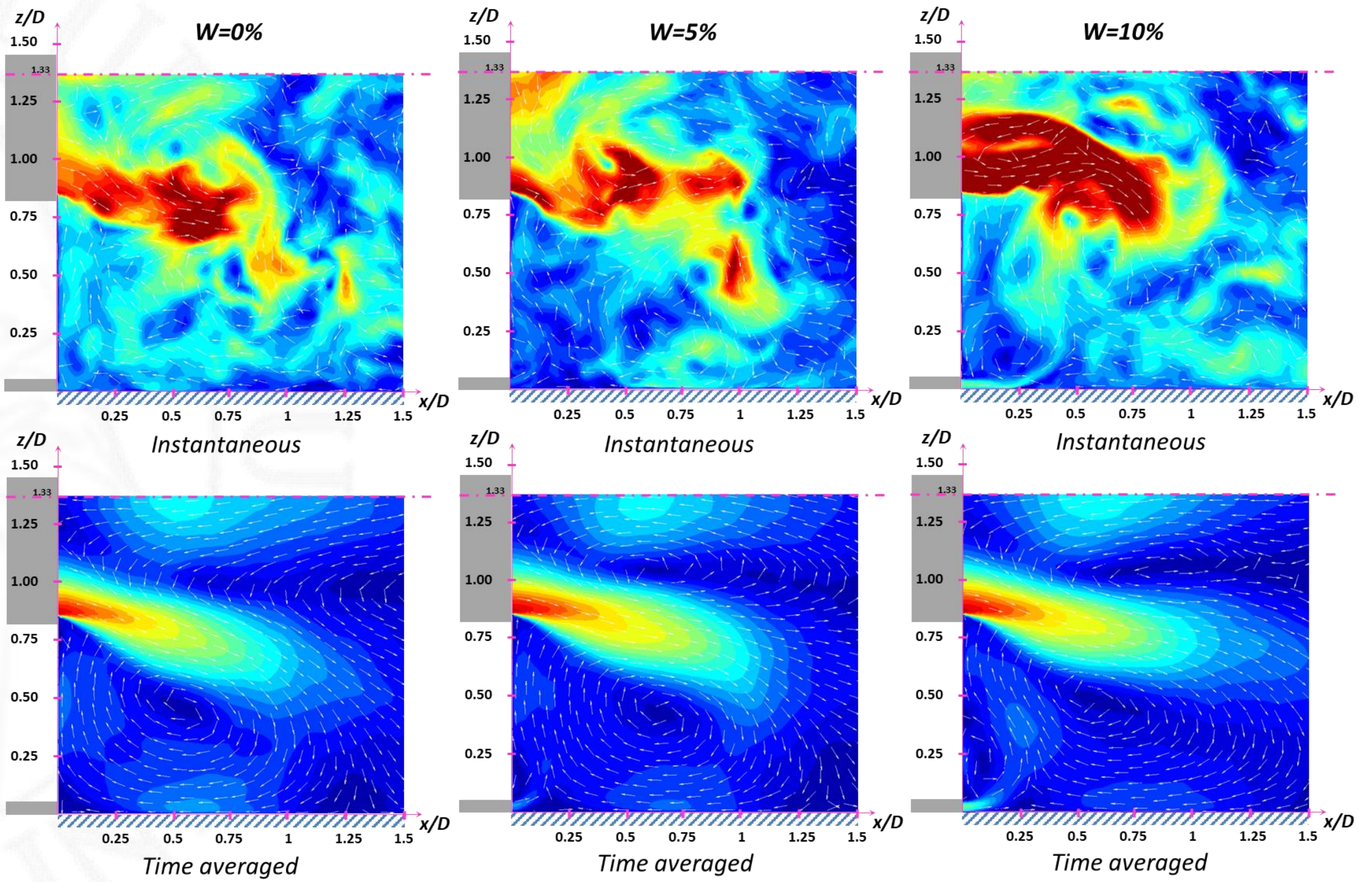


Numerical Results

Flow field

- Increase in W is affecting high speed swirling jet region
- Highly unsteady and turbulent flow field in the shear layers

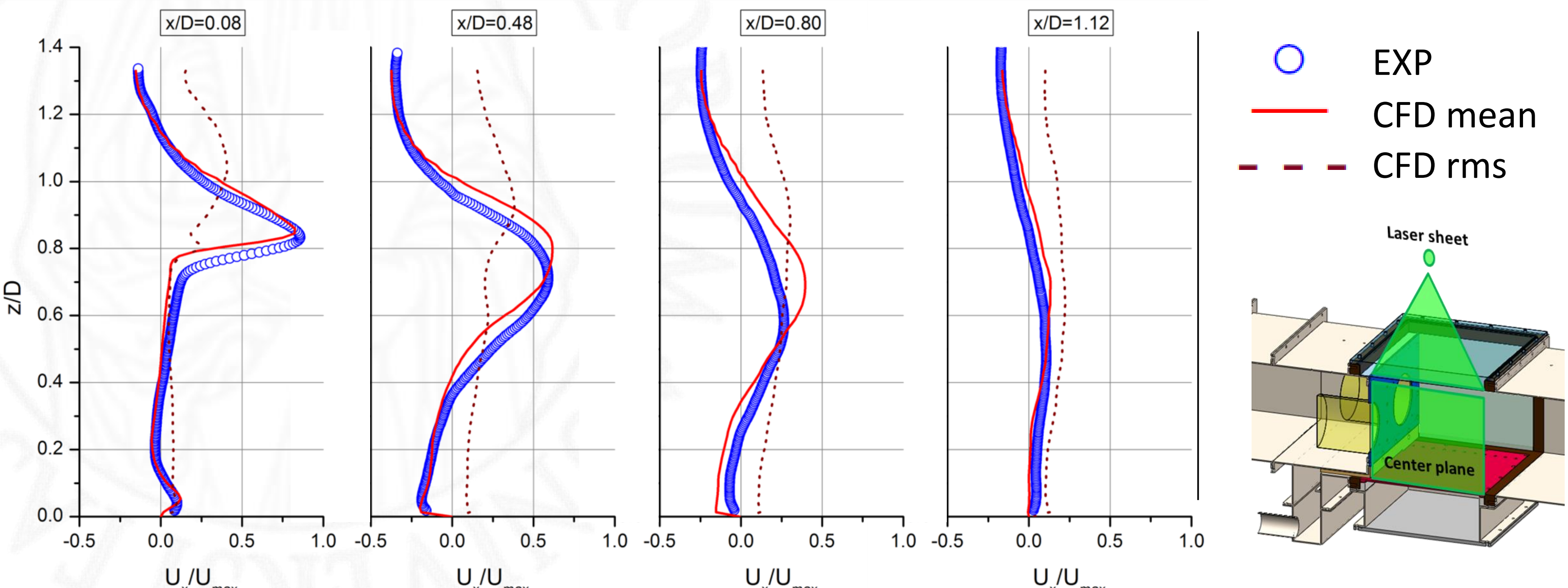




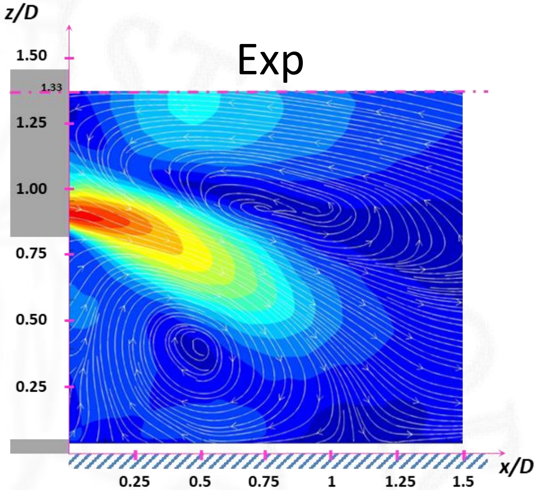
Numerical Results

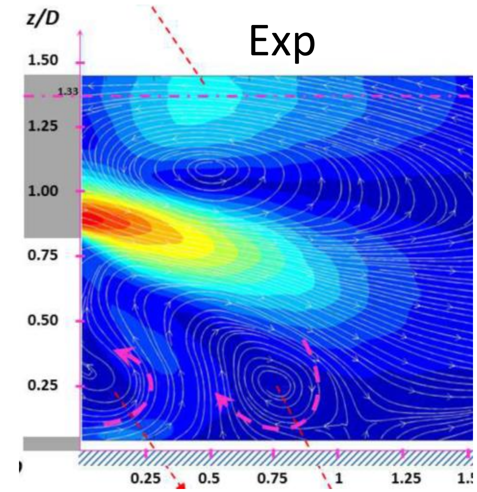
Comparison with experimental data

- Reference condition: W=5%
  - Reasonable agreement between Exp and CFD
  - Differences due to to turbulence modelling & geometrical inconsistency due to manufacturing



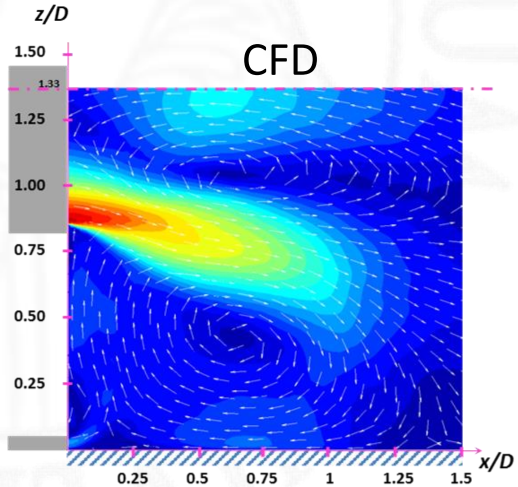
Numerical vs. Experimental

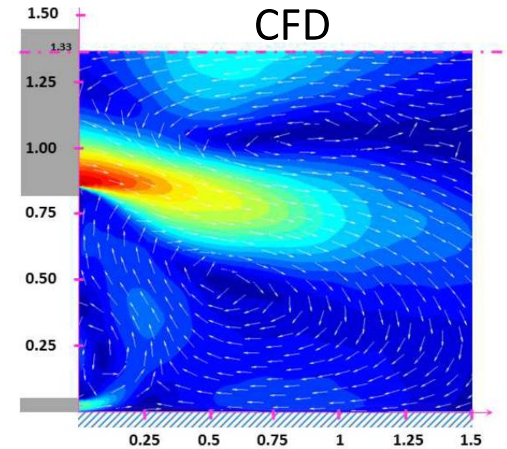




W=5%

W=10%



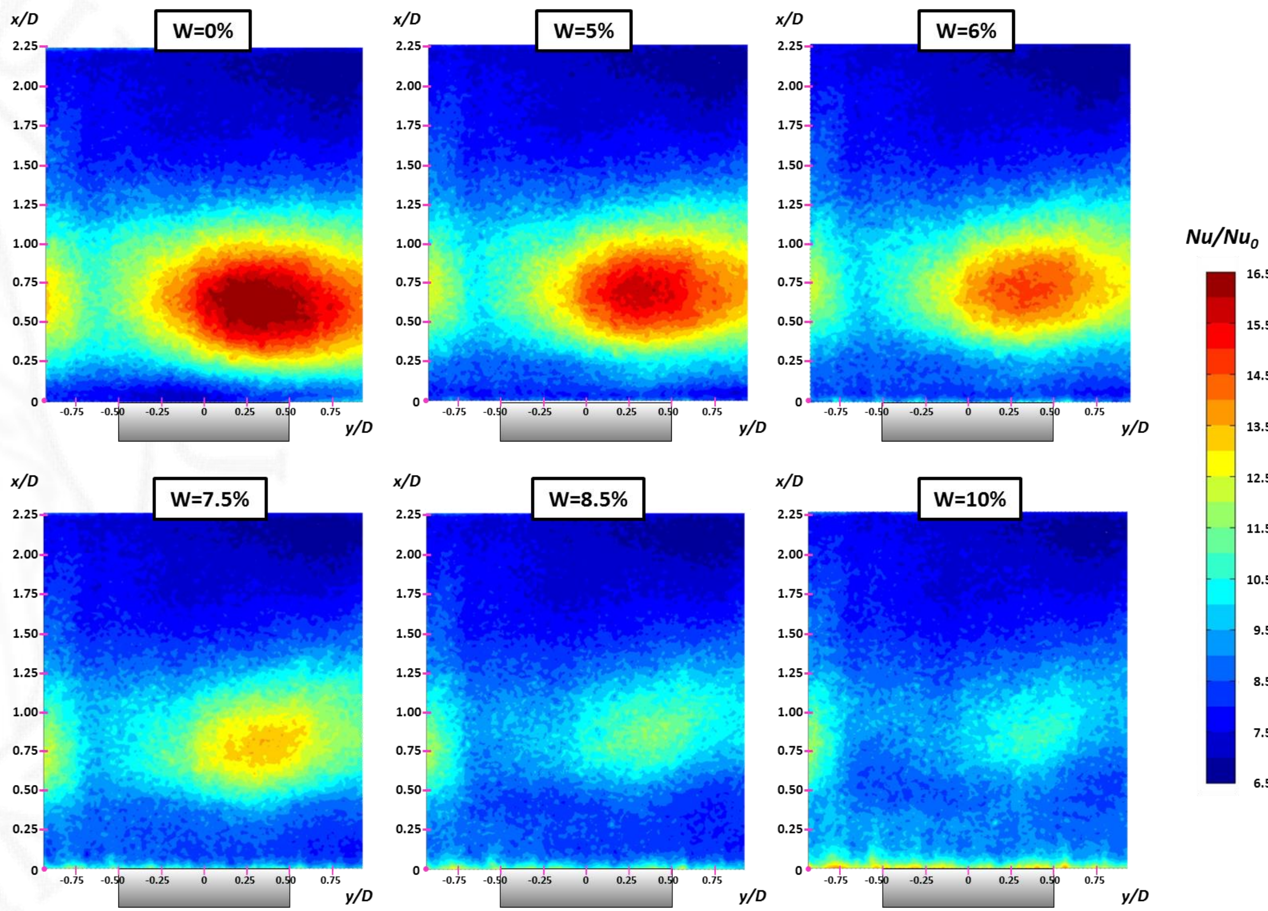


Experimental results - Heat transfer

2D maps - Heat transfer enhancement factor

$$Nu_0 = 0.023 \cdot Re_{main}^{0.8} \cdot Pr^{0.3}$$

- High heat transfer region due to swirling jet impingement
- Slot coolant increase leads to reduced Nu/Nu_0 peak values
  - Mainstream jet lift
  - Corner vortex structures counteracting
- Increasing convection at the slot exit
- Cooling system effects negligible downstream of x/D≈1.6

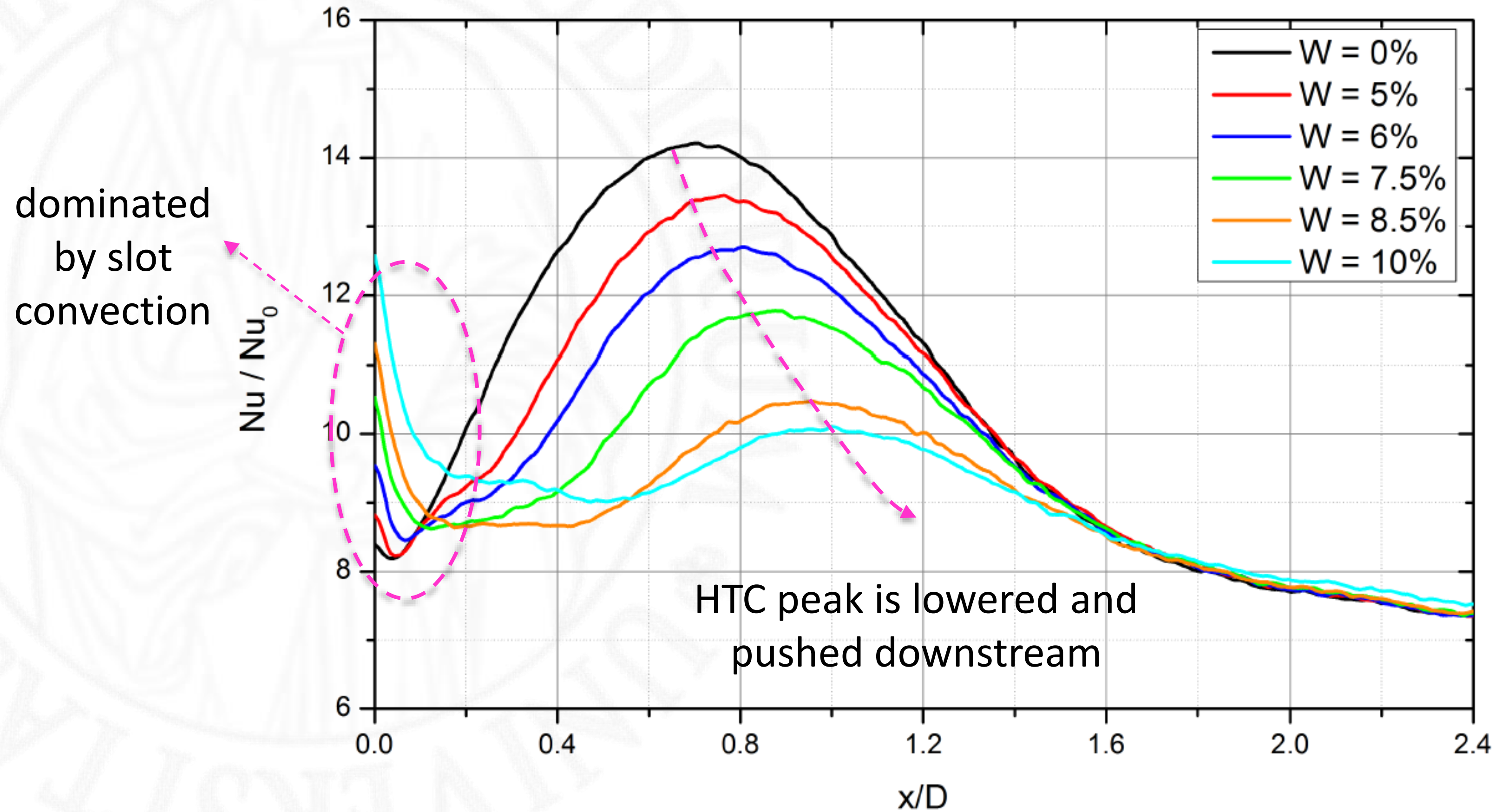


Experimental results - Heat transfer

Laterally averaged axial profiles

$$Nu_0 = 0.023 \cdot Re_{main}^{0.8} \cdot Pr^{0.3}$$

- Non monotonic behavior of HTC with slot coolant flow W



Conclusions

- Interaction between swirling main flow and slot cooling flow is complex

- Effects of coolant injection on flow field and liner heat transfer studied
  - 2D Particle Image Velocimetry
  - Steady state technique using Thermochromic Liquid Crystals
  - Scale resolving CFD simulations

- Slot cooling has significant effect on combustor liners
  - Has impact on flow field
  - Substantial impact on heat transfer augmentation with respect to classical smooth channel correlations