Combustor-Turbine Interactions

Experimental Investigation

Effects of representative lean burn combustor outflow on flow field and film effectiveness through HP cooled vanes

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Background and motivations

Secondary flows and turbine aerodynamics

Hot Streaks migration

Film-cooling behaviour

Heat transfer on airfoil + endwall

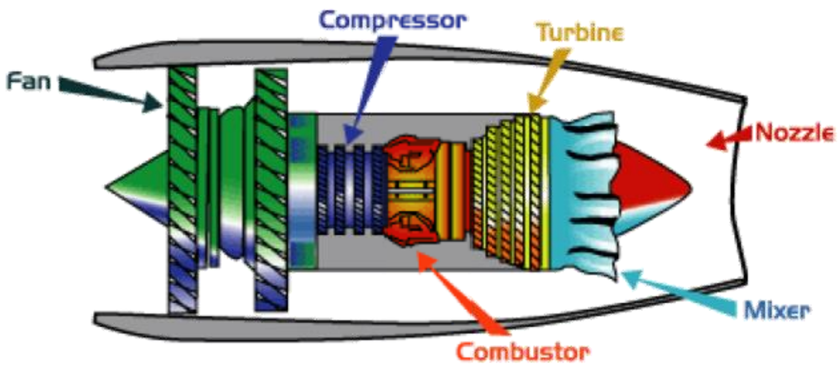
ANNULAR COMBUSTOR EXIT P AND T NON-UNIFORMITIES AFFECT HP TURBINE PERFORMANCE

TOPIC OF STUDY SINCE 80's

Engine Life and efficiency

Background and motivations

BUT: Combustor/Turbine characterization historically based on separated approaches



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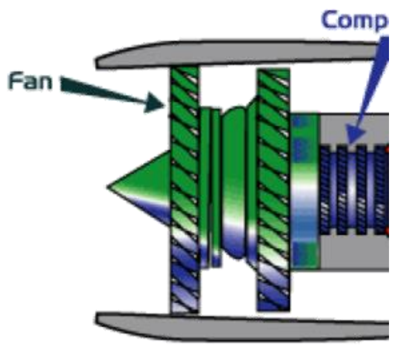
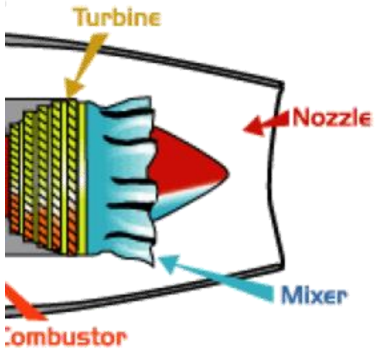


Compressor Department

Combustor Department



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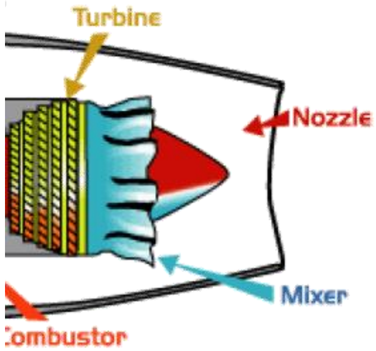


Predicted combustor exit conditions (2D)

Compressor Department

Combustor Department

Turbine Department

1D profiles of temperature, pressure, velocity

Averaged (0D) Tu/ lengthscale

Plane 40

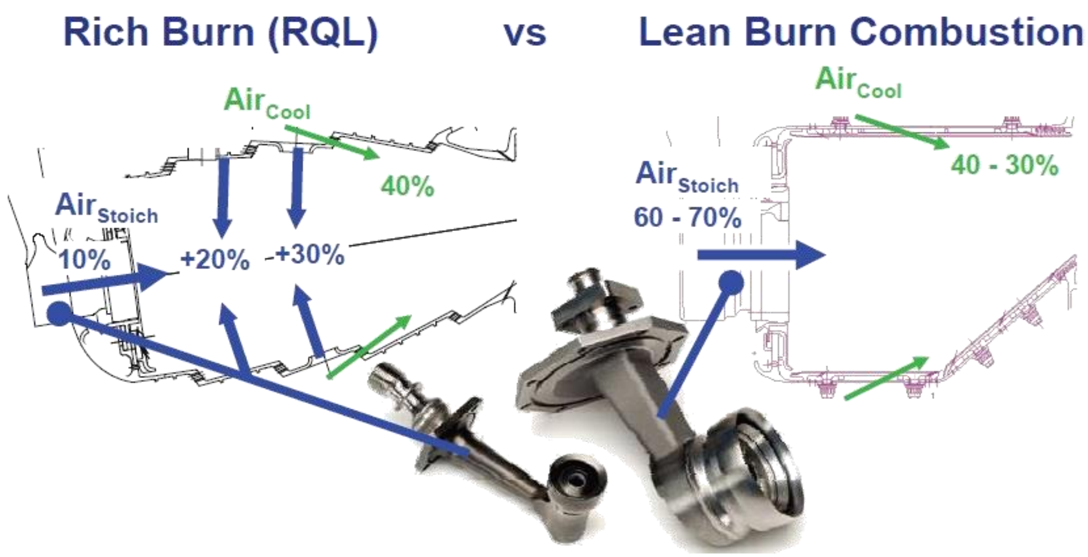
Turbine modelling/design (RANS)

Background and motivations – Lean Burn Combustors

- **Implementation of lean burn combustion for high OPR future aero-engine**
  - Control of local FAR conditions
  - Limitation of temperature peaks
  - NO_x abatement

- **Implications**
  - More air dedicated to combustion process
  - Coolant has to be reduced by 50%

    → More effective cooling schemes



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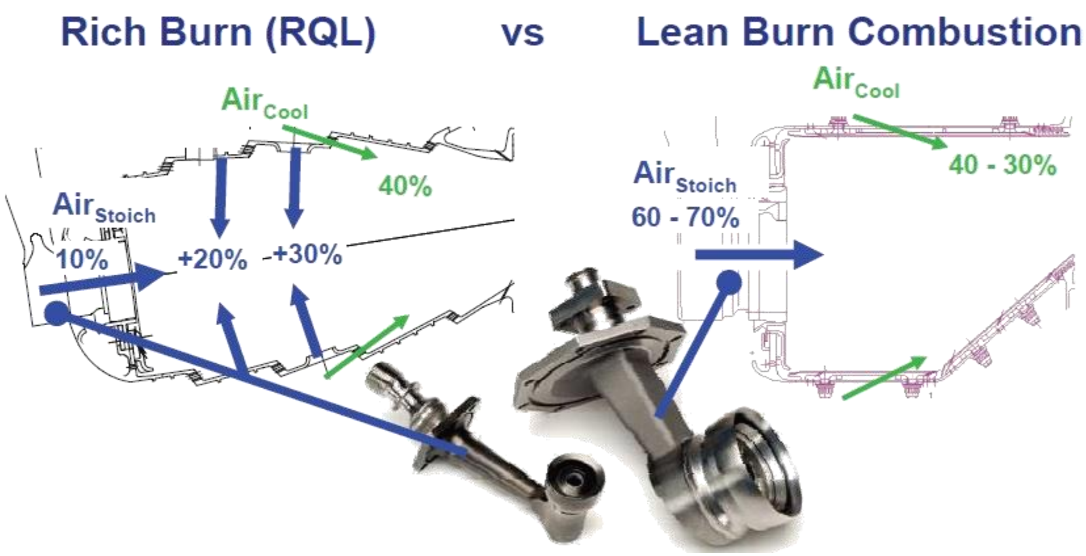

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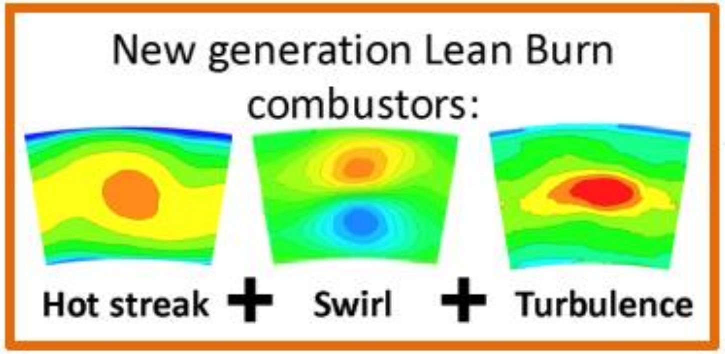
Highly unsteady /non-uniform combustor outflow

Challenge for traditional turbine modelling/design procedures



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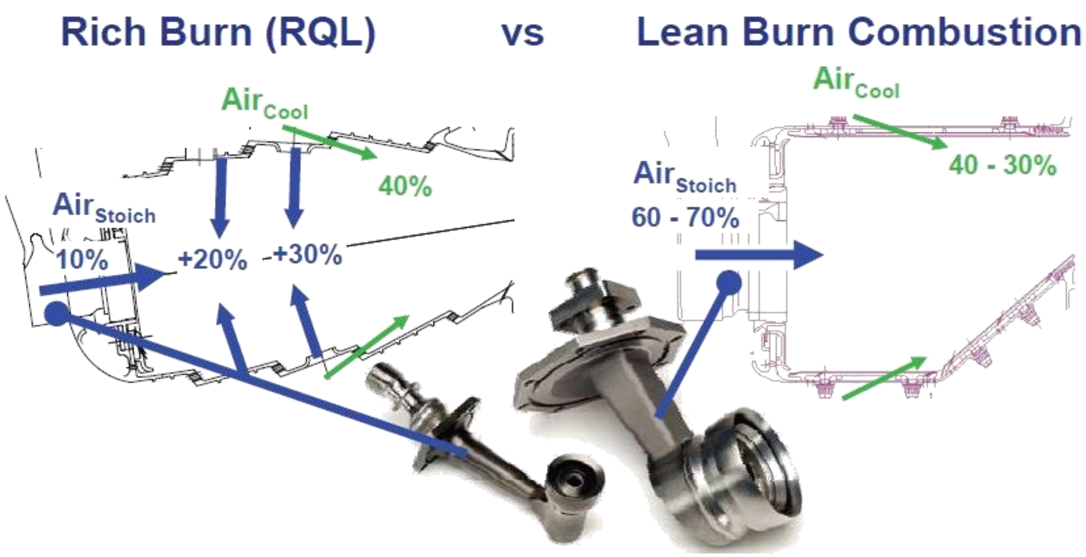

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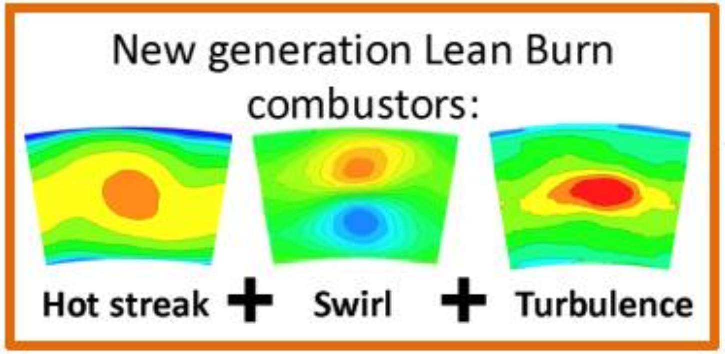
Challenge for traditional turbine modelling/design procedures

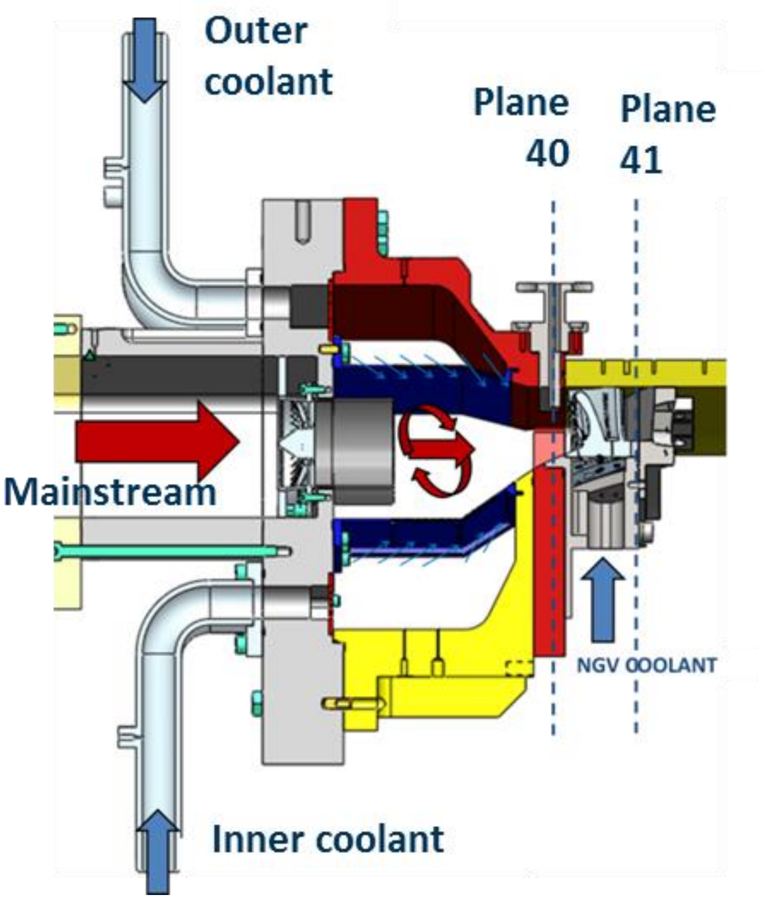
Necessity for experimental investigations with representative combustor outflow conditions



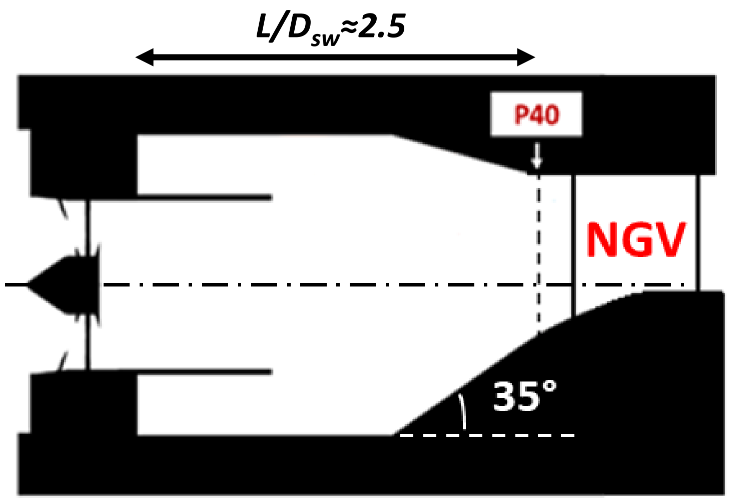
FACTOR Insight on combustor-turbine interactions

UniFi: AeroEngine Test Rig

- **Three sector non-reactive test rig**
- **Combustor simulator:**
- 3 swirlers + ducts designed to achieve representative flow conditions without combustion
- Lean combustor chamber air split
  - 65% swirlers (≈260°C)
  - 35% liners with effusion holes (no dilutions)
- Inner liner strongly convergent (35°)

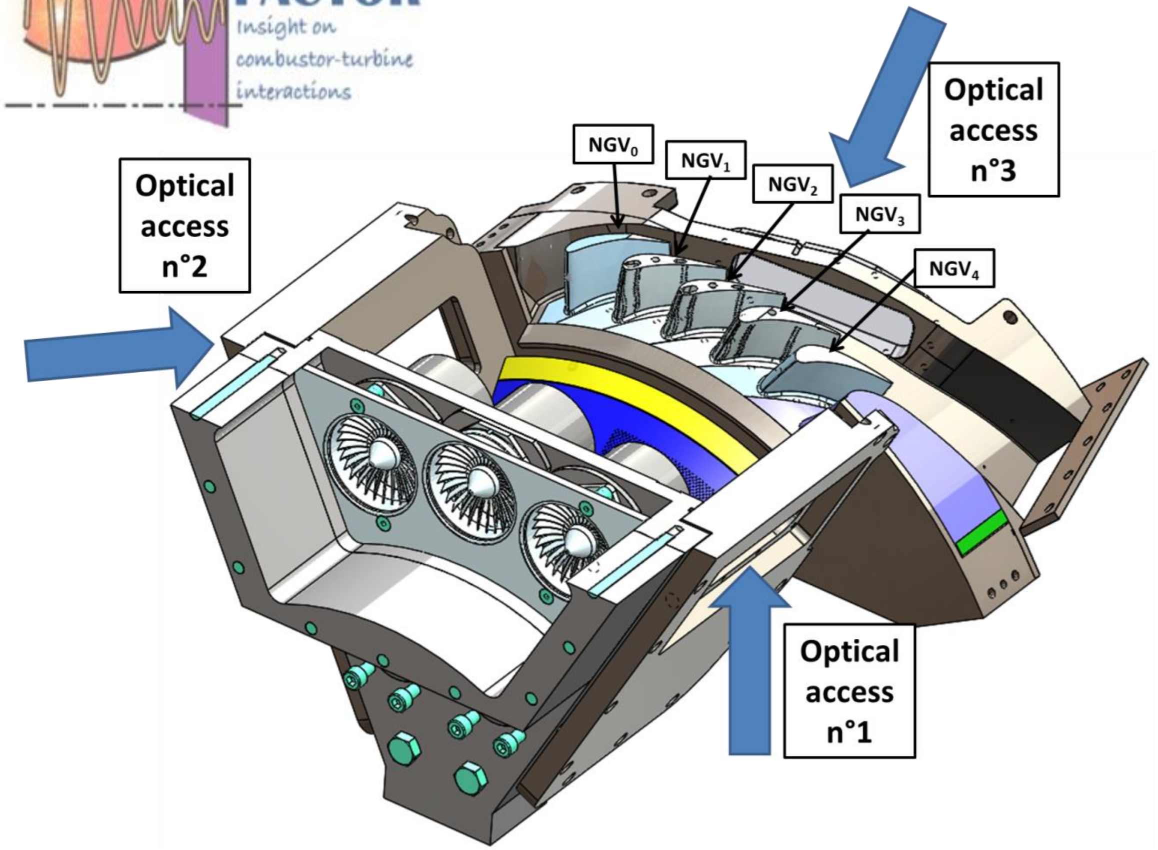


FACTOR Swirler

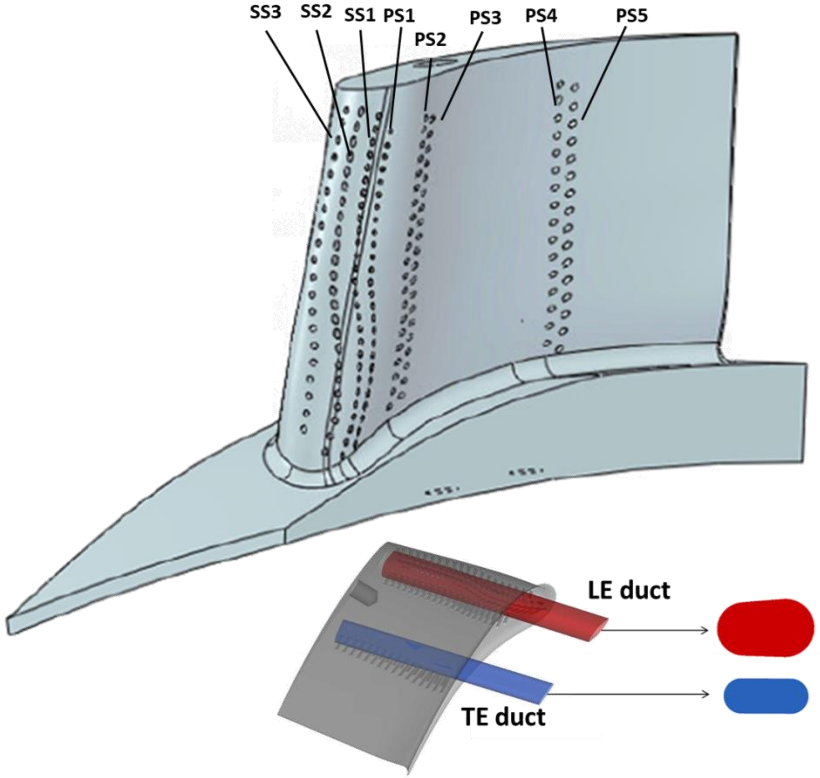


FACTOR
Insight on combustor-turbine interactions

UniFi: AeroEngine Test Rig



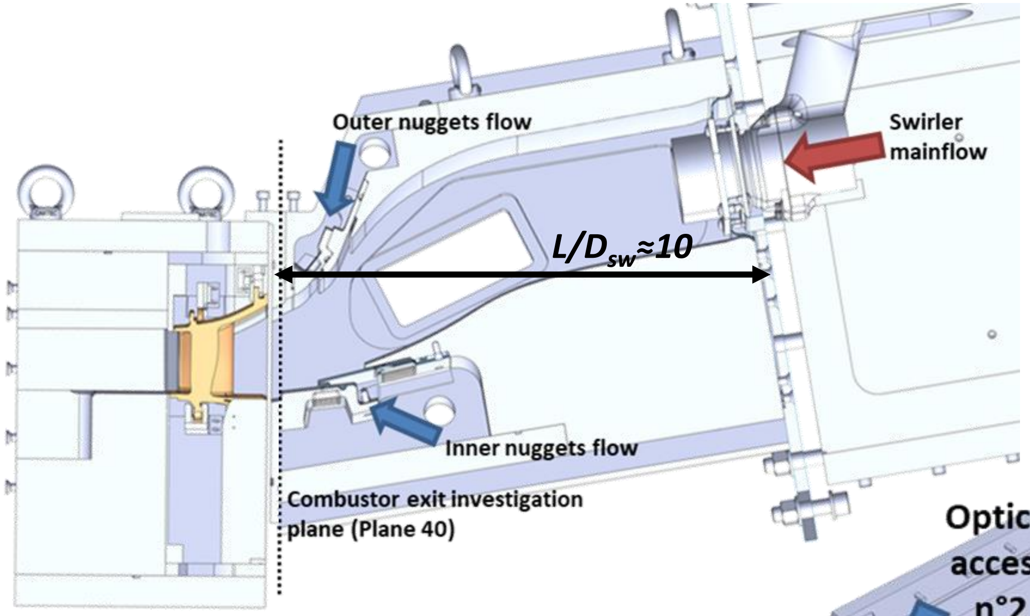
- ○ 5 airfoils (3 fully film cooled)
- ○ Swirler-Vane count ratio 1:2, LE aligned with centerline
- ○ NGVs feed by a plenum chamber
  - ○ Two feeding cavities for each NGV
- ○ **CFD friendly**

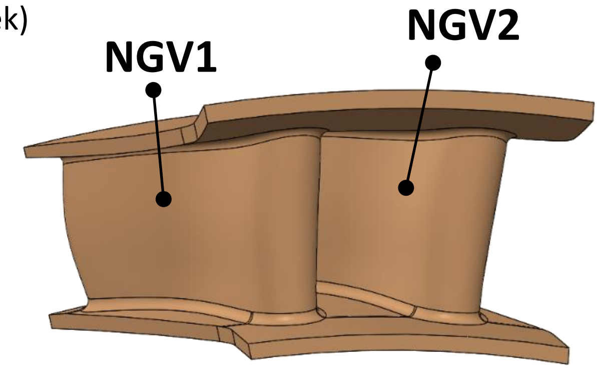


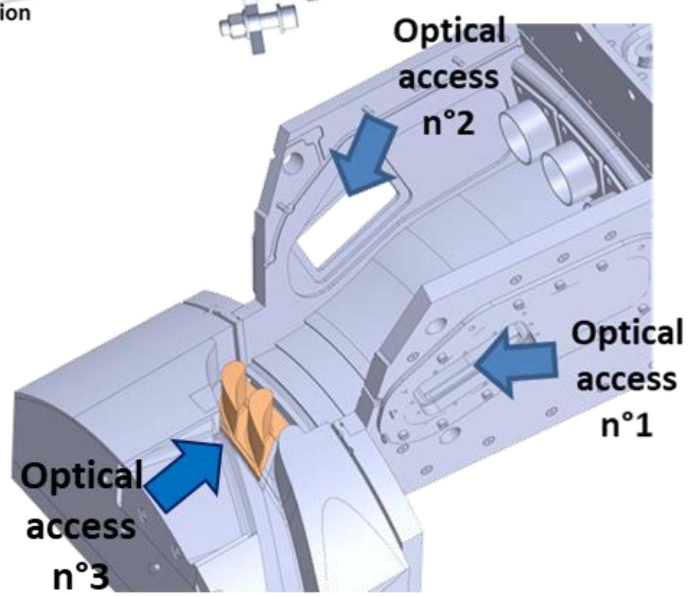
- ○ Different optical accesses for film measurements
- ○ Slot on P40 and P41 for traversing 5hole probe and HWA

UniFi: Industrial (land-based) Test Rig

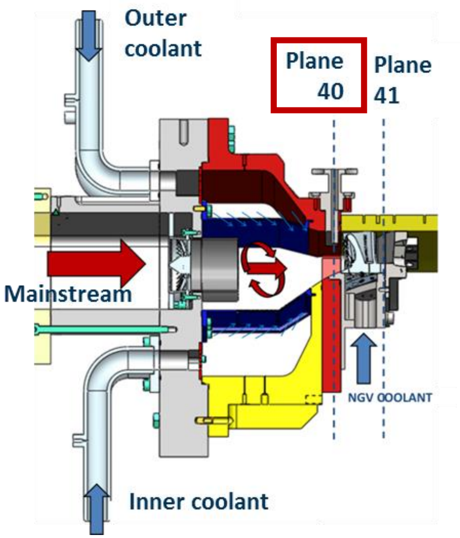
- Developed within Smart Technologies" program
  - Co-funded by Regione Toscana and Baker Hughes
- 3-sector combustor simulator
  - Longer combustion chamber
  - Real hardware swirlers and combustor «shape»
  - Non-reactive
  - Heated mainflow (≈300°C)
  - Ambient temperature cooling nuggets
- NGV cascade
  - 2 vanes – 3 passages
    - RH fully cooled doublet
    - Not cooled plastic model for thermal test (Peek)

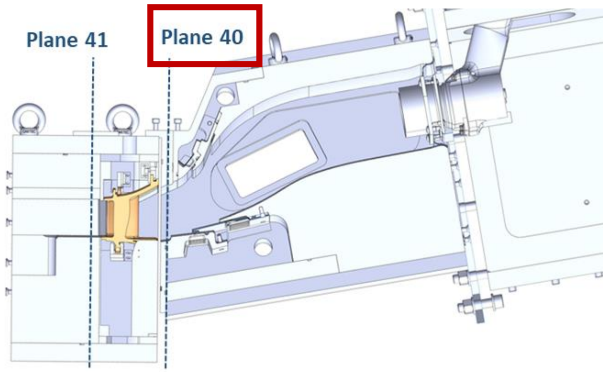






Test Campaign(s)





- Aerothermal characterization on comb. outlet plane
  - Verification of NGV inlet boundaries

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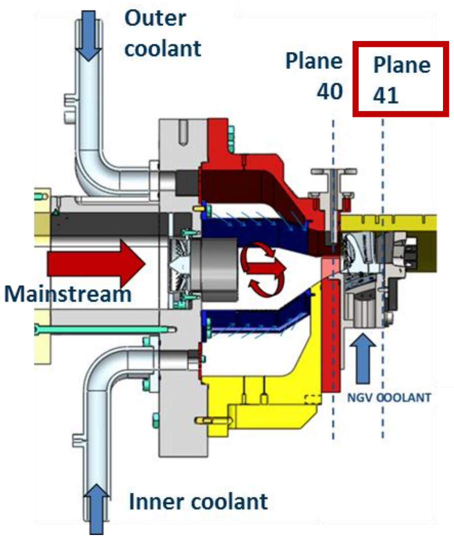

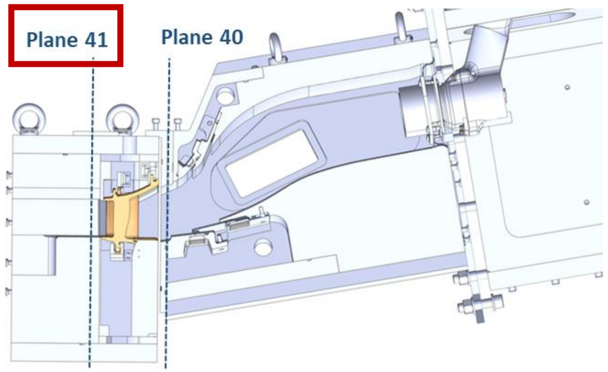

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  - Swirl effect on secondary flows / pressure losses

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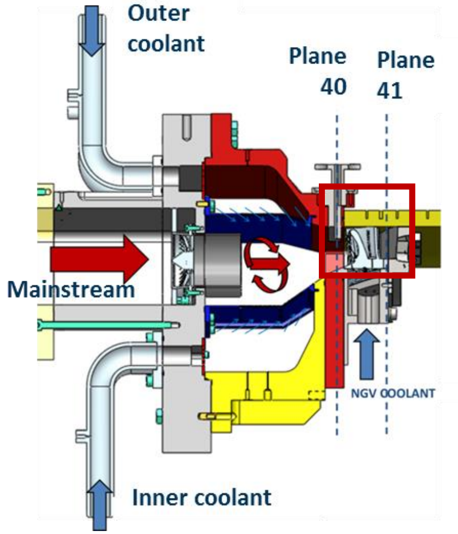

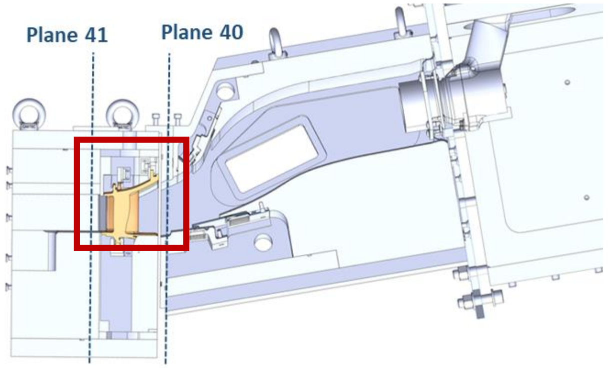

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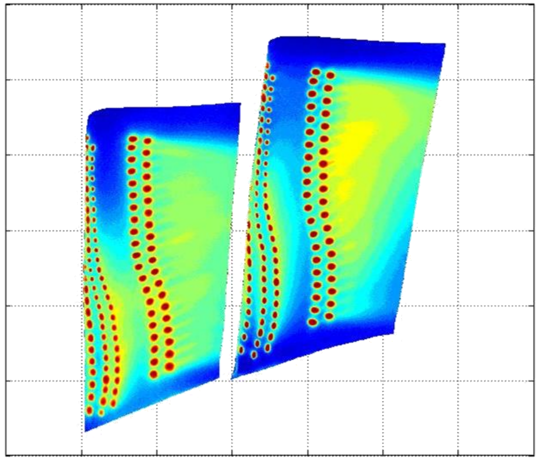
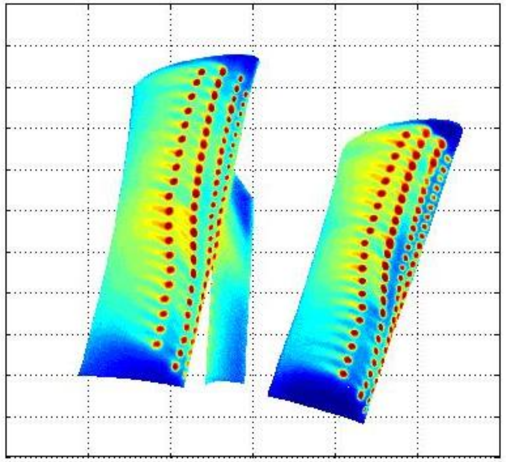
- NGV optical measurements
  - Adiabatic effectiveness: swirl effect on film-cooling

*Adiabatic effectiveness measurements on **aero-engine test case***





Bacci, T., Becchi, R., Picchi, A., and Facchini, B. Adiabatic effectiveness on high-pressure turbine nozzle guide vanes under realistic swirling conditions. ASME J. Turbomach., 141:011008–1, 2019.

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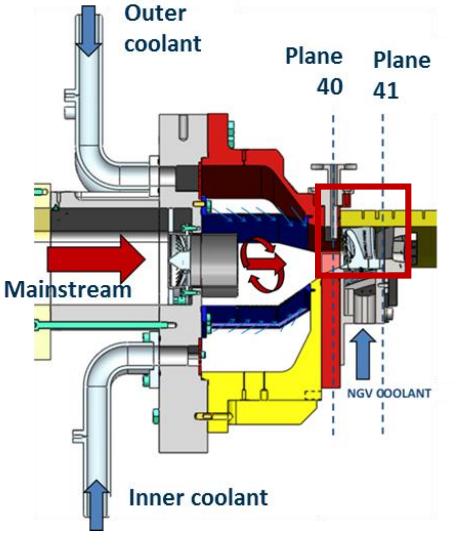
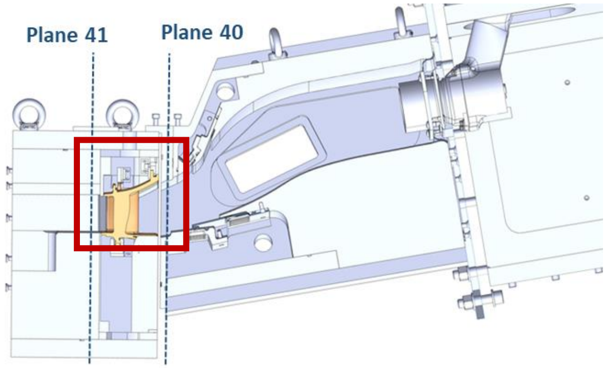


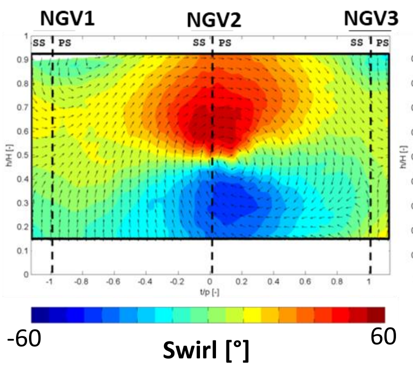


- Aerothermal characterization on comb. outlet plane
  - Verification of NGV inlet boundaries
- Aerothermal characterization on NGV outlet plane
  - Hot Streaks migration
  - Swirl effect on secondary flows / pressure losses
- NGV optical measurements
  - Adiabatic effectiveness: swirl effect on film-cooling
  - HTC-Taw with hot streaks: swirl effect on HTC and T distribution through NGV

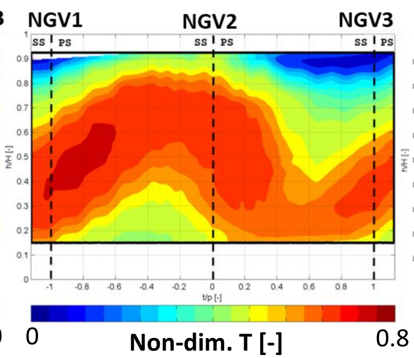
Only for industrial test case!!

Comb. Exit conditions

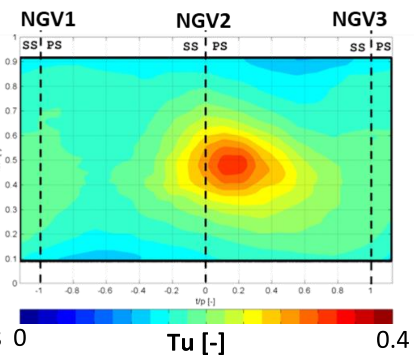
Aeroengine Test Case



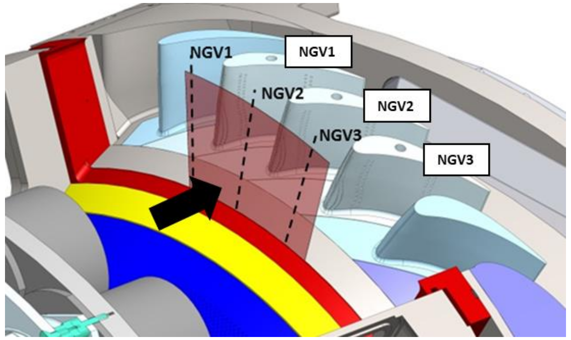
5-hole probe traversing

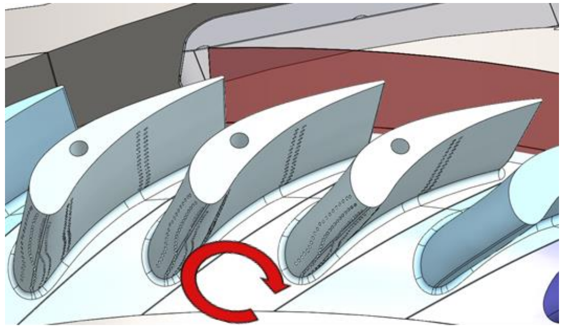


TC traversing

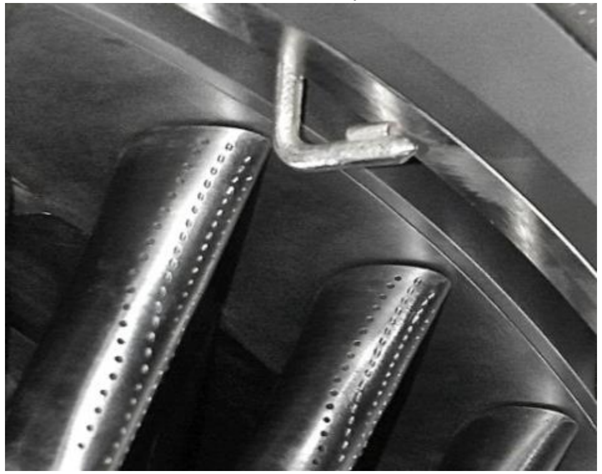


HWA traversing



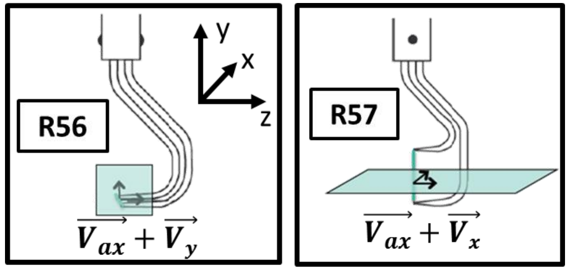


5-hole probe + embedded TC traversing on combustor exit plane



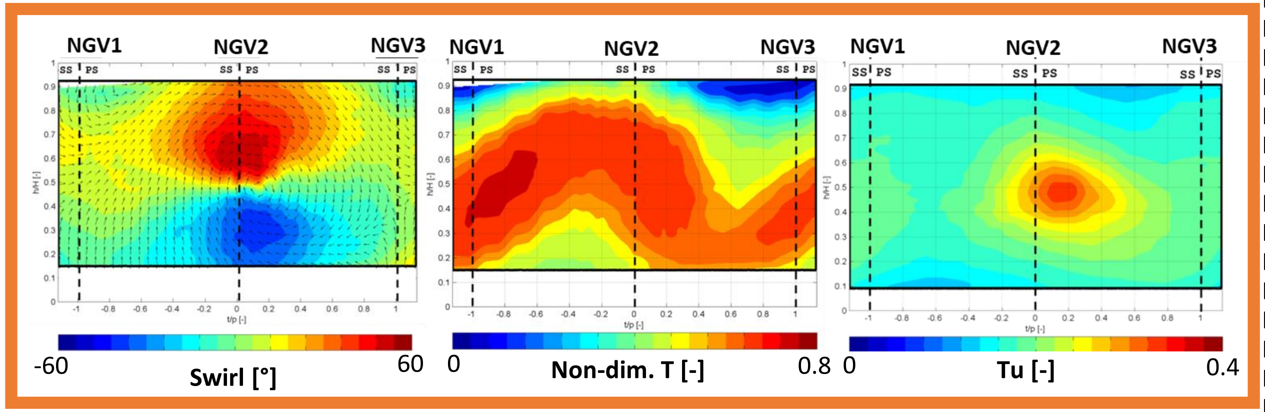
HWA traversing on combustor exit plane

HWA: double test with split fiber probes



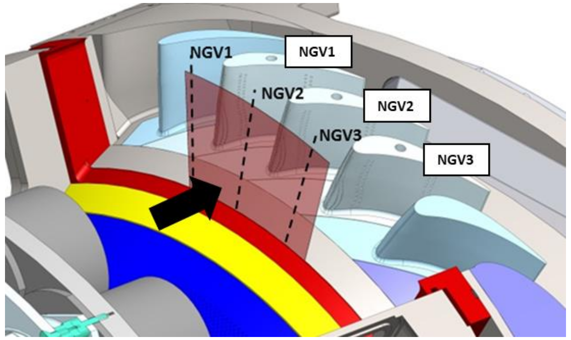
Comb. Exit conditions

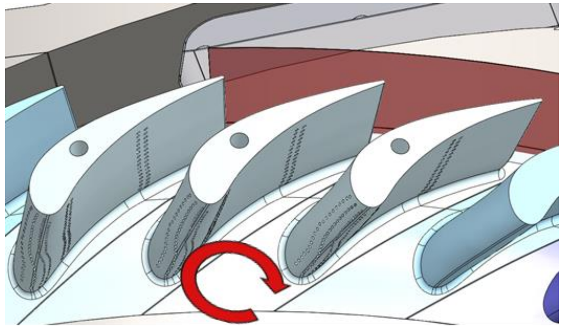
Aeroengine Test Case

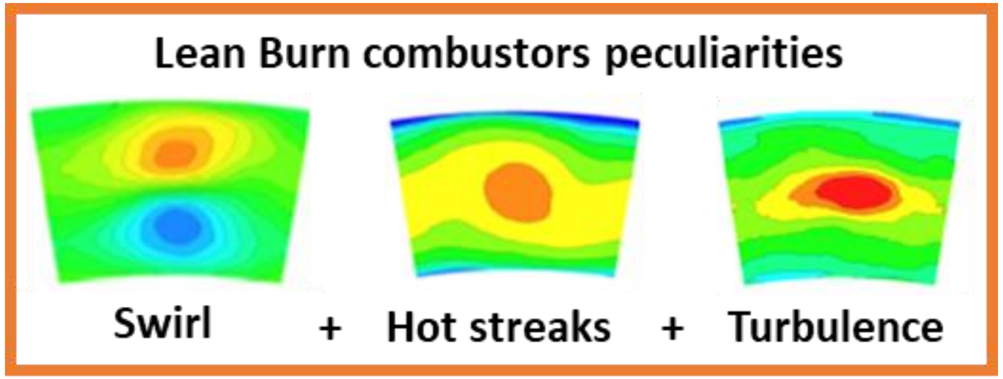


TC traversing

HWA traversing



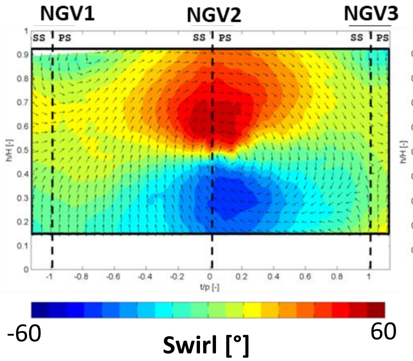




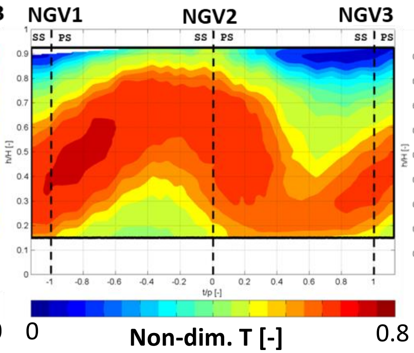
Combustor-exit flow features representative of desired characteristics

Comb. Exit conditions

Aeroengine Test Case



5-hole probe traversing



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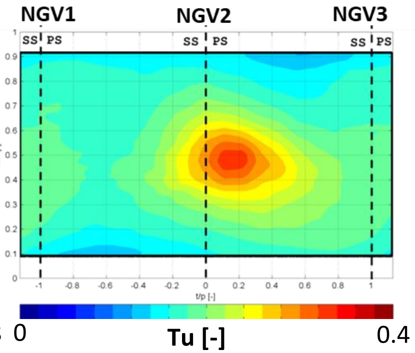

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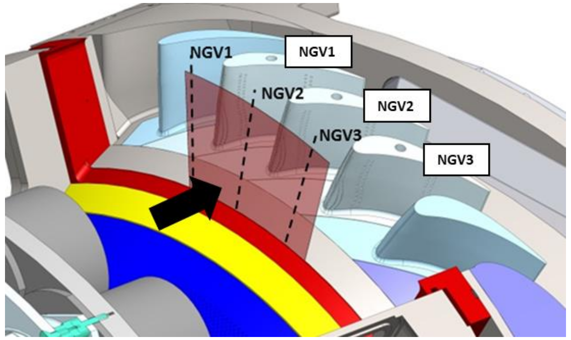
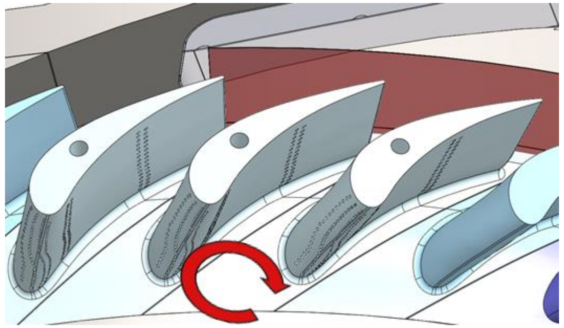
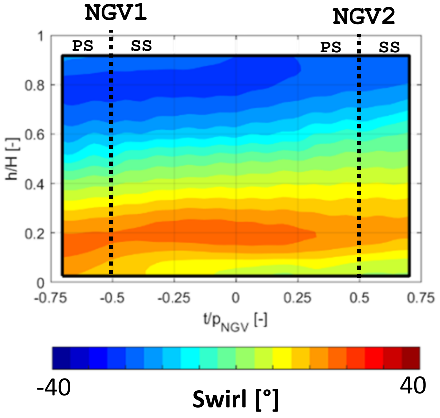




Industrial (land-based) Test Case



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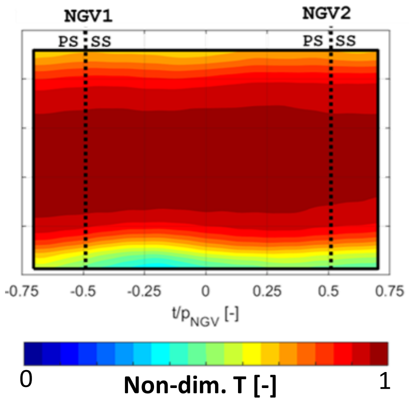

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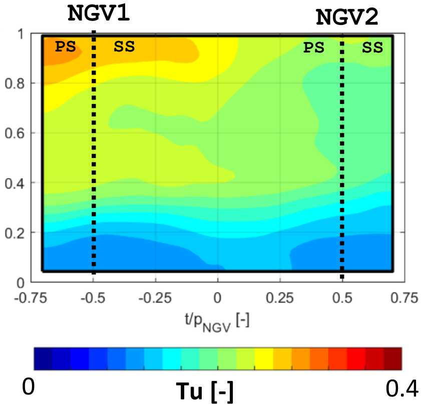

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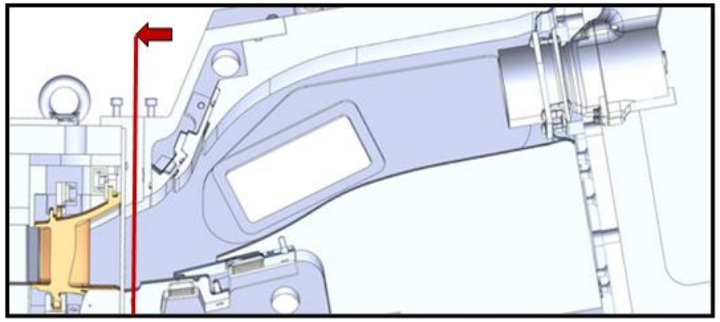
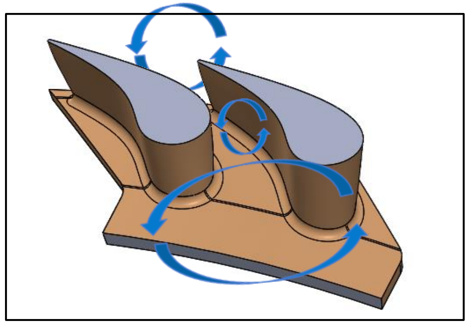




Comb. Exit conditions

Next of the presentation: Focus on newest results on Industrial Test Case

Goal of the investigations

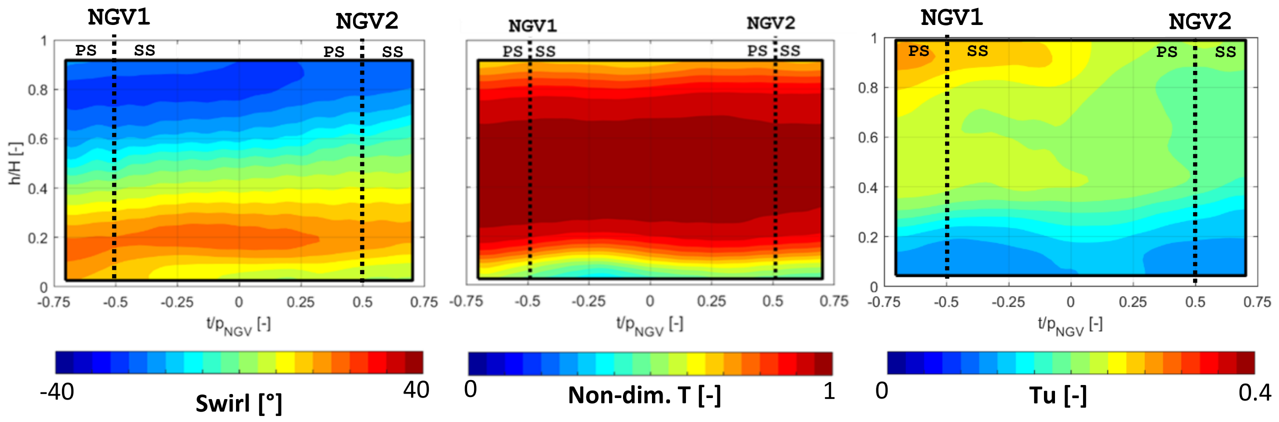
EXP

- Analysis of comb. exit flow features on NGV performance
  - Pressure losses / Secondary flows
  - Hot Streaks migration across NGV
  - **NGV Film coverage**
  - **NGV Heat transfer coefficient**
- Identification of possible design issues

Shown in this presentation

0.4

Industrial (land-based) Test Case



5-hole probe traversing **TC traversing** **HWA traversing**

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  Shown in this presentation
- Identification of possible design issues

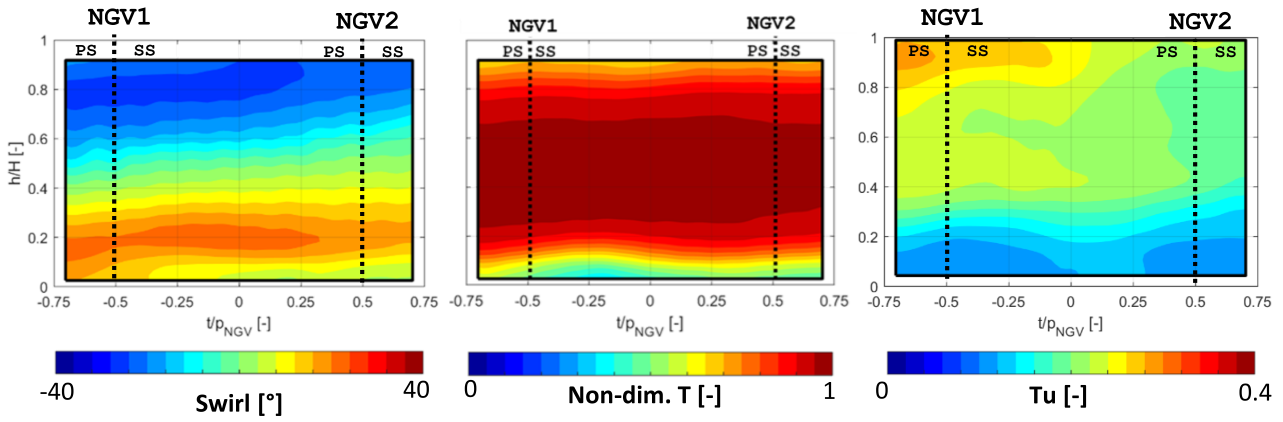
0.4

CFD

- Benchmark of current practice for numerical modelling
- Understand limitations of standard predictive approaches
- Tuning of Hi-Fi CFD codes

Ongoing activity

Industrial (land-based) Test Case



5-hole probe traversing **TC traversing** **HWA traversing**

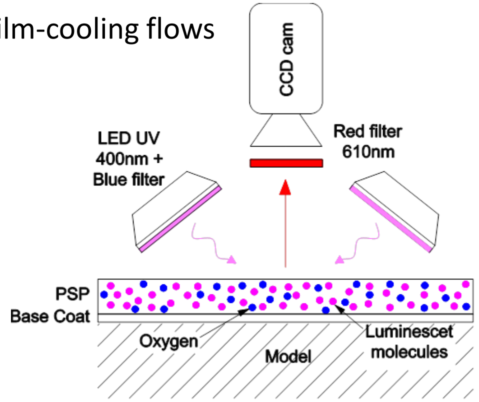
NGV cascade – Adiabatic effectiveness

$$\eta_{ad} = \frac{T_{main} - T_{film}}{T_{main} - T_{cool}}$$

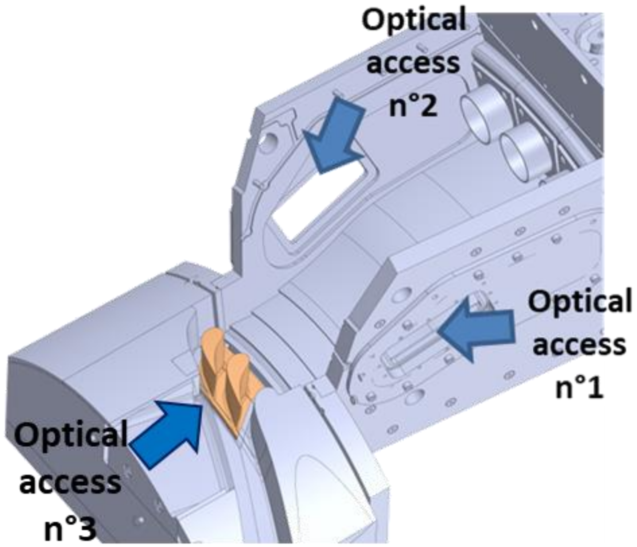
Pressure Sensitive Paint (PSP)

- Fluorescence behaviour
- LED-excited
- Response proportional to O_2 pressure

- **Pressure distribution**
- **Adiabatic Effectiveness**
  - CO_2 for film-cooling flows



Industrial Test Case

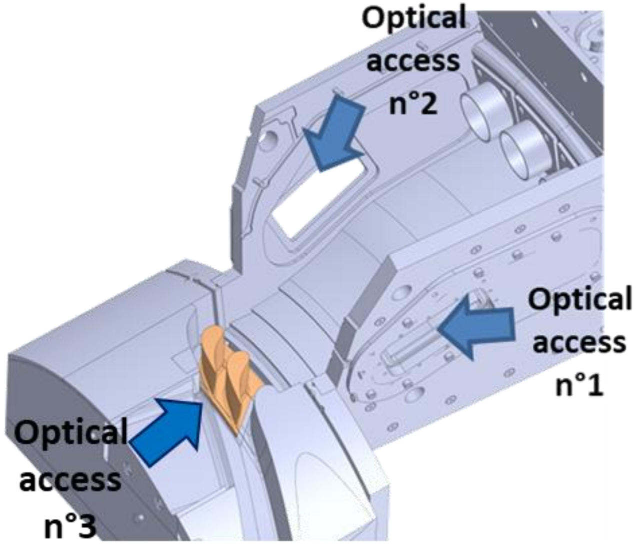


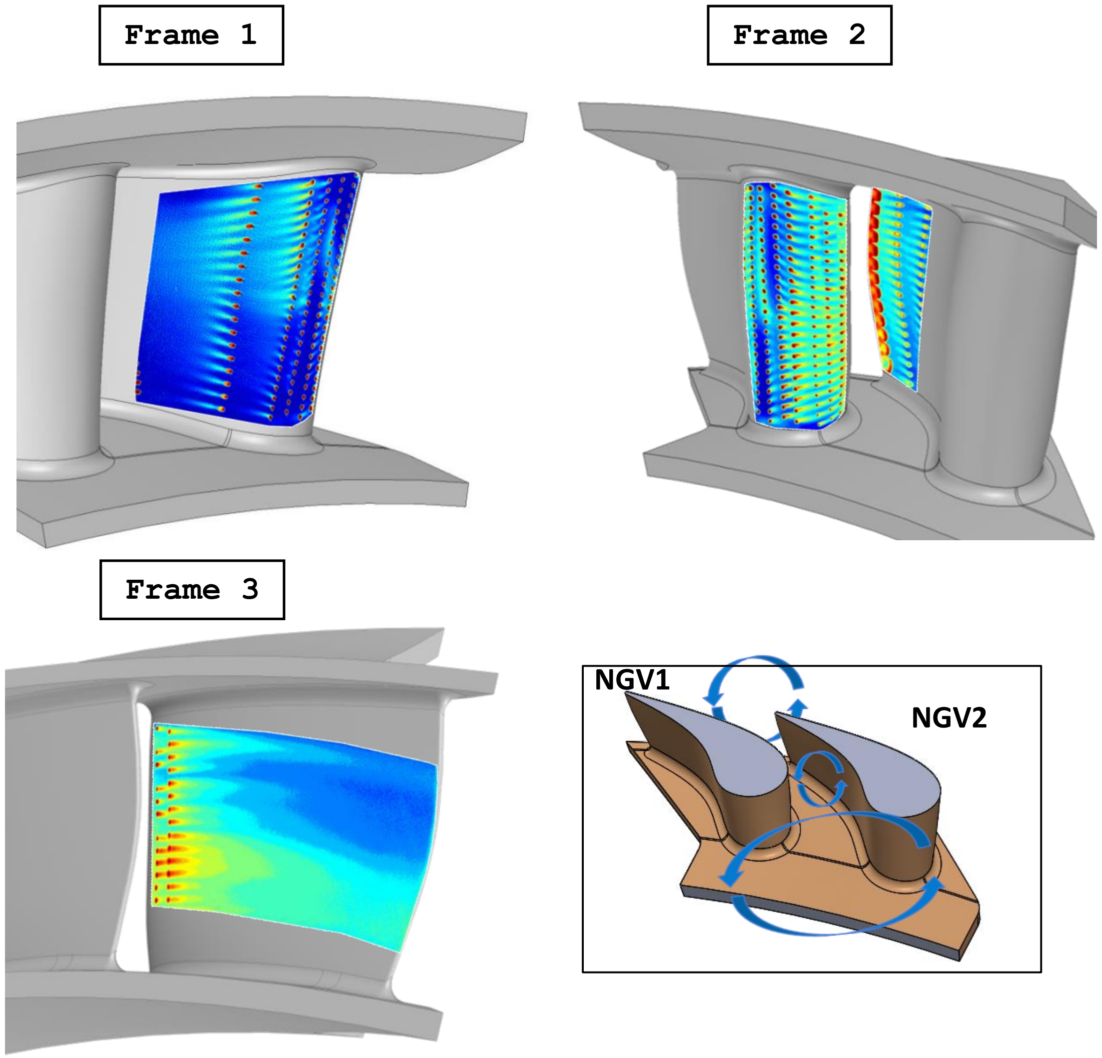
Fast Response PSP
to achieve unsteady behaviour

- f_{acq}=1kHz

NGV cascade – Adiabatic effectiveness

- Investigation through three optical accesses:
  - Map of central passage surfaces
  - **F1: PS of NGV2**
  - **F2: LE of NGV1 + TE/PS of NGV2**
  - **F3: SS of NGV1**
- Effects of inlet swirl on film coverage…

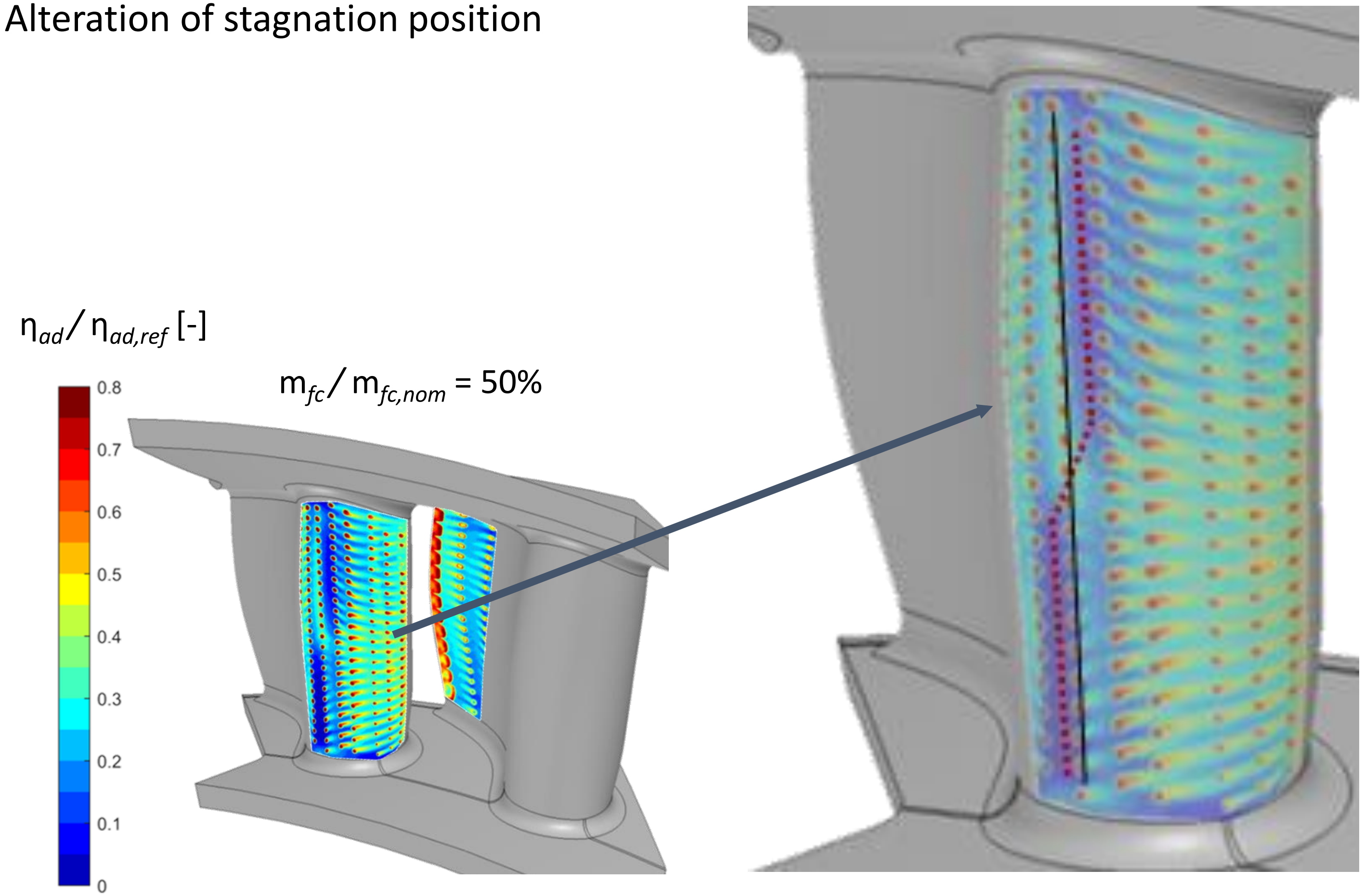


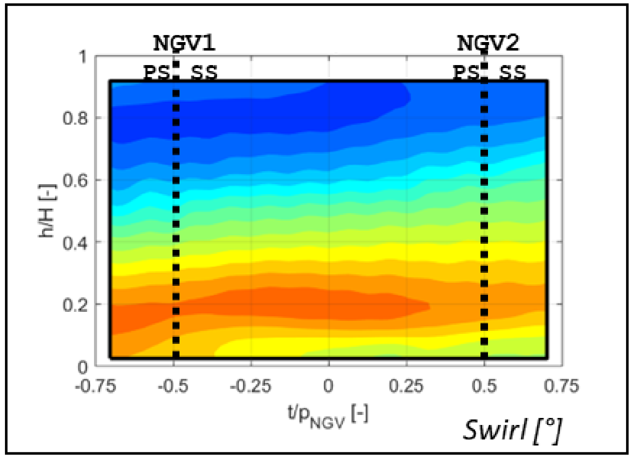


NGV cascade – Adiabatic effectiveness (ind. test case)

Effects of swirl

- Alteration of stagnation position





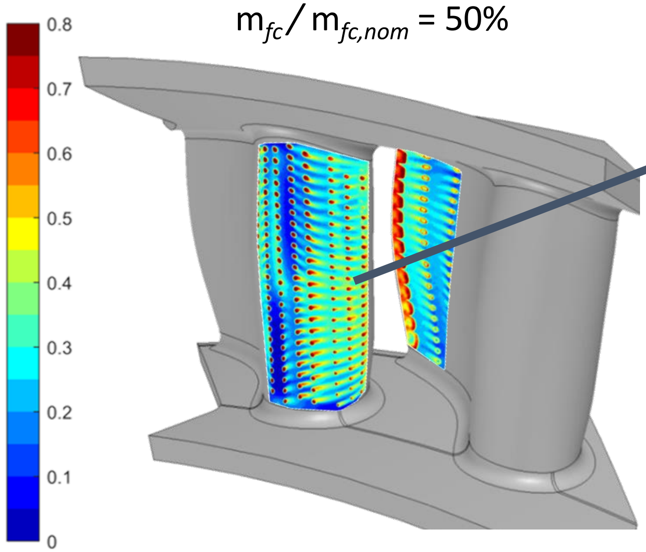
NGV cascade – Adiabatic effectiveness (ind. test case)

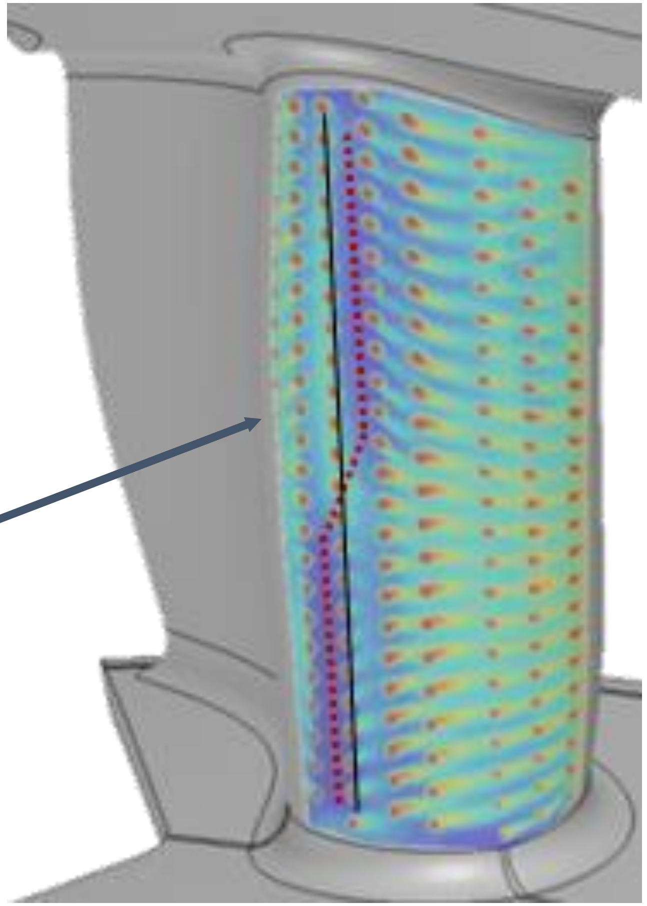
Effects of swirl

- Alteration of stagnation position
- Different coverage between tip/hub areas on PS/SS

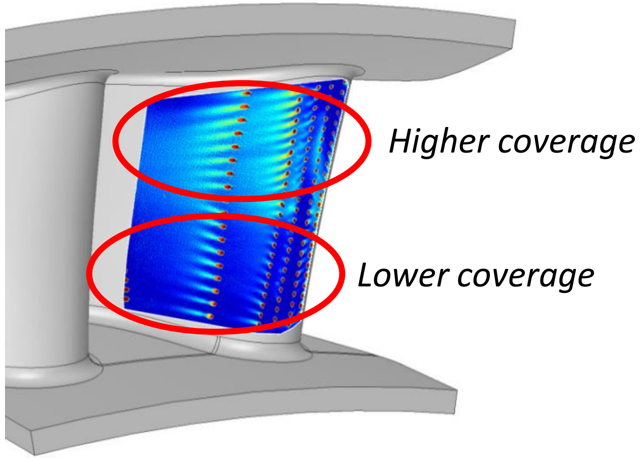
$\eta_{ad} / \eta_{ad,ref}$ [-]

$m_{fc} / m_{fc,nom}$ = 50%

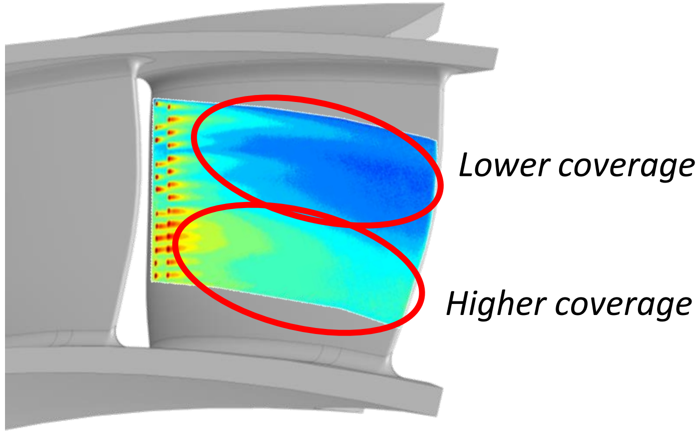




Frame 1



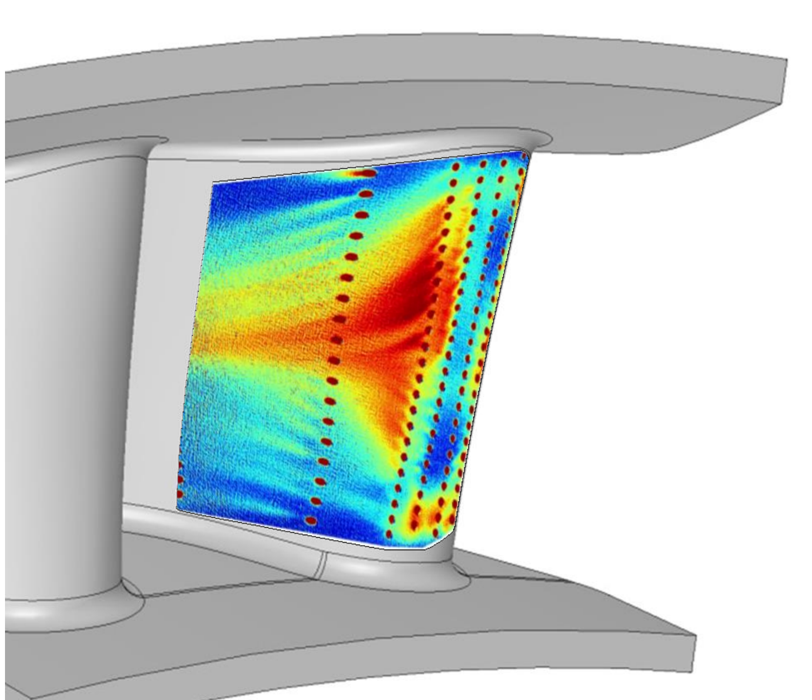
Frame 3



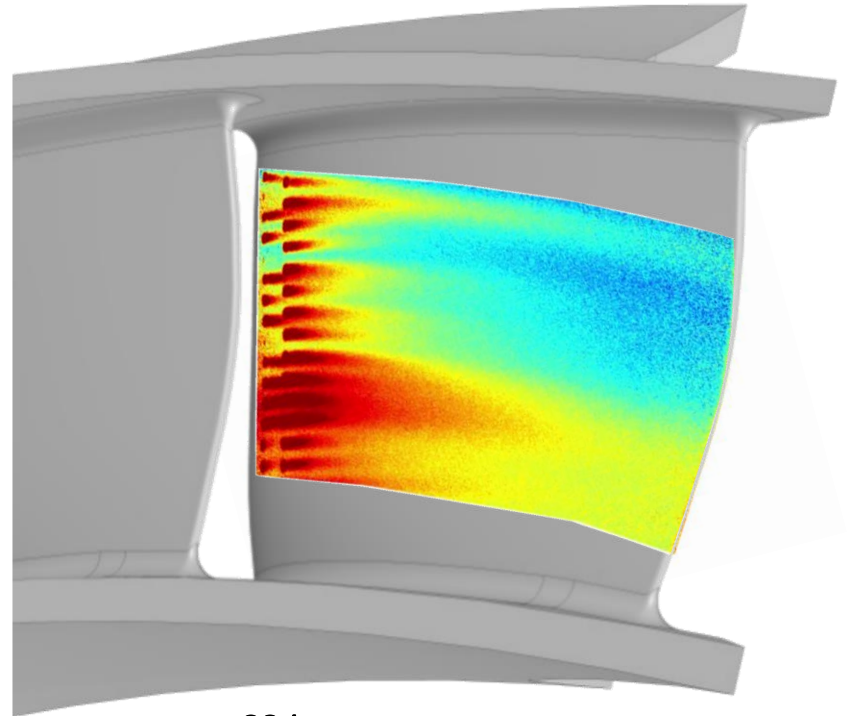
NGV cascade – Adiabatic effectiveness (ind. test case)

Effects of swirl

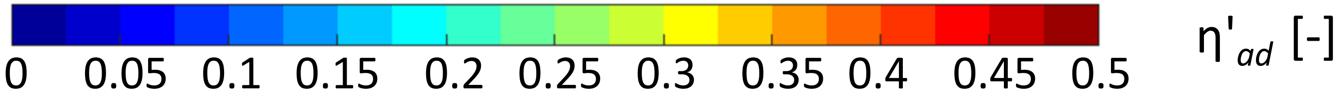
- Alteration of stagnation position
- Different coverage between tip/hub areas on PS/SS
- Unsteady behaviour
- Fluctuation of stagnation spots at LE
  ➔ Fuctuation of swirl position and shape



PS instantaneous coverage

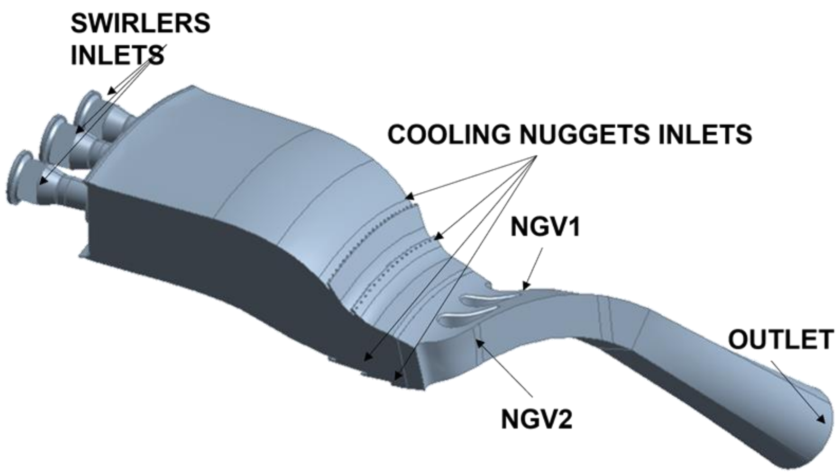


SS instantaneous coverage

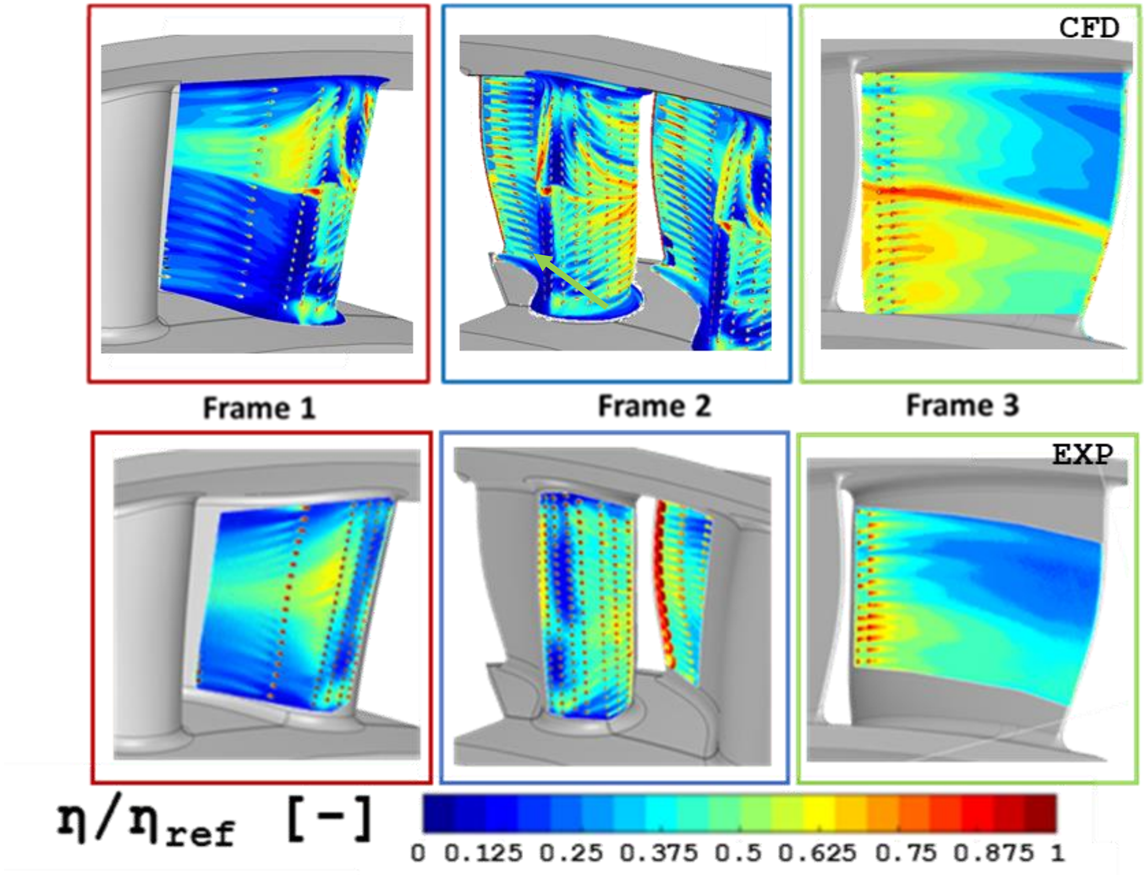


Measurements vs CFD predictions

- **CFD RANS** simulations of integrated combustor-nozzle cascade domain
- Internal cooling system meshed and resolved



CFD trisector domain

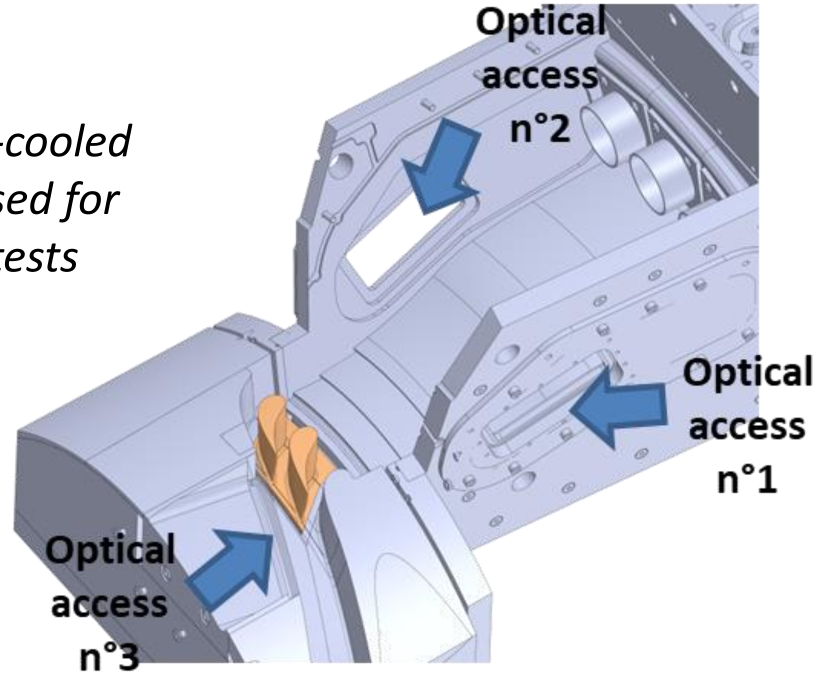


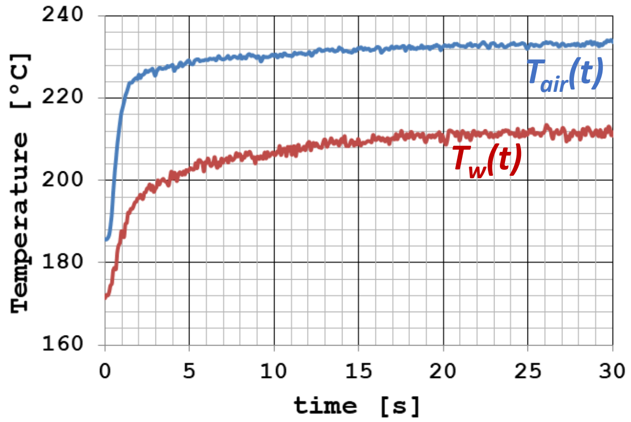
➢**OUTCOME: CFD satisfactorily replicates the coolant alternate spread on higher/lower half of the PS/SS** due to main flow **BUT underestimation of turbulent mixing ➔** wide margin for improvement (such as scale-resolving methods)

NGV cascade – HTC/T_{aw} (ind. test case)

- Test approach
  - Transient test
  - Mesh-heater ➔ Mainstream ΔT≈50-60 K
- Operating conditions
  - Tswirler≈260°C
- Novel data analysis approach for HTC/Taw reconstruction from:
  - IR measurement of NGV temperature evolution Tw(t)
  - Air temperature evolution on **one point** of Plane 40 by fast thermocouple Tair(t)

Peek not-cooled NGV is used for HTC/T_{aw} tests



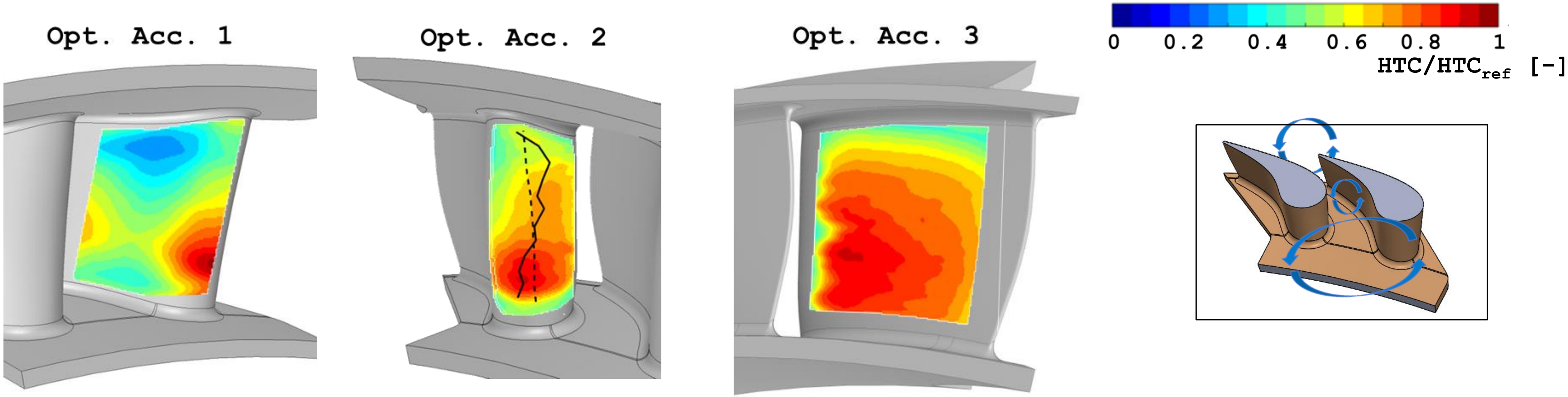


➔ **HTC**
T_{aw}

Post-processing procedure not reported in the presentation. Can be found in:

Bacci, T., Picchi, A., Facchini, B., and Cubeda, S. A new experimental approach for heat transfer coefficient and adiabatic wall temperaturemeasurements on a nozzle guide vane with inlet temperature distortions. ASME J. Turbomach., 144:031007–1, 2022

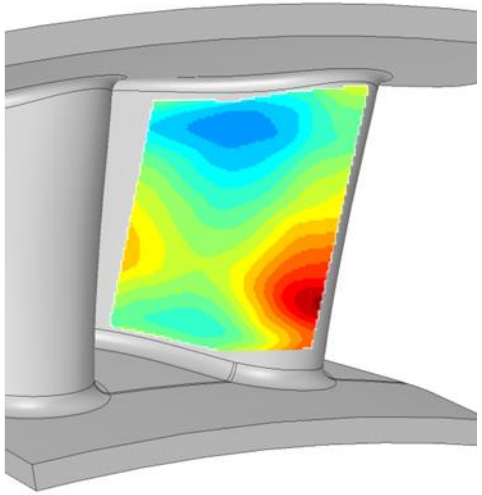
NGV cascade – HTC/T_{aw} (ind. test case)



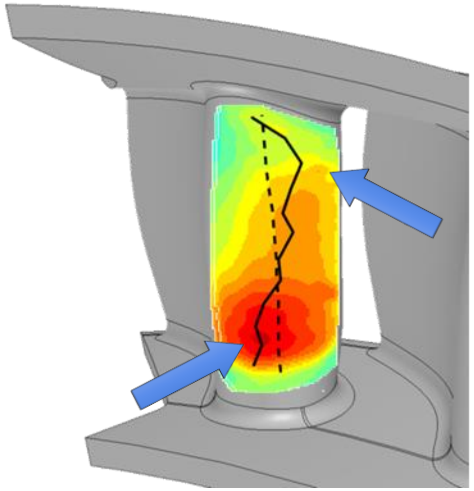
- HTC pattern
  - Streamwise reduction on PS
  - Transition on SS

NGV cascade – HTC/T_{aw} (ind. test case)

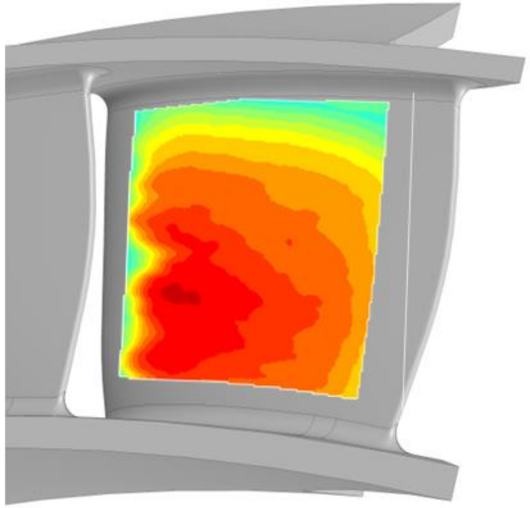
Opt. Acc. 1

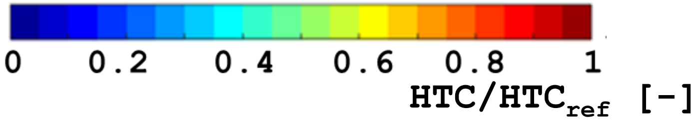


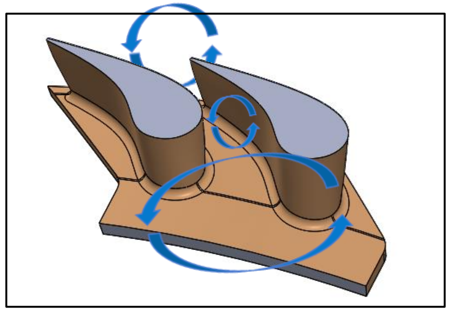
Opt. Acc. 2



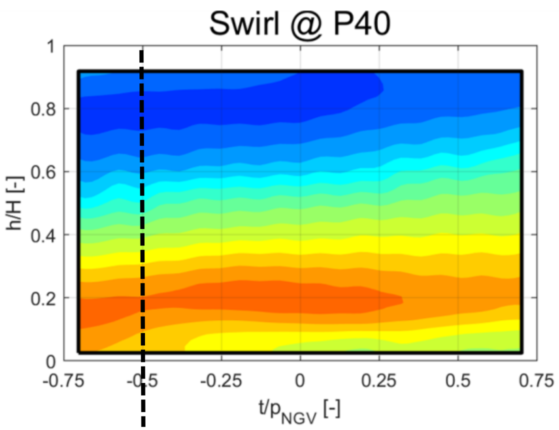
Opt. Acc. 3



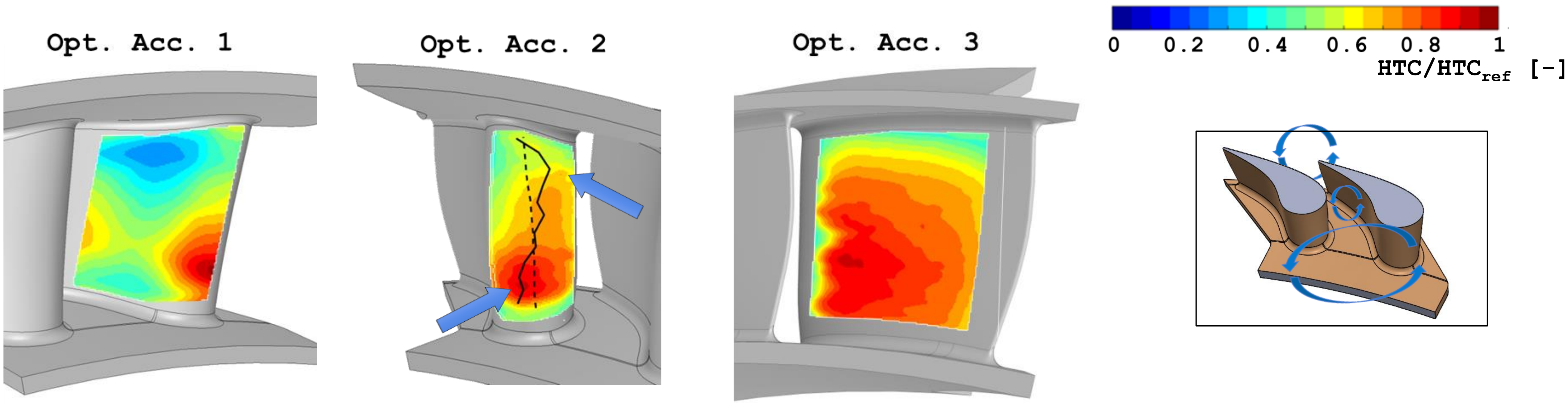




- HTC pattern
  - Streamwise reduction on PS
  - Transition on SS
  - High HTC on LE
    - **Swirl-Induced twisted shape**

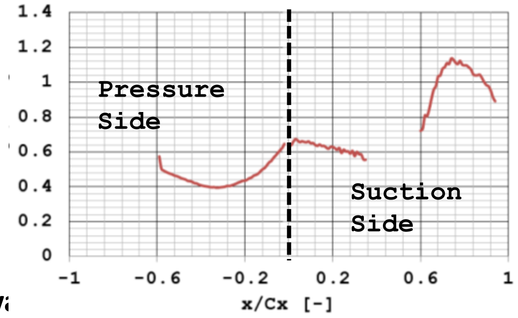


NGV cascade – HTC/T_{aw} (ind. test case)

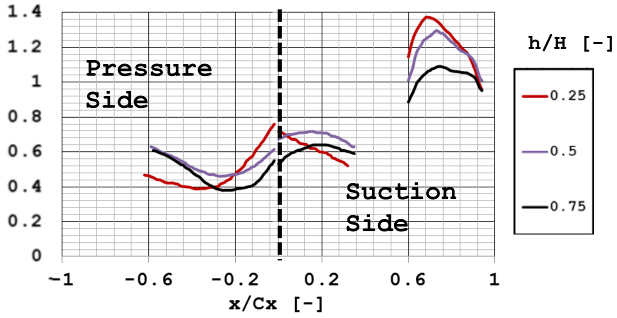


- HTC pattern
  - Streamwise reduction on PS
  - Transition on SS
  - High HTC on LE
    - **Swirl-Induced twisted shape**
    - **3D pattern with hub-to-tip differences (incidence, va load, streamlines divergence/convergence,…)**

1D Span-wise average profile



1D Profiles at different vane height



Measurements vs CFD predictions

- Comparison between experimental data and numerical predictions of HTC (**not-cooled NGV**):

HTC calculated by using **two-point method:**

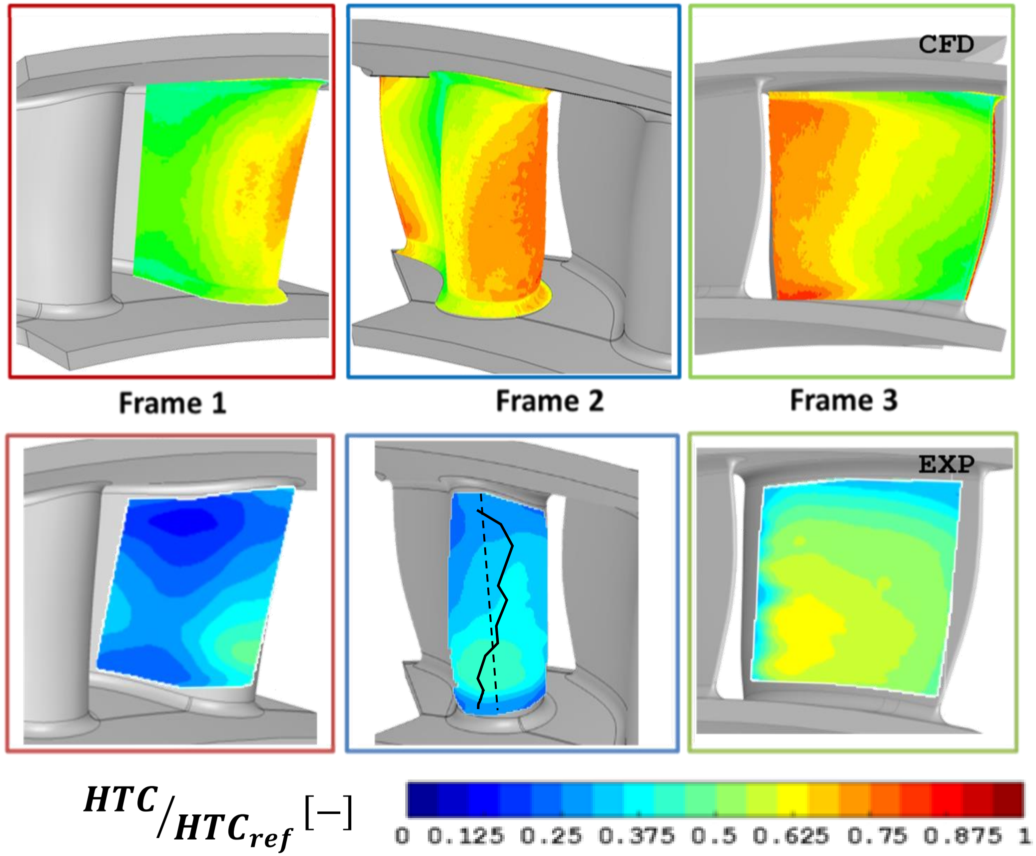
- **First simulation**: adiabatic (adiabatic wall temperature T_{aw} is retrieved)
- **Second simulation**: specified wall temperature T_w is imposed, equal to T_{aw} detracted by arbitrary ΔT which determines a wall heat flux q_w:

$$HTC = \frac{q_w}{T_{aw} - T_w} = \frac{q_w}{\Delta T}$$

$$HTC_{adim} = \frac{HTC}{HTC_{ref}}$$

Max HTC value at airfoil nose

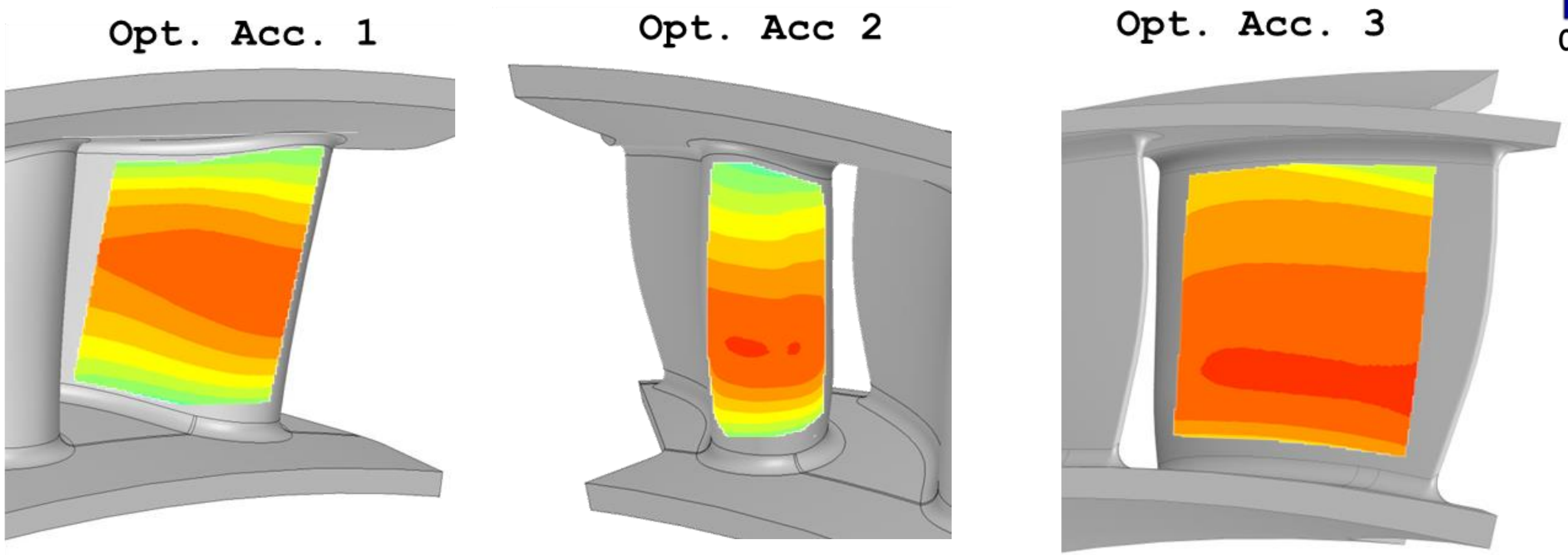
Higher HTC_{ref} than in previous slide due to higher CFD values

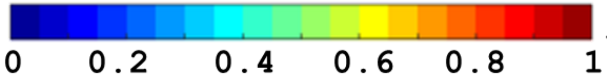


➢ **OUTCOME: HTC values are significantly overpredicted**

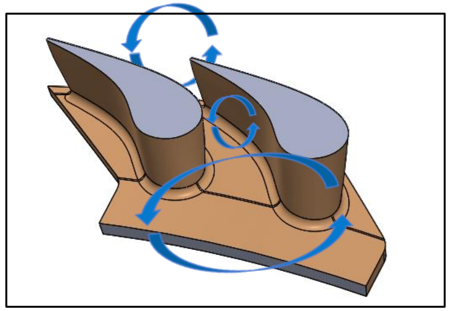
➔ **More advanced CFD methods must be considered**

NGV cascade – HTC/T_{aw} (ind. test case)

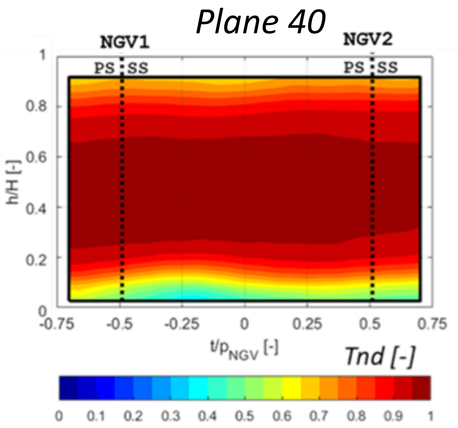




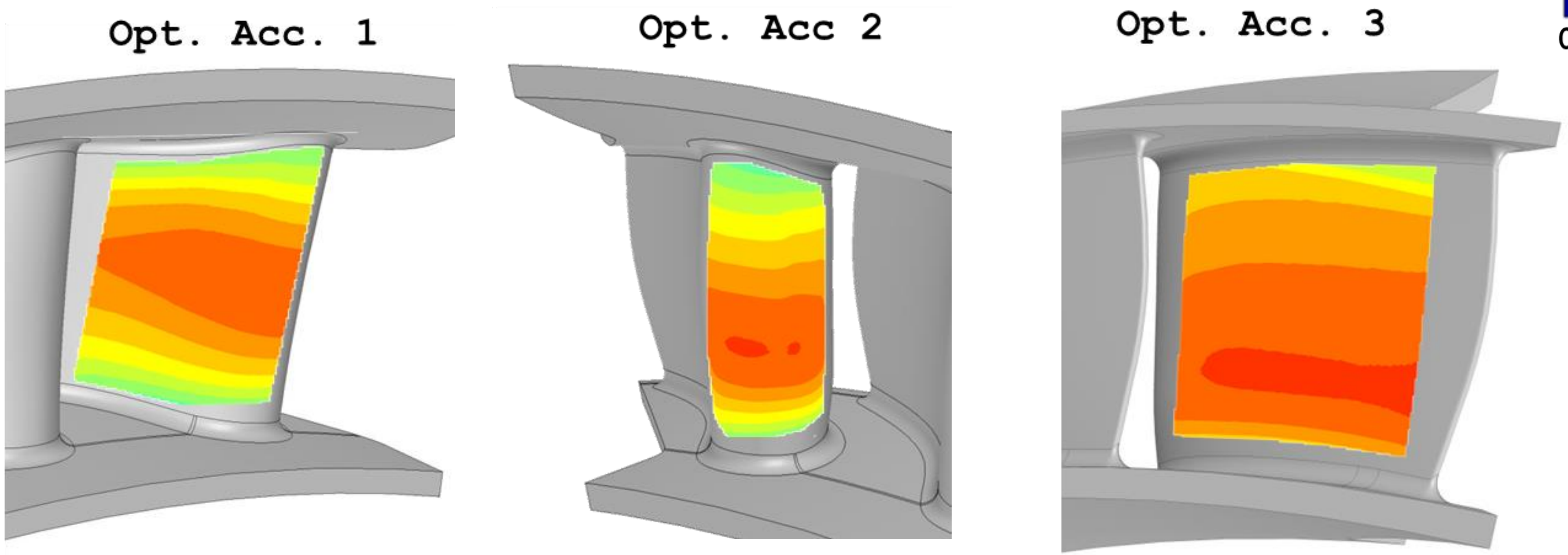
$$Taw_{nd} = \frac{T_{aw} - T_{nuggets}}{T_{swirler} - T_{nuggets}} \quad [-]$$

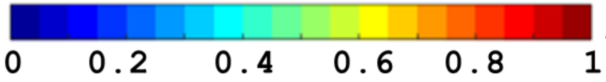


- Taw pattern
  - 2D pattern (Plane 40 distribution)



NGV cascade – HTC/T_{aw} (ind. test case)





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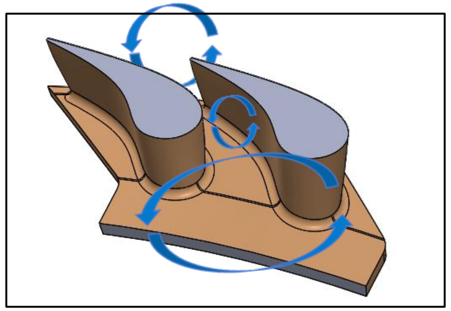
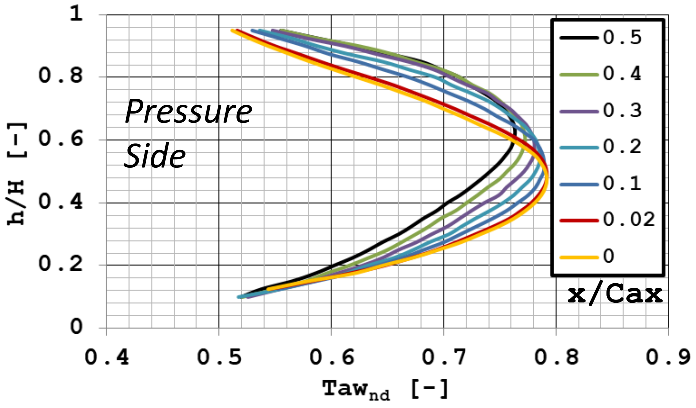
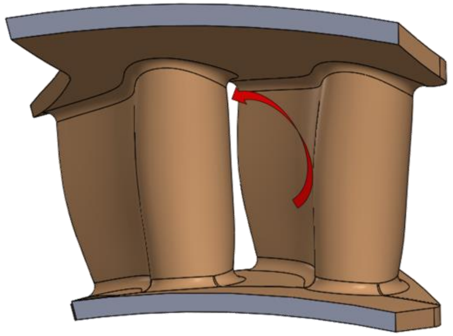


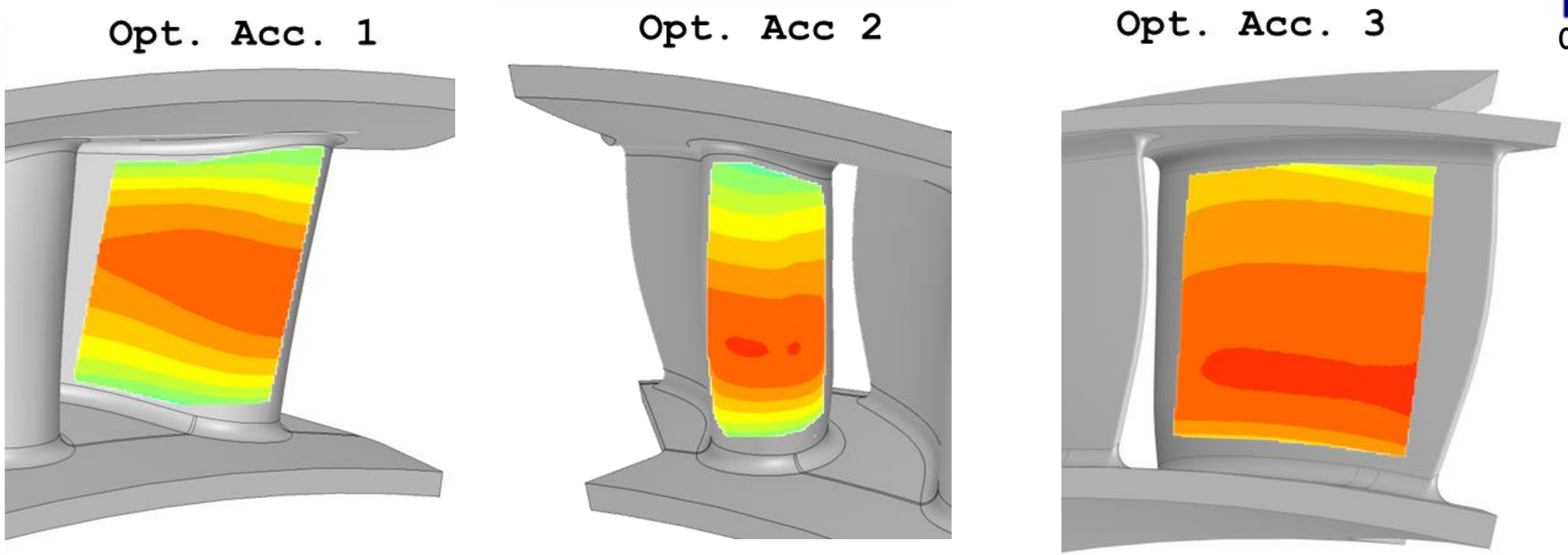
- Taw pattern
  - 2D pattern (Plane 40 distribution)
  - T reduction on PS
    - Hot spot moved towards tip (swirl)

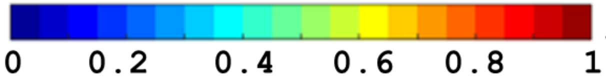
1D Radial Profiles at different axial positions





NGV cascade – HTC/T_{aw} (ind. test case)





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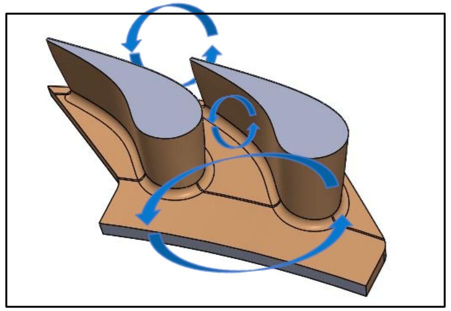
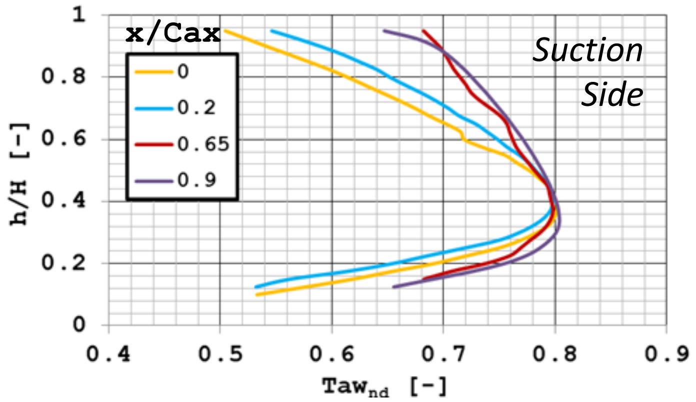
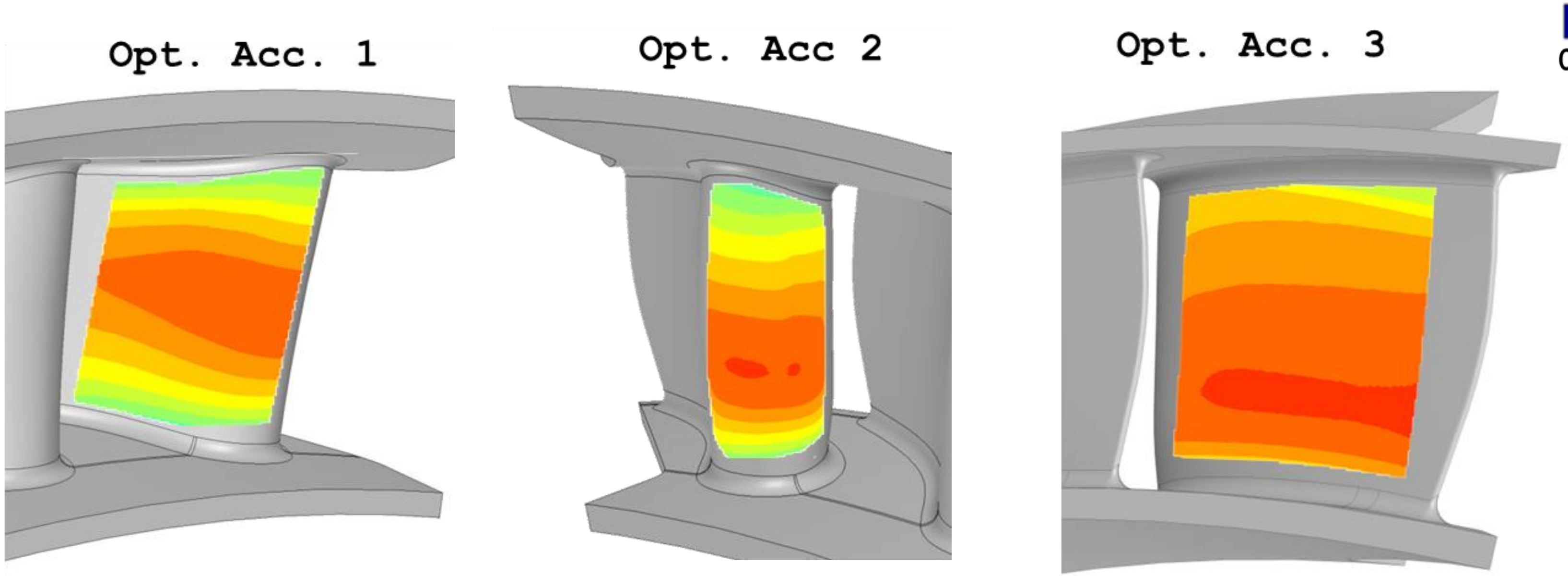


- Taw pattern
  - 2D pattern (Plane 40 distribution)
  - T reduction on PS
    - Hot spot moved towards tip (swirl)
  - Limited T reduction on SS
    - Limited displacement towards hub
    - Higher flow momentum

1D Radial Profiles at different axial positions



NGV cascade – HTC/T_{aw} (ind. test case)



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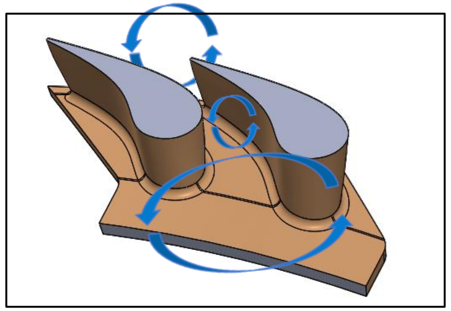

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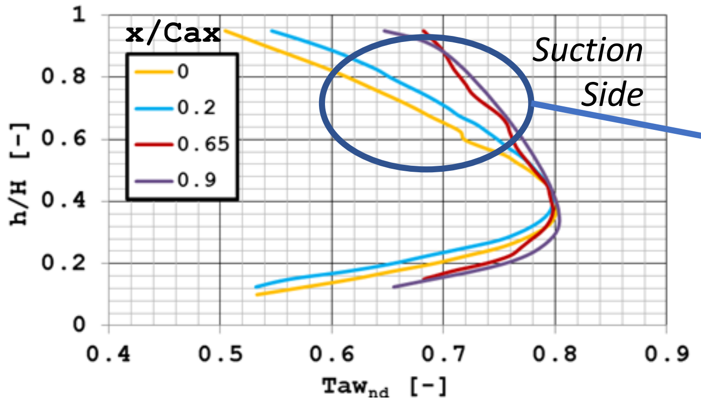
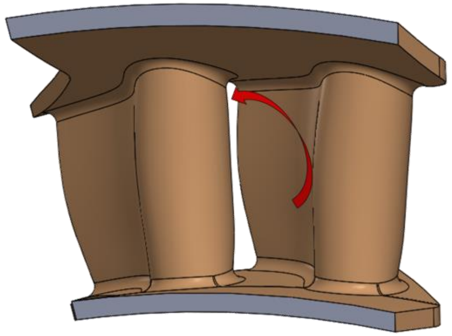
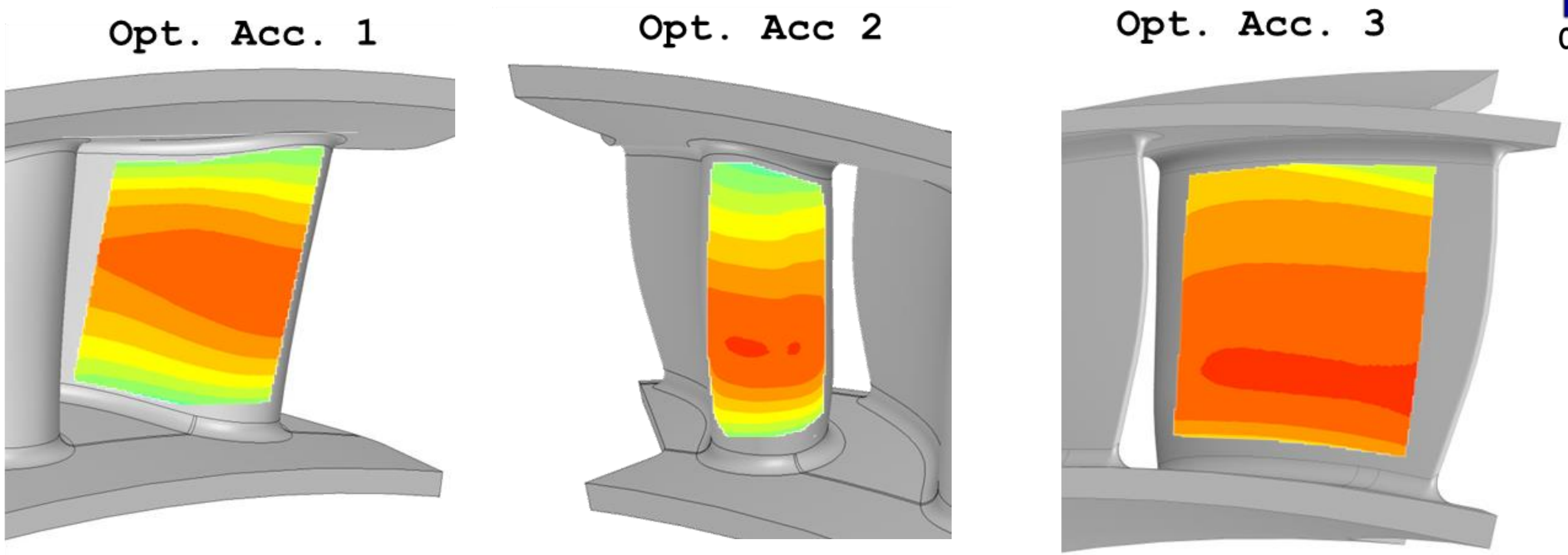
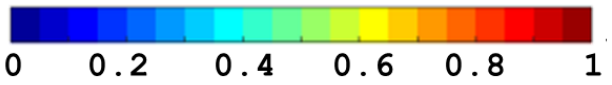


T increase in tip area of SS due to hot PS flow carried over by swirling flow



NGV cascade – HTC/T_{aw} (ind. test case)





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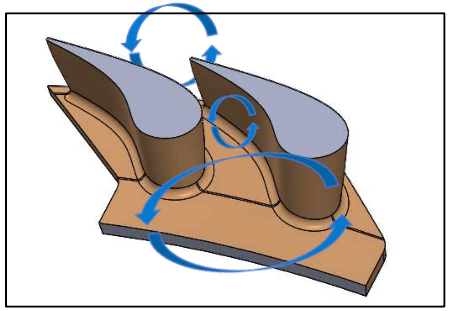

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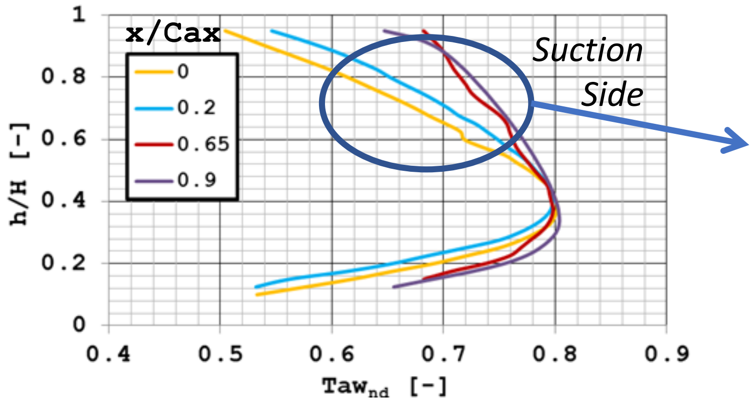
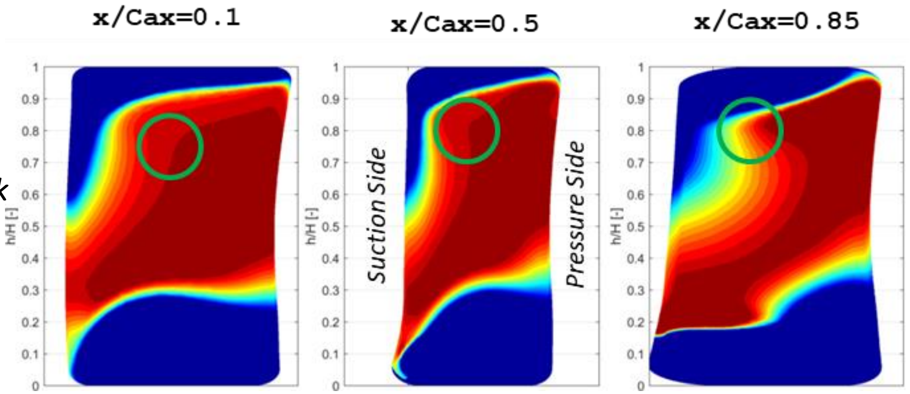


Hot streak tracking through central passage

Confirmed by preliminary CFD

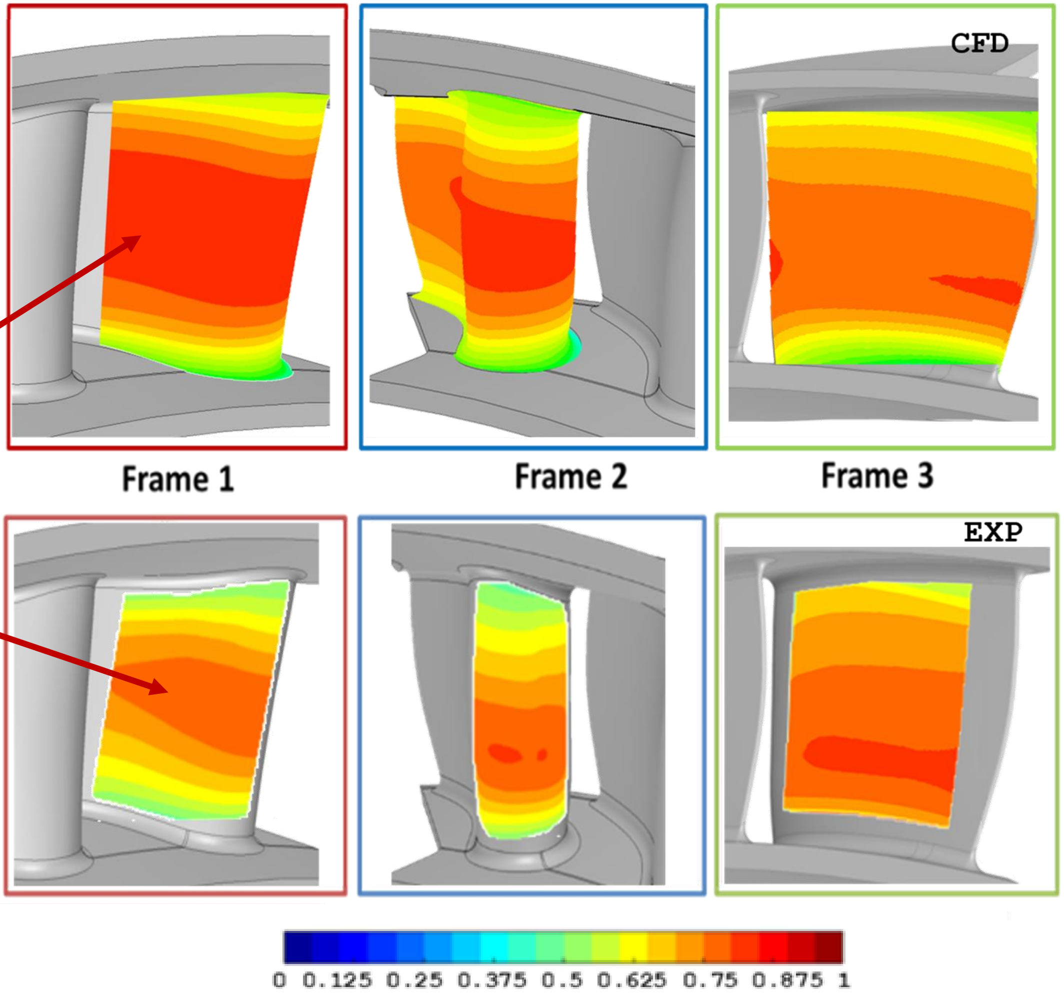


Measurements vs CFD predictions

- Comparison between experimental data and numerical predictions of T_{aw} (**not-cooled NGV**)

Taw calculated from the simulation with imposed adiabatic wall

$$T_{aw,nd} = \frac{T_{aw} - T_{nuggets}}{T_{swirler} - T_{nuggets}}$$



Different MAX values
- **Underprediction of turbulent mixing**
- **Heat losses across combustion chamber in test rig**

➢ **OUTCOME: Acceptable comparison in terms of measured pattern**

Combustor Turbine Interactions – Experimental Investigation
Conclusions & Perspectives

Goal of the investigations

- Analysis of comb. exit flow features on NGV performance
  - **NGV Film coverage**
  - **NGV Heat transfer coefficient**

→ **Areas with poor film coverage**

→ **Highly 3D HTC-Taw pattern**

Combustor Turbine Interactions – Experimental Investigation
Conclusions & Perspectives

Goal of the investigations

- Analysis of comb. exit flow features on NGV performance
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  - **NGV Heat transfer coefficient**

Areas with poor film coverage

Highly 3D HTC-Taw pattern

- Identification of possible design issues

Design challenge for both stator and rotor cascade

Combustor Turbine Interactions – Experimental Investigation Conclusions & Perspectives

Goal of the investigations

- Analysis of comb. exit flow features on NGV performance
  - **NGV Film coverage**
  - **NGV Heat transfer coefficient**

→ **Areas with poor film coverage**

Highly 3D HTC-Taw pattern

↓

Design challenge for both stator and rotor cascade ⚠

- Identification of possible design issues
- **CFD benchmark: ongoing**
  - RANS approach fails to accurately predict mixing and heat loads

Reference

- Koupper, C., Caciolli, G., Gicquel, L., Duchaine, F., Bonneau, G., Tarchi, L., and Facchini, B., 2014. “Development of an Engine Representative Combustor Simulator Dedicated to Hot Streak Generation”. Journal of Turbomachinery, 136(11), Aug., pp. 111007–111007–10.

- Bacci, T., Lenzi, T., Picchi, A., Mazzei, L., and Facchini, B. Flow field and hot streak migration through a high pressure cooled vanes with representative lean burn combustor outflow. ASME J Eng Gas Turb Power, 141:041020–1, 2019.

- Bacci T, Picchi A, Lenzi T, Facchini B. Turbulence intensity measurements across a NGV cooled cascade with representative Lean Burn combustor outflow. Proceedings of 13th European Conference on Turbomachinery Fluid Dynamics & Thermodynamics, ETC2019-100

- Koupper, C., Gicquel, L., Duchaine, F., Bacci, T., Facchini, B., Picchi, A., Tarchi, L., and Bonneau, G., 2015. “Experimental and Numerical Calculation of Turbulent Timescales at the Exit of an Engine Representative Combustor Simulator”. Journal of Engineering for Gas Turbines and Power, 138(2), Sept., pp. 021503–021503–10.

- Bacci, T., Becchi, R., Picchi, A., and Facchini, B. Adiabatic effectiveness on high-pressure turbine nozzle guide vanes under realistic swirling conditions. ASME J. Turbomach., 141:011008–1, 2019.

- Bacci, T., Picchi, A., Facchini, B., and Cubeda, S. A new experimental approach for heat transfer coefficient and adiabatic wall temperaturemeasurements on a nozzle guide vane with inlet temperature distortions. ASME J. Turbomach., 144:031007–1, 2022.

- Babazzi, G., Bacci, T., Picchi, A., Fondelli, T., Lenzi, T., Facchini, B., and Cubeda, S., 2022. “Development and Application of a Concentration Probe for Mixing Flows Tracking in Turbomachinery Applications”. Journal of Turbomachinery, 144(3)

- Babazzi, G., Bacci, T., Picchi, A., Facchini, B., Cubeda, S. Film cooling and cold streaks tracking on a fully cooled nozzle guide vane under representative combustor outflow conditions, (GT2022-81360), 2022.

- Bacci, T., Picchi, A., Babazzi, G., Facchini, B., and Cubeda, S. Heat transfer coefficient and adiabatic wall temperature measurements on a high-pressure turbine nozzle guide vanes with representative inlet swirl and temperature distortions. ASME J. Turbomach, TURBO-22-1165, 2022.

- Tomasello, S.G., Bacci, T., Andreini, A., Facchini, B., Cubeda, S., Andrei, L. Numerical prediction of heat transfer coefficient and adiabatic effectiveness on a nozzle guide vane with representative combustor outflow, (GT2022-82128), 2022.

Combustor-Turbine Interactions

Experimental Investigation

Effects of representative lean burn combustor outflow on flow field and film effectiveness through HP cooled vanes

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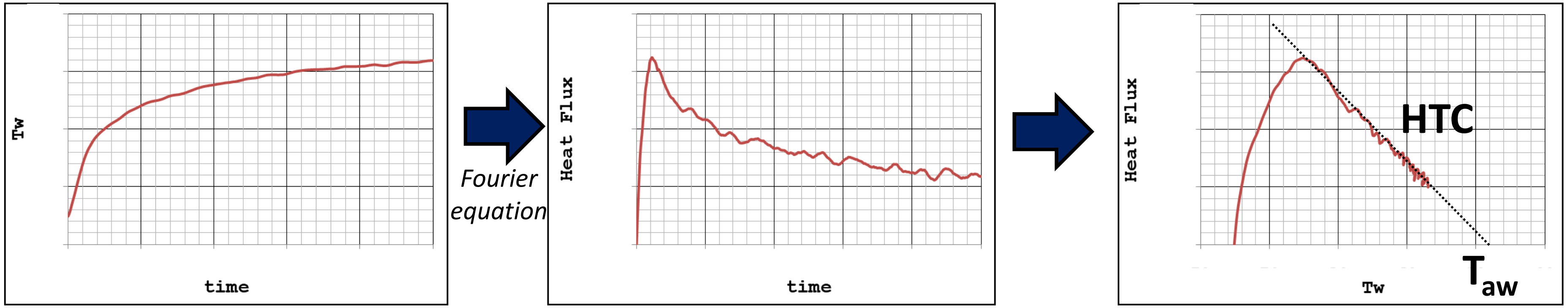
Back-up slides

HTC/Taw post-processing

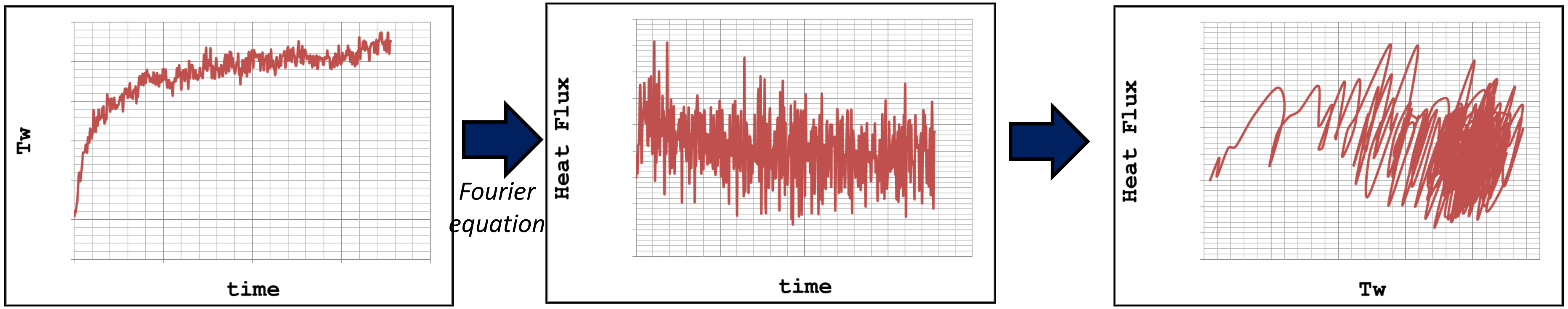
HTC Post-Processing procedure

- Conventional approach (linear regression)

$$\dot{q} = HTC.(T_{aw} - T_w)$$



- T-distortions inflow (comb-turbine interaction studies)

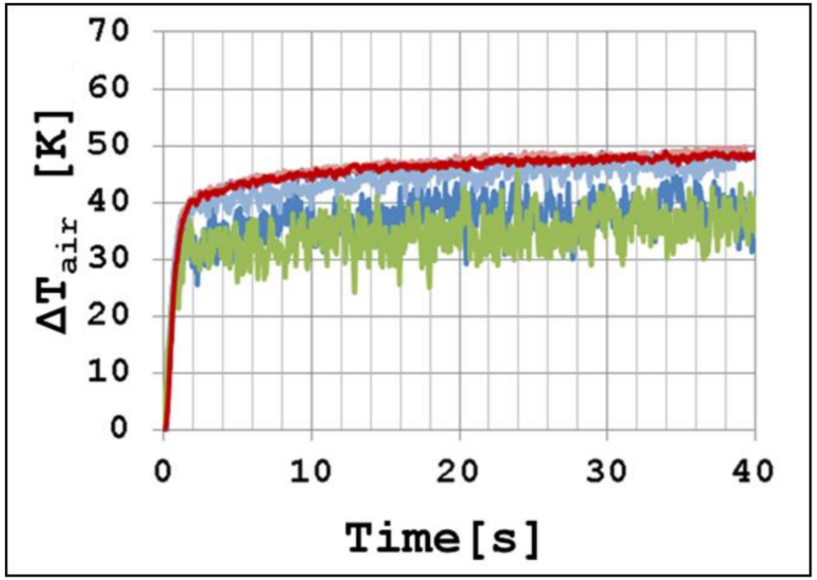


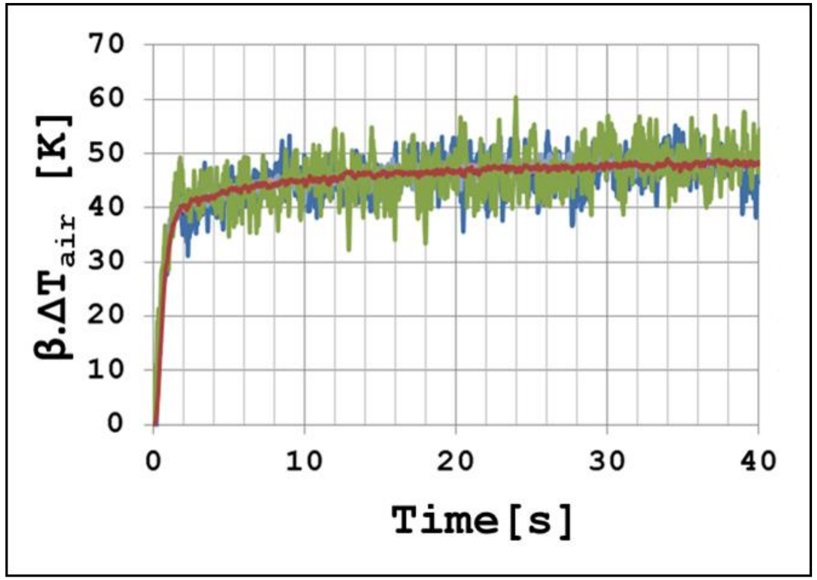
Not possible to retrieve HTC-Taw through conventional approach

HTC Post-Processing procedure

- Developed approach

1. Verification that air temperature evolution in different annulus locations is «similar» ➔ can be scaled with constant value





Results from different acquisition on Plane 40 (i.e. different mesh heater activations with TC moved in different positions)

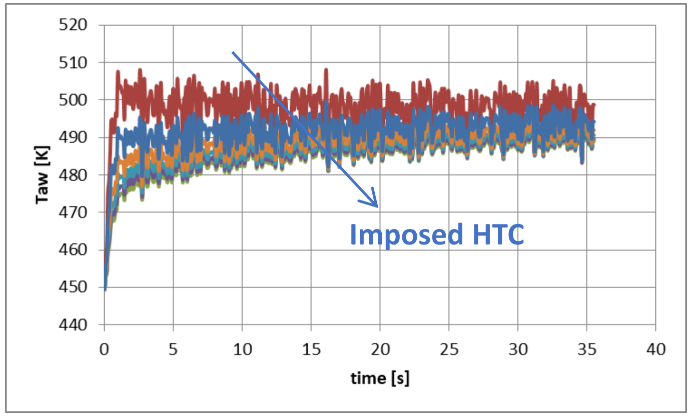
➔ Same can be said for Taw evolution on the NGV (constant aero-conditions and rec. factor)

HTC Post-Processing procedure

- Developed approach

2. Measurement of $T_w(t)$ and calculation of $T_{aw}(t)$ from analytical relation imposing different HTC values

$$T_w(tN) - T_w(t_0) = \sum_{j=1}^{N} \left[1 - exp\left(\frac{HTC^2 \alpha(t_N - \tau_j)}{k^2}\right) erfc\left(\frac{HTC\sqrt{\alpha(t_N - \tau_j)}}{k}\right)\right] (T_{aw_j} - T_{aw_{j\_1}})$$



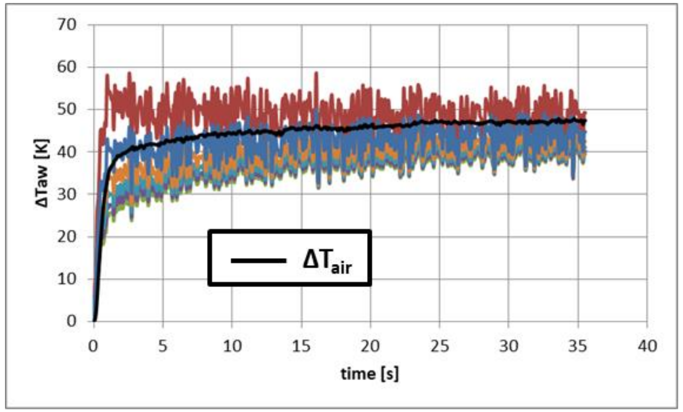
➔ The higher is the imposed HTC, the more increasing is the calculated Taw trend

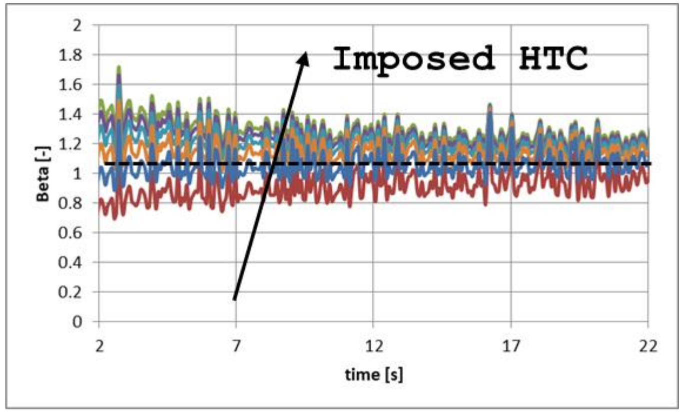
HTC Post-Processing procedure

- Developed approach

3. Comparison between $T_{air}(t)$ measured on Plane 40 and calculated $T_{aw}(t)$ trends

$$\Delta T_{aw}(t)/\Delta T_{air}(t) = Cost = \beta$$





Post-process interval

Expected uncertainty ≈ ***12%*** *(evaluated from numerical experiments)*

CHECK: angular coefficient (m) closest to zero

MEASURED HTC: imposed HTC for minimum |m|

MEASURED Taw: Calculated Taw (mean on post-process interval)