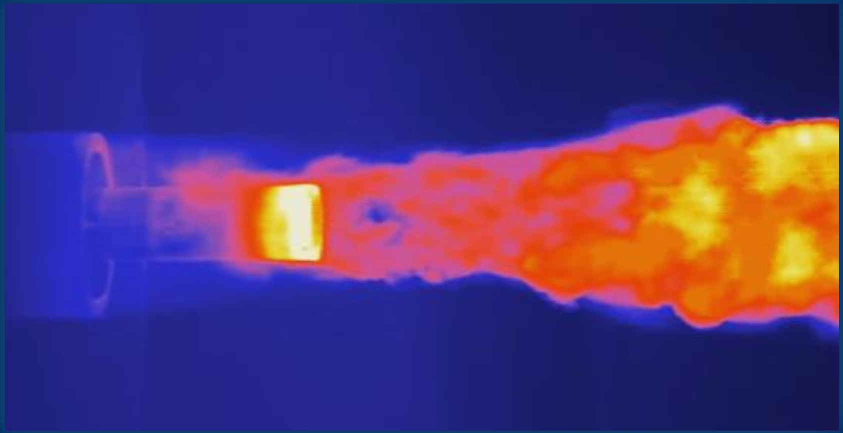
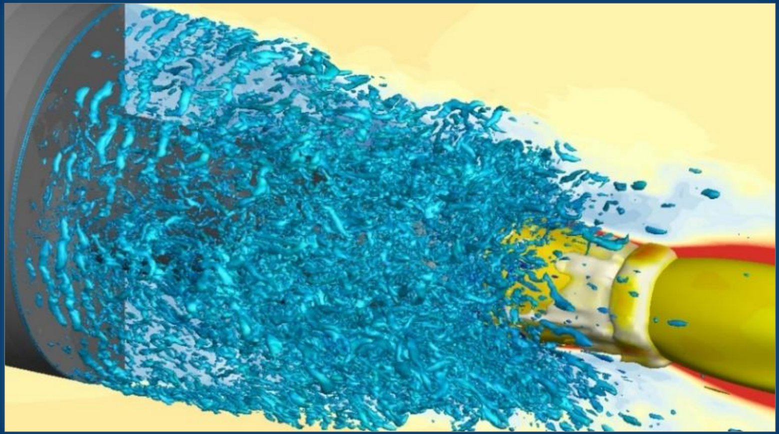


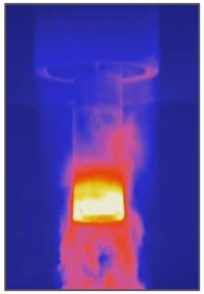


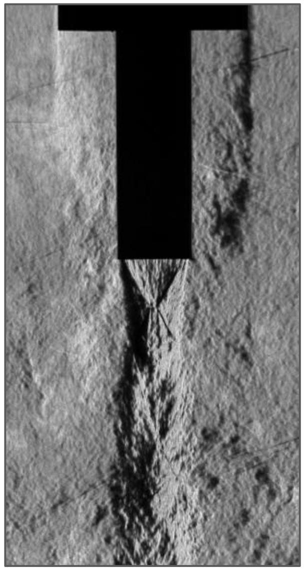
Hot Plume Impact on Rocket Base Flows

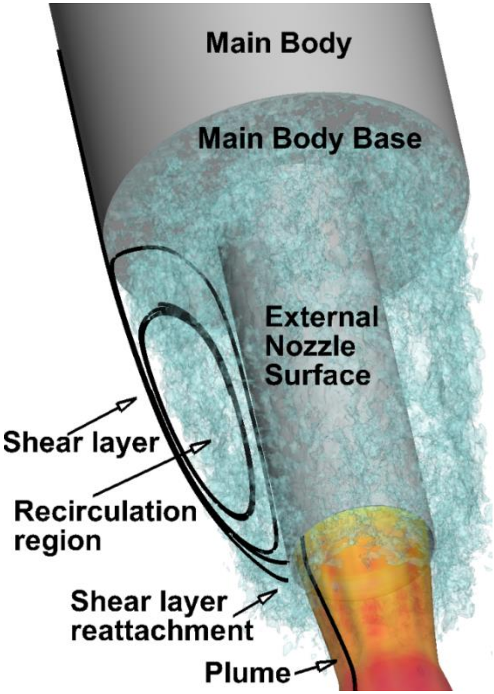
D. Kirchheck, D. Saile, A. Gülhan, AS-HYP, DLR Köln
J.-E. Schumann, V. Hannemann, K. Hannemann, AS-RFZ, DLR Göttingen
M. Fertig, T. Eggers, AS-RFZ, DLR Braunschweig

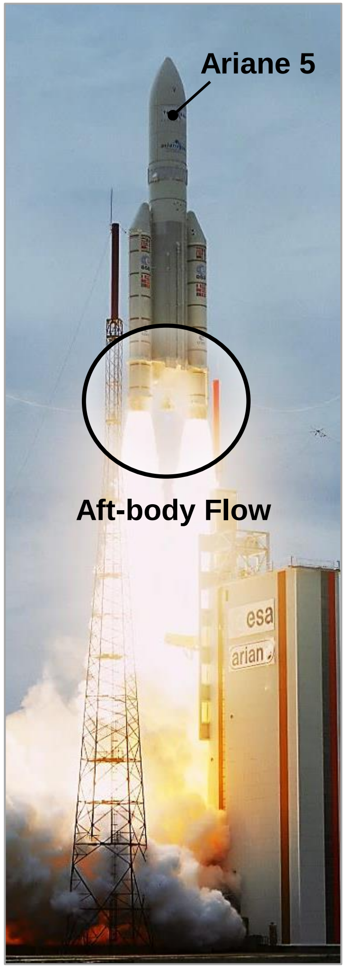
Introduction

- **Aft-body flows** of generic space transportation system geometries in transonic flight
- Highly **unsteady flow-fields**, dominated by recirculation regions and flow-flow interaction
- Unsteady loads due to **buffet**
- Convective **heating**









[1]

[1] ESA/CNES/Arianespace: Optique vidéo du CSG, 2009.
Published: 07.03.2009, ID: 238930

Introduction

GOALS

1. Investigate the impact of hot plumes on rocket base flows
2. Validate CFD and experimental methods and maximize information output on a challenging flow problem

METHODS

- Compare reference cases using cold and hot exhaust plumes
- Apply and compare WTT & CFD and make use of their specific advantages

+ WTT

- Additional parameter studies
  - Ma_∞, L/D, …

+ CFD

- Additional parameter studies
  - T_w, OFR, …

Investigate impact on wake flow dynamics and mechanical/thermal loads from different perspectives

Content

- Introduction
- **Tools & Methods**
  - Experiments
  - Numerics
- Results
  - Cold Plume Test Case
  - Hot Plume Test Case
- Conclusion & Outlook

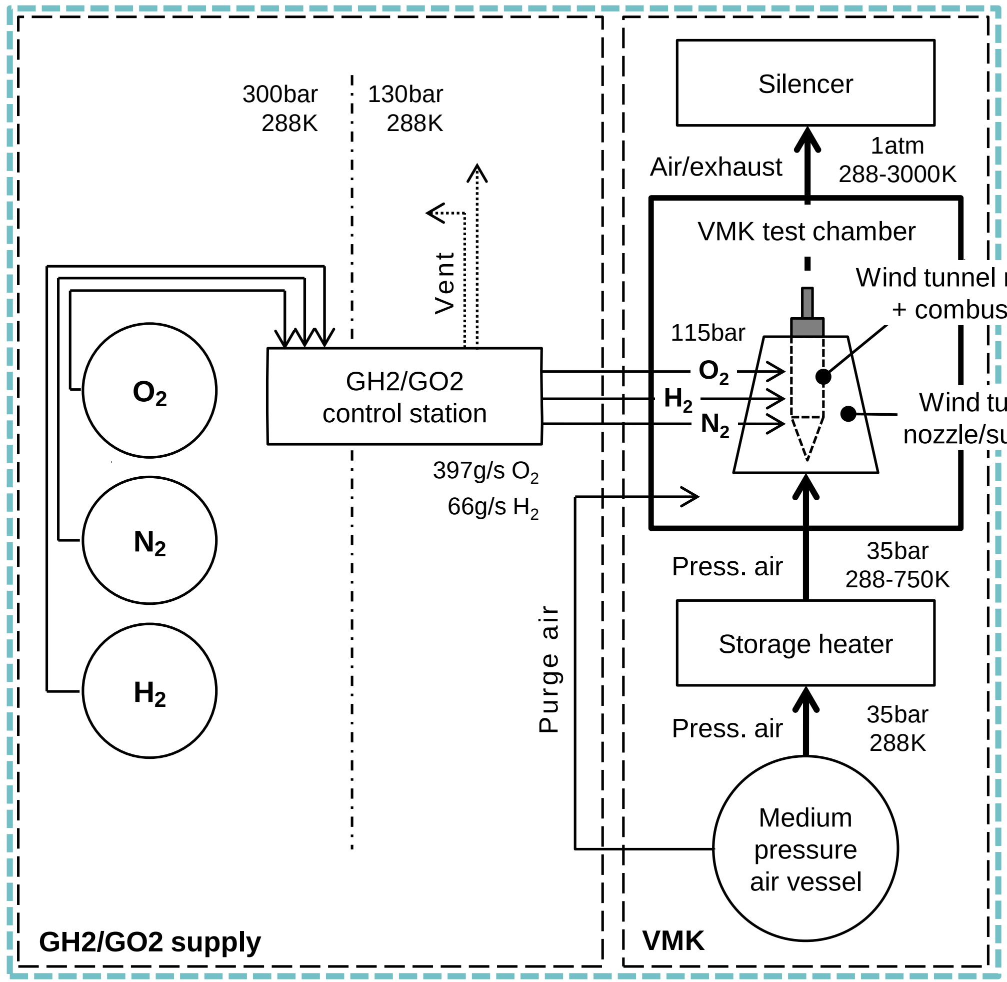
Tools & Methods

EXPERIMENTS

Hot Plume Testing Facility (HPTF)

- Wind Tunnel
  - Vertical Test Section Cologne (VMK)
- GH2/GO2 Supply Facility
  - Gas reservoir
  - Control station
  - Supply lines
- Test Specimen
  - Wind tunnel model incl. combustion chamber

> ➢ First design loop in 2014 [2]
> ➢ Operation since 2017

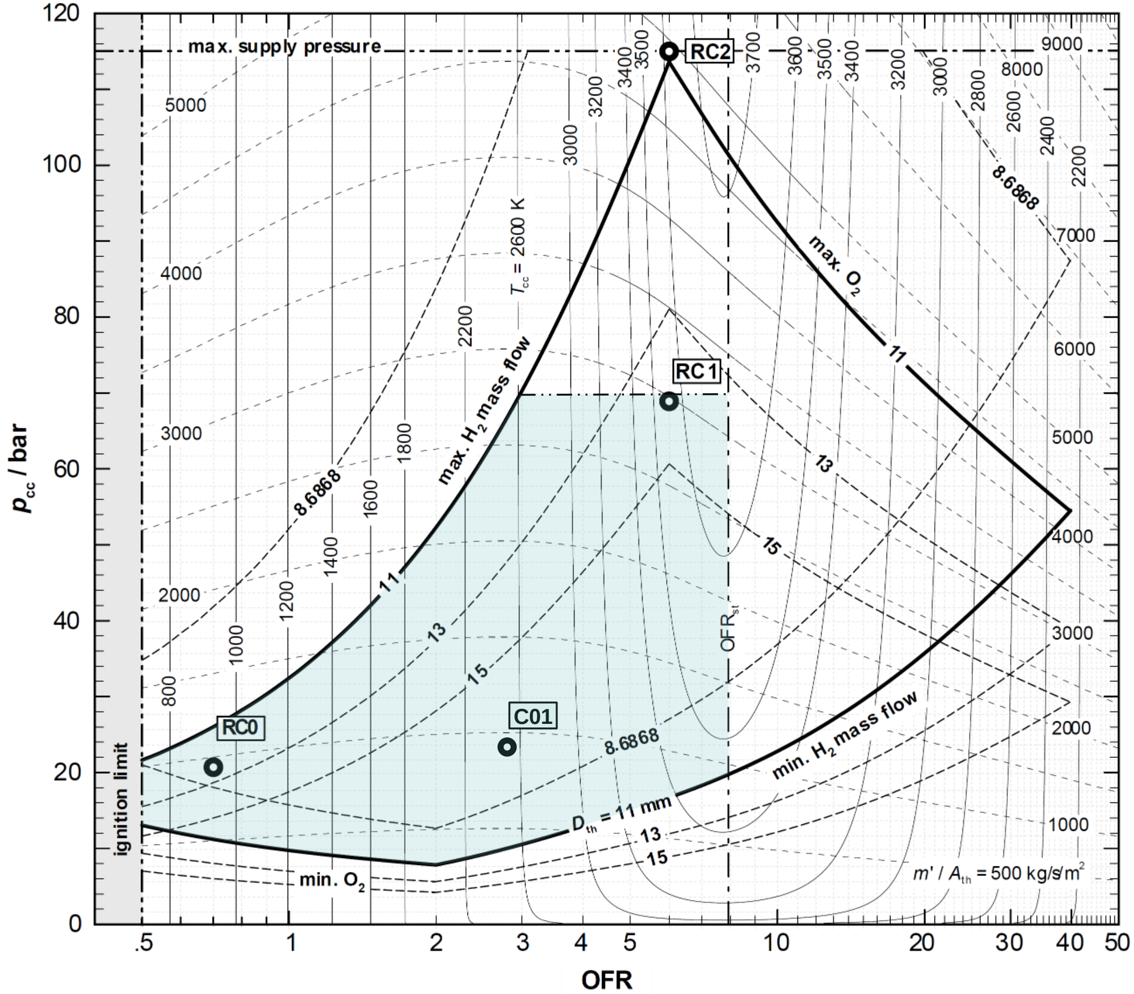


Hot Plume Testing Facility (HPTF)

[2] SAILE, D., KIRCHHECK, D., GÜLHAN, A., BANUTI, D.: Design of a hot plume interaction facility at DLR Cologne. In: 8th European Symposium on Aerothermodynamics for Space Vehicles (ATD). Lisbon, Portugal (2015)

HPTF Operating Range

- Reference condition for hot plume tests (RC0):
  - p_{cc} = 20.7 bar
  - T_{cc} = 925 K
  - OFR = 0.7



[3]

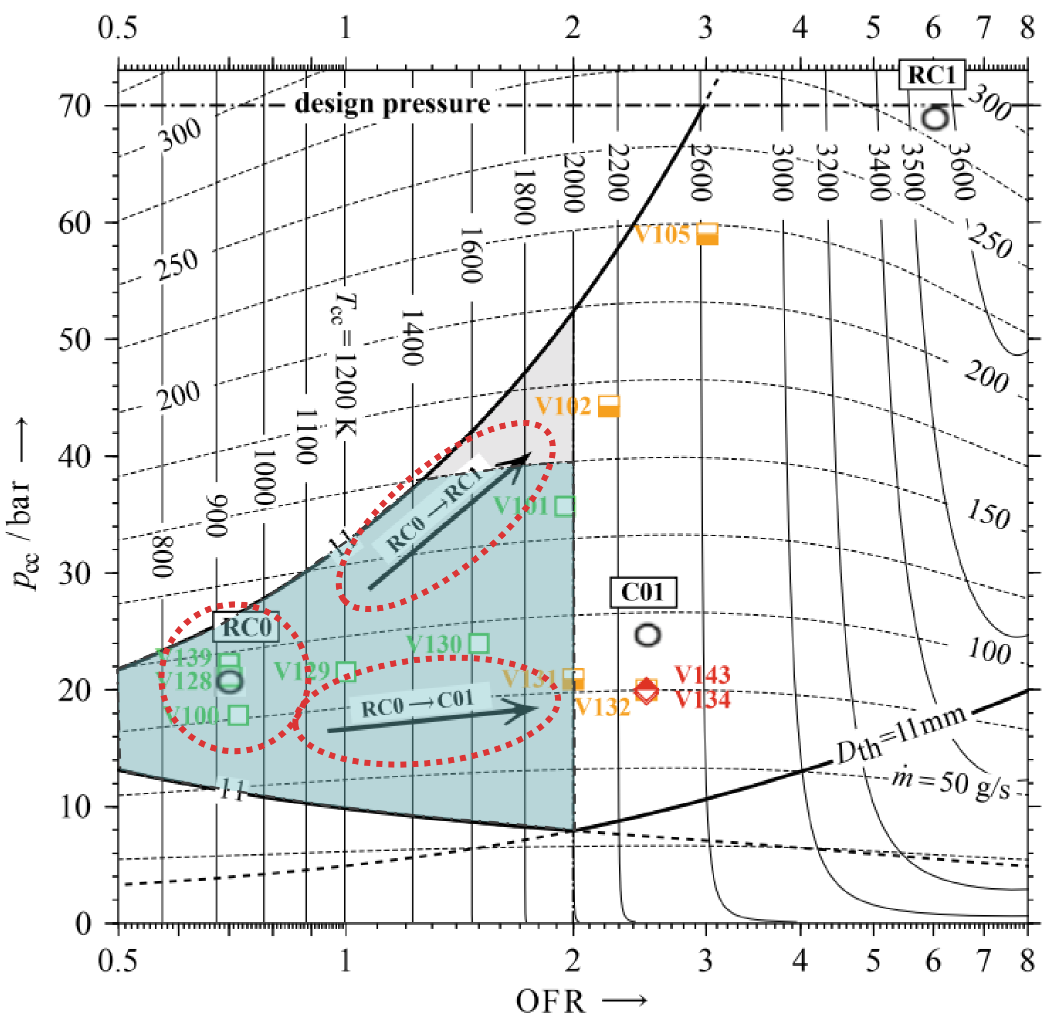
[3] KIRCHHECK, D., GÜLHAN, A.: Interaktionsteststand für realistische Raketentreibstrahlen mit umströmender Atmosphäre. In: Deutscher Luft- und Raumfahrtkongress, Munich, Germany, 5–8 Sep 2017.

EXPERIMENTS

HPTF Operating Range

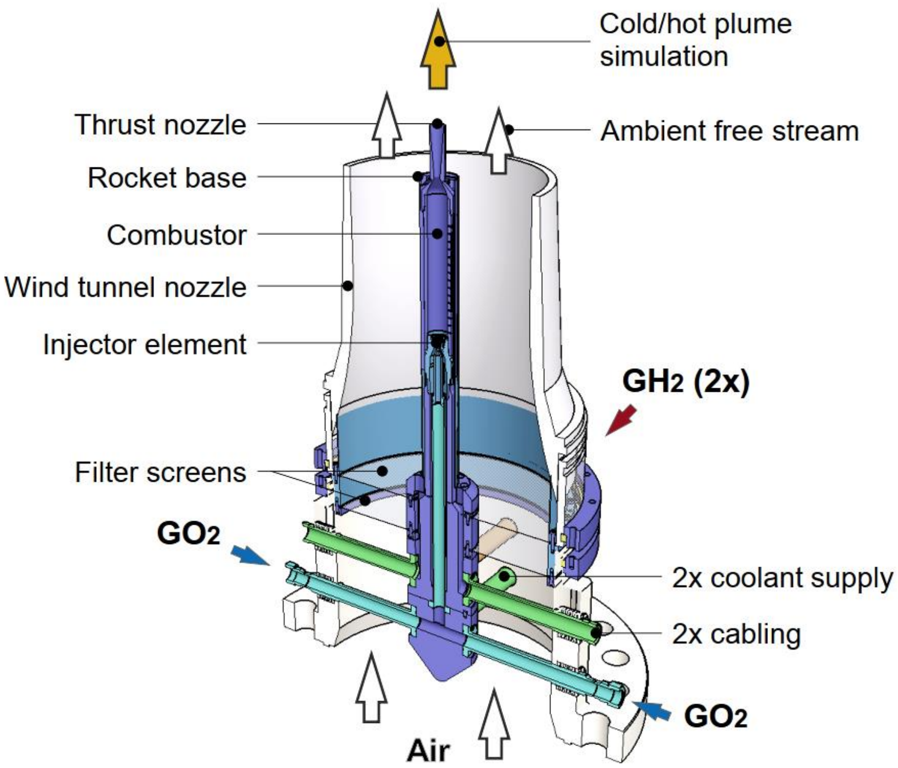
- Characterization tests performed for RC0 and off-design conditions

➢ Suitability of the given design at RC0 and elevated conditions proven for: [4]
  - $0.6 < OFR < 2.0$
  - $p_{cc} < 40$ bar
  - $\dot{m}_{tot} < 150$ g/s

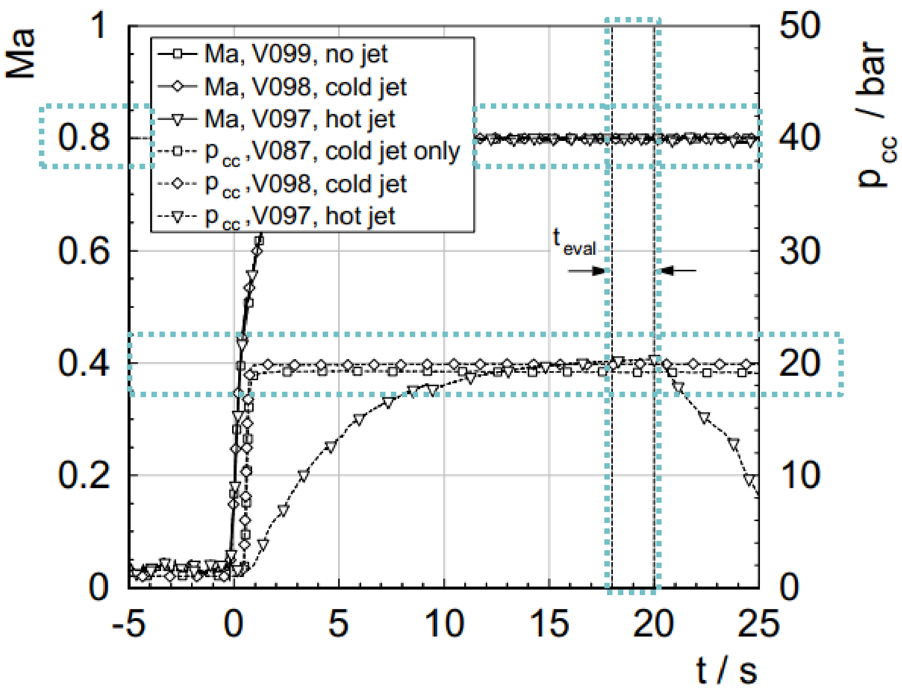


[4] KIRCHHECK, D., GÜLHAN, A.: Characterization of a GH2/GO2 Combustor for Hot Plume Wind Tunnel Testing. In: SFB/TRR40 Annual Report 2018.

Test Setup and Test Conditions

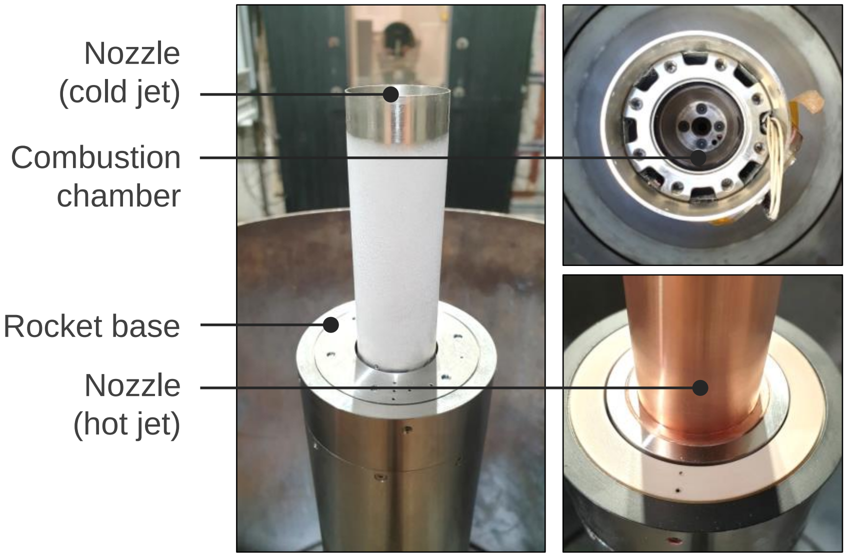


… for the Cold and Hot Exhaust Jet

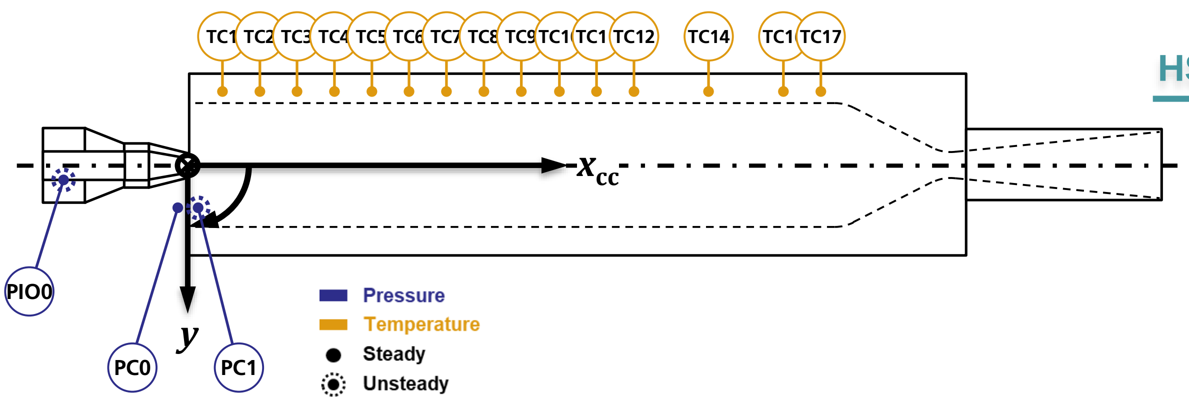


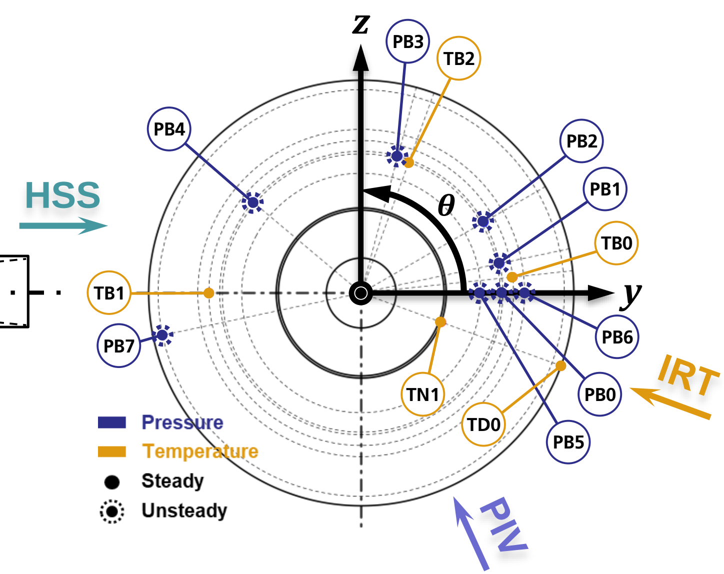
Jet flow	Ma_∞	p_∞ bar	T_∞ K	p_{cc} bar	T_{cc} K	$\dot{m}_{cc}$ g/s	OFR	u_e m/s
Cold jet	0.80	0.987	255.4⋆	19.90	288.0⋆	459.9⋆	–	619.8⋆
Hot jet	0.80	0.992	255.4⋆	20.27	918.7⋆	89.40	0.693	2803.9⋆

EXPERIMENTS
Measurements & Instrumentation



- Pressure (steady/unsteady) and thermocouple measurements
- High-speed Schlieren (**HSS**)
- Particle Image Velocimetry (**PIV**)
- Infrared Thermography (**IRT**)



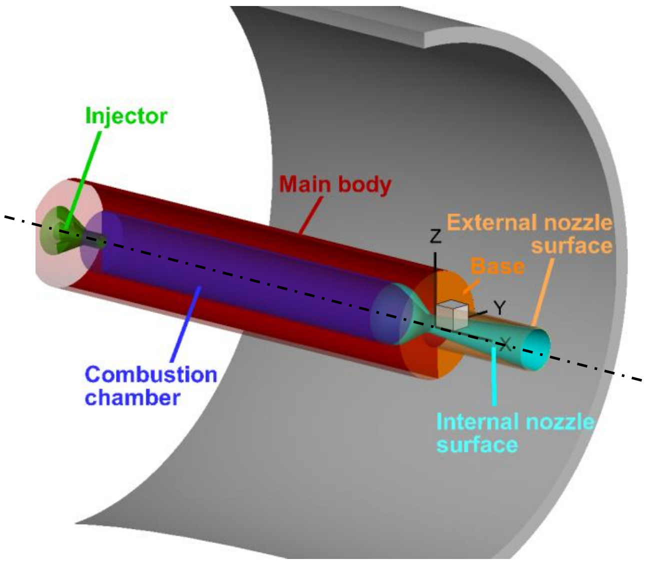


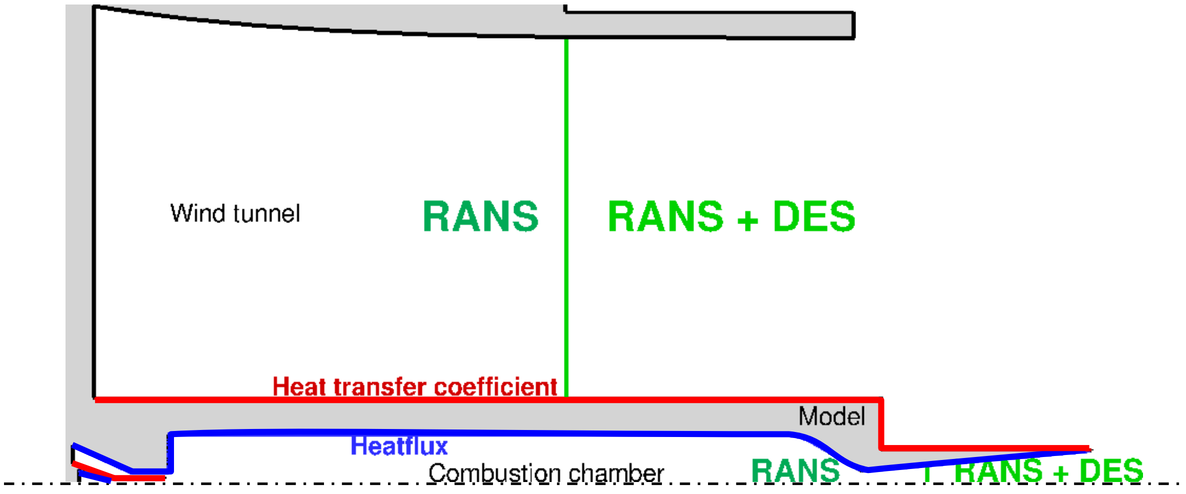
Tools & Methods

NUMERICS

Numerical Method

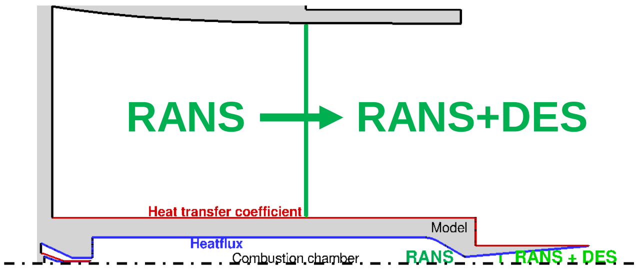
- General
  - DLR flow solver TAU (2^{nd} order, hybrid grids)
  - *k*-ω SST turbulence modelling
- Thermally coupled simulations
  - 2D axisymmetric RANS and coupling to ANSYS Mechanical
  - AUSMDV Upwind scheme and detailed chemistry

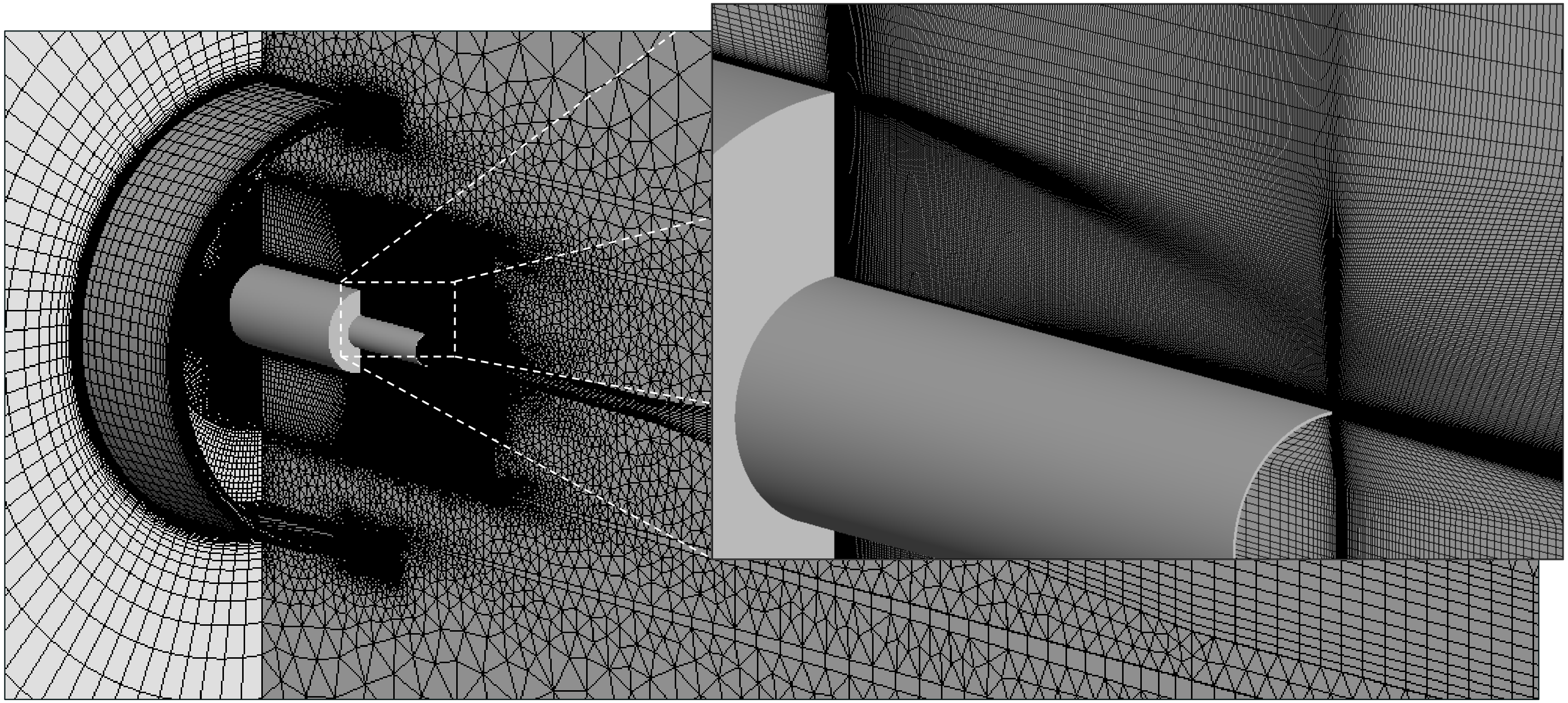




Numerical Method

- Scale resolving simulations of external flow
  - Improved Delayed Detached Eddy Simulation (IDDES)
  - Low-dissipation low-dispersion central scheme
  - Non-reacting two gas mixture (plume + ambient air)
  - ~31 Million grid points

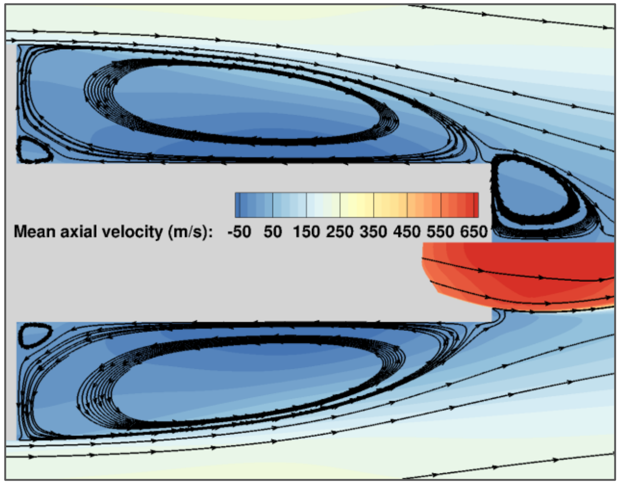


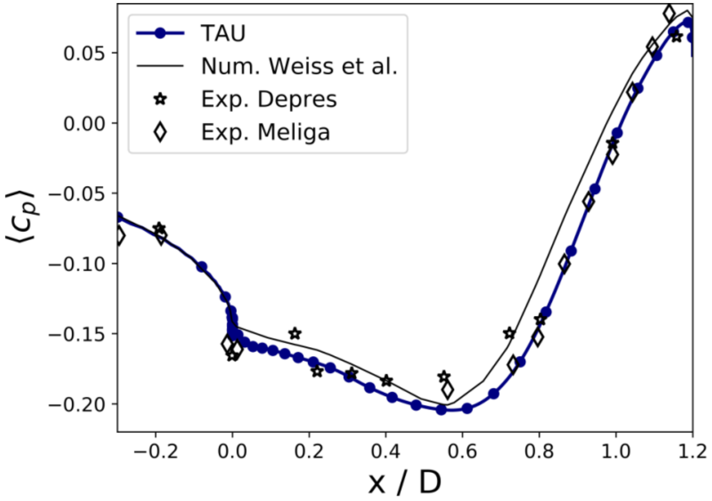


IDDES Validation Studies

- Preliminary studies based on reference data from literature [5]

- Grid study [6]
  - Optimize grid resolution and design, validate implemented grid sensors and determine sensitivity of the solution to grid changes
- Parameter study
  - Optimize modelling and determine sensitivity to parameter changes
  - Very good agreement with experimental data

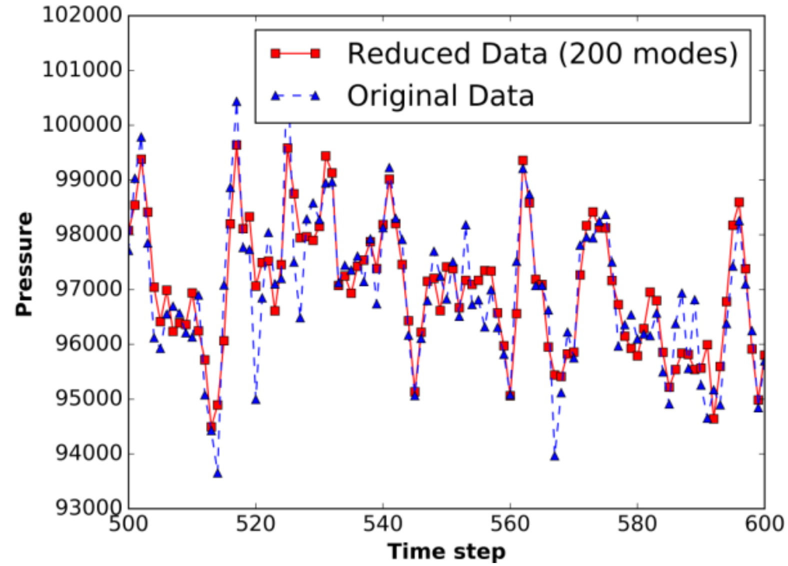




[5] WEISS et al.: On the dynamics of axisymmetric turbulent separating/reattaching flows." Physics of Fluids 21.7 (2009): 075103.
[6] SCHUMANN, J.-E., HANNEMANN, V., HANNEMANN, K.: Investigation of structured and unstructured grid topology and resolution dependence for scale-resolving simulations of axisymmetric detaching-reattaching shear layers, In: Progress in Hybrid RANS/LES methods. Springer, 2020.

Data Reduction Strategy

- Data reduction method for aft-body flow data [7]
  - Proper Orthogonal Decomposition (POD) reduces file size
  - Python script to extract the surface pressure time series in the desired format
  - ➢ Data reduction by up to a factor of 10^6



	Spatial points	Variables	Time steps	Total data values
Original data set	$25 \cdot 10^6$	10	1000	$250 \cdot 10^9$
Wall pressure	$200 \cdot 10^3$	1	1000	$200 \cdot 10^6$
Relevant region and freq.	$20 \cdot 10^3$	1	1000	$20 \cdot 10^6$

	Spatial points	Modes	Time sequence	Total data values
POD without domin. modes	$20 \cdot 10^3$	200	1000	$4.2 \cdot 10^6$
POD with domin. modes	$20 \cdot 10^3$	10	1000	$210 \cdot 10^3$

10^{-6}

[7] FERTIG, M., SCHUMANN, J.-E., HANNEMANN, V., EGGERS, T., HANNEMANN, K.: Efficient analysis of transonic base flows employing hybrid URANS/LES methods. In: SFB/TRR 40 Annual Report 2017, pp. 115–126.

Content

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- Tools & Methods
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- **Results**
  - Cold Plume Test Case
  - Hot Plume Test Case
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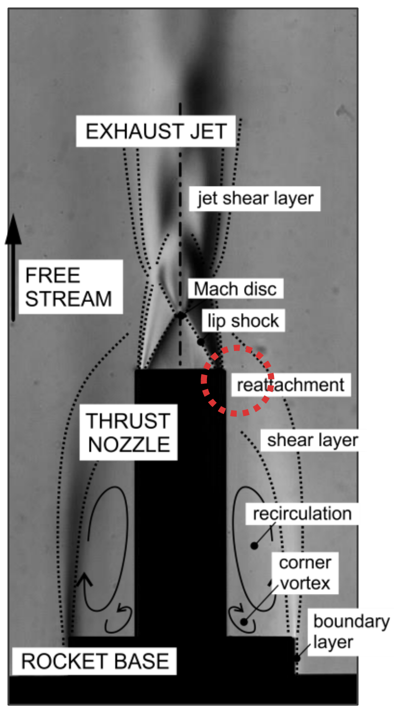
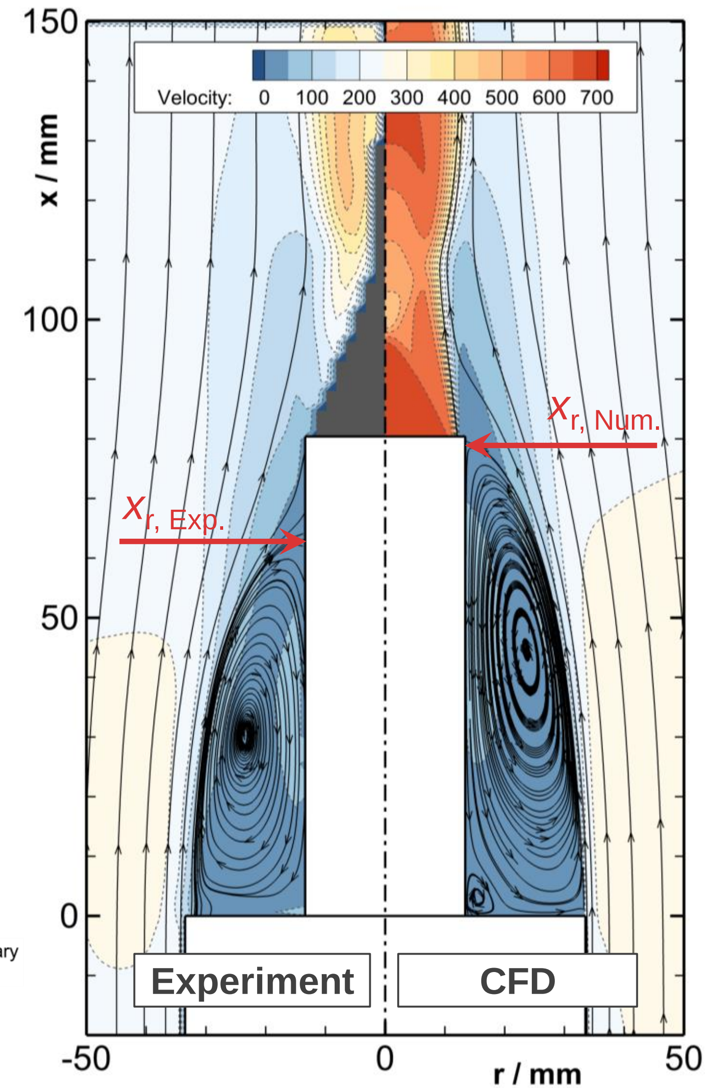
Results

COLD PLUME TEST CASE

Mean Flow Field

- Comparison of the mean flow features between HSS, PIV and CFD results
- Prominent flow features for comparison:
  - Shock distance from nozzle exit
  - Vortex center location
  - Reattachment location
  - …

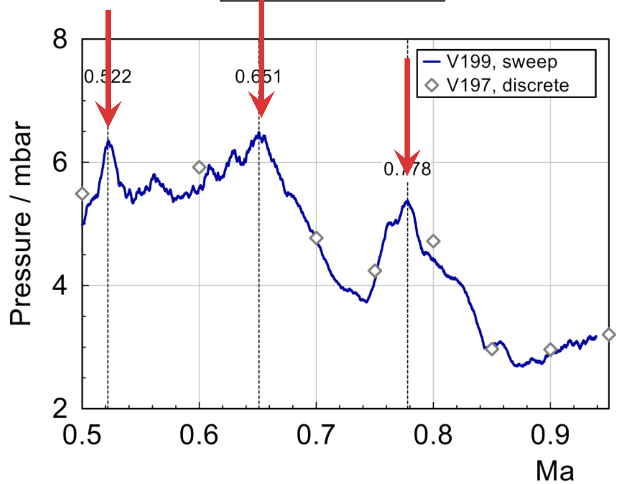




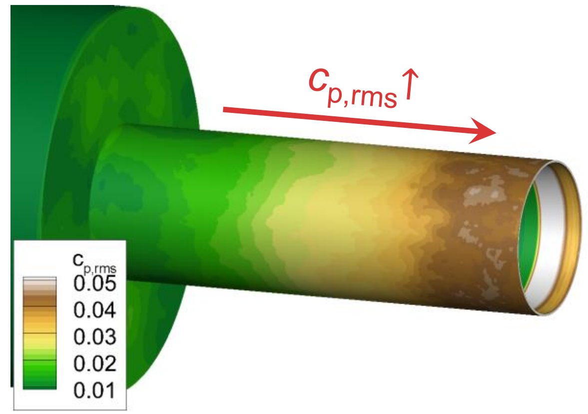
- ➢ Good agreement of the basic flow structure
- ➢ Reattachment location
  - 20% farther downstream in the CFD

Base Pressure Data

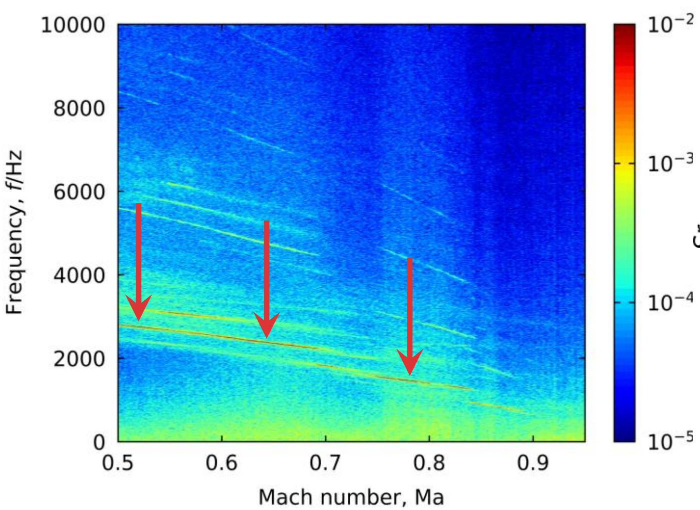
Experiment

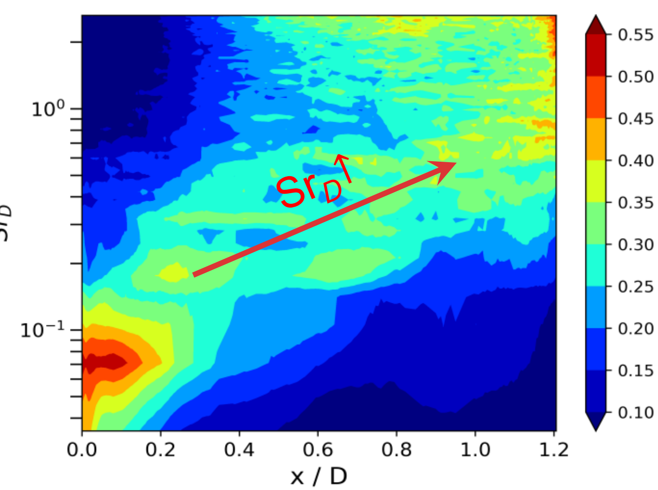


CFD



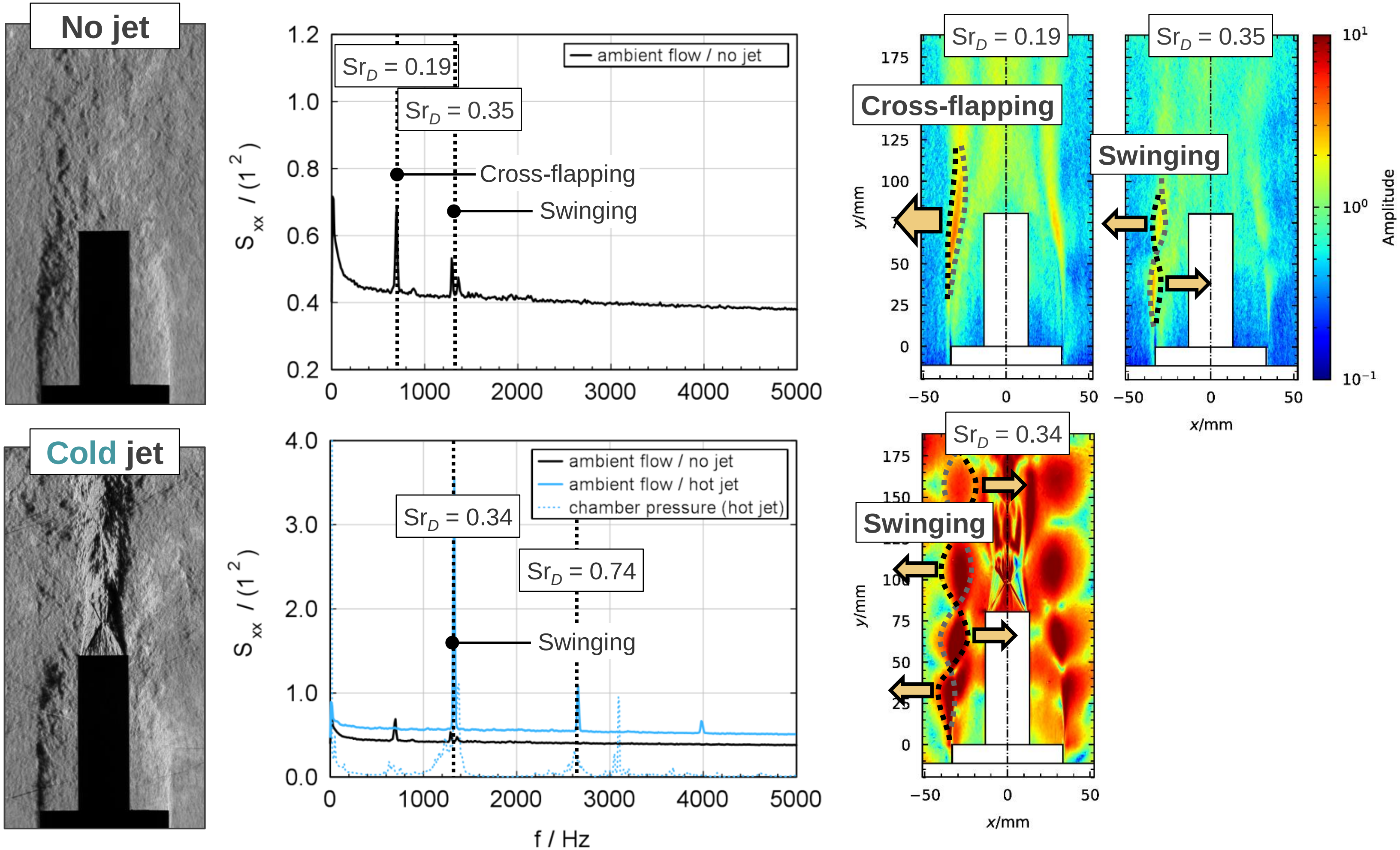
- RMS pressure and frequency analysis for varying Mach number from **WTT** results
  - ➢ Significant variation during ascent, thus potentially critical Mach numbers





- RMS pressure and frequency analysis as local distribution from **CFD** results
  - ➢ Local distribution of fluctuation level and frequency impacts load predictions

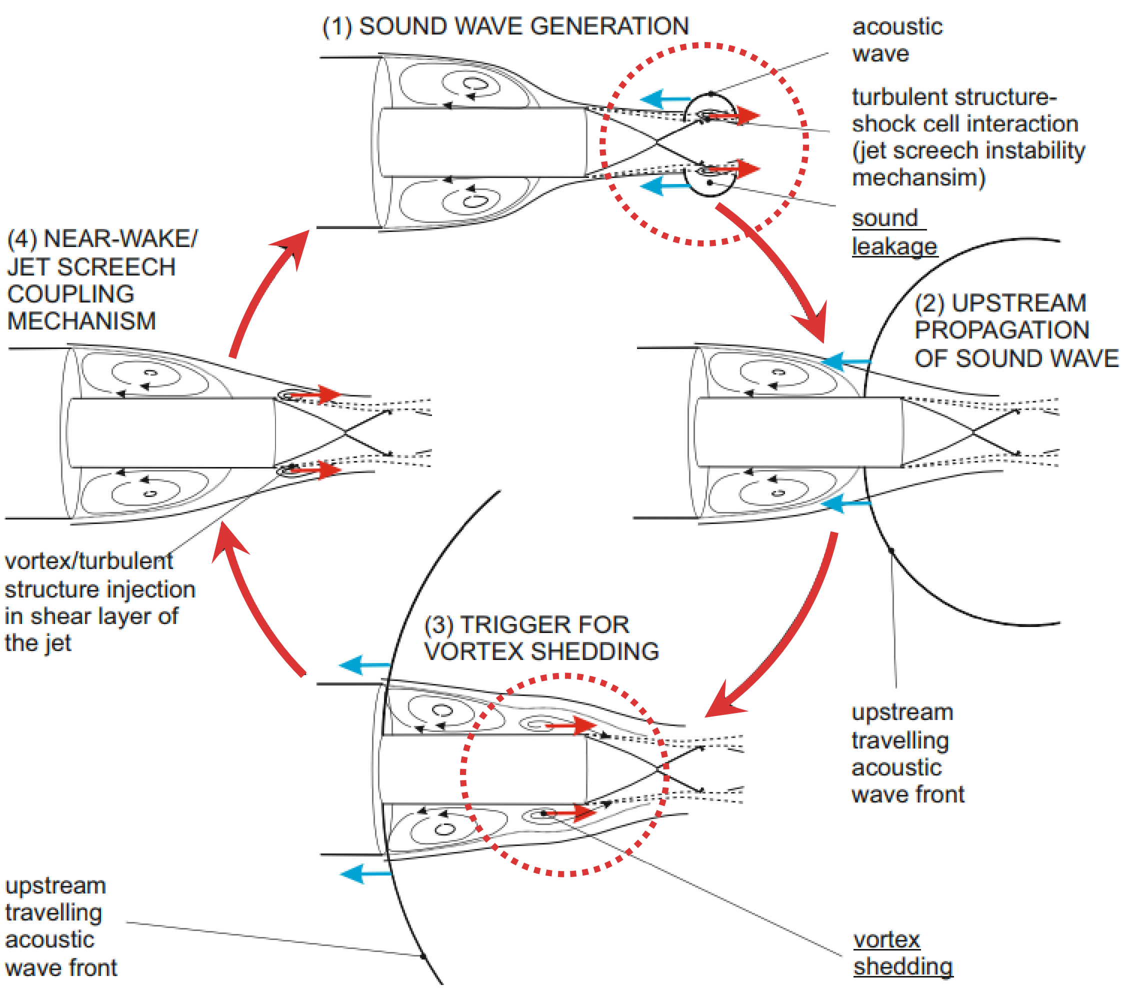
HSS Spectral Analysis



➢ Modal analyzes of the High-speed Schlieren recordings reveal a strong amplification of the swinging motion of the shear layer at cold plume conditions

Jet–Wake Flow Coupling Hypothesis

- Hypothesis from D. SAILE (SFB/TRR40) cold plume testing [7]
- Strong indication for resonant coupling of near-wake and jet shear layer instabilities
- Development of a concept of dynamic mode coupling and analytical extrapolation to a real flight trajectory



[8]

[8] SAILE, D.: Experimental Analysis on Near-Wake Flows of Space Transportation Systems. Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen. Ph.D. Thesis (2019).

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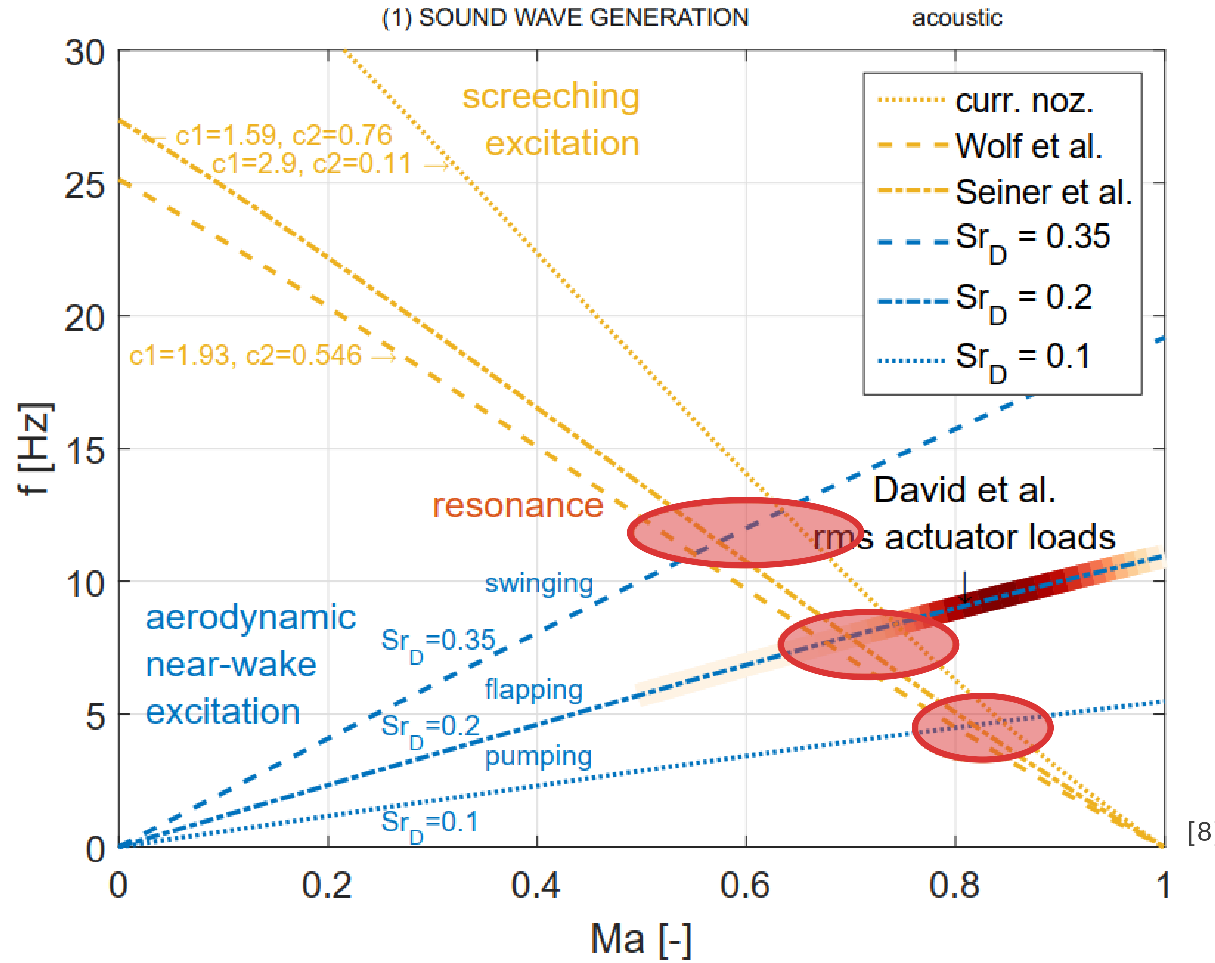
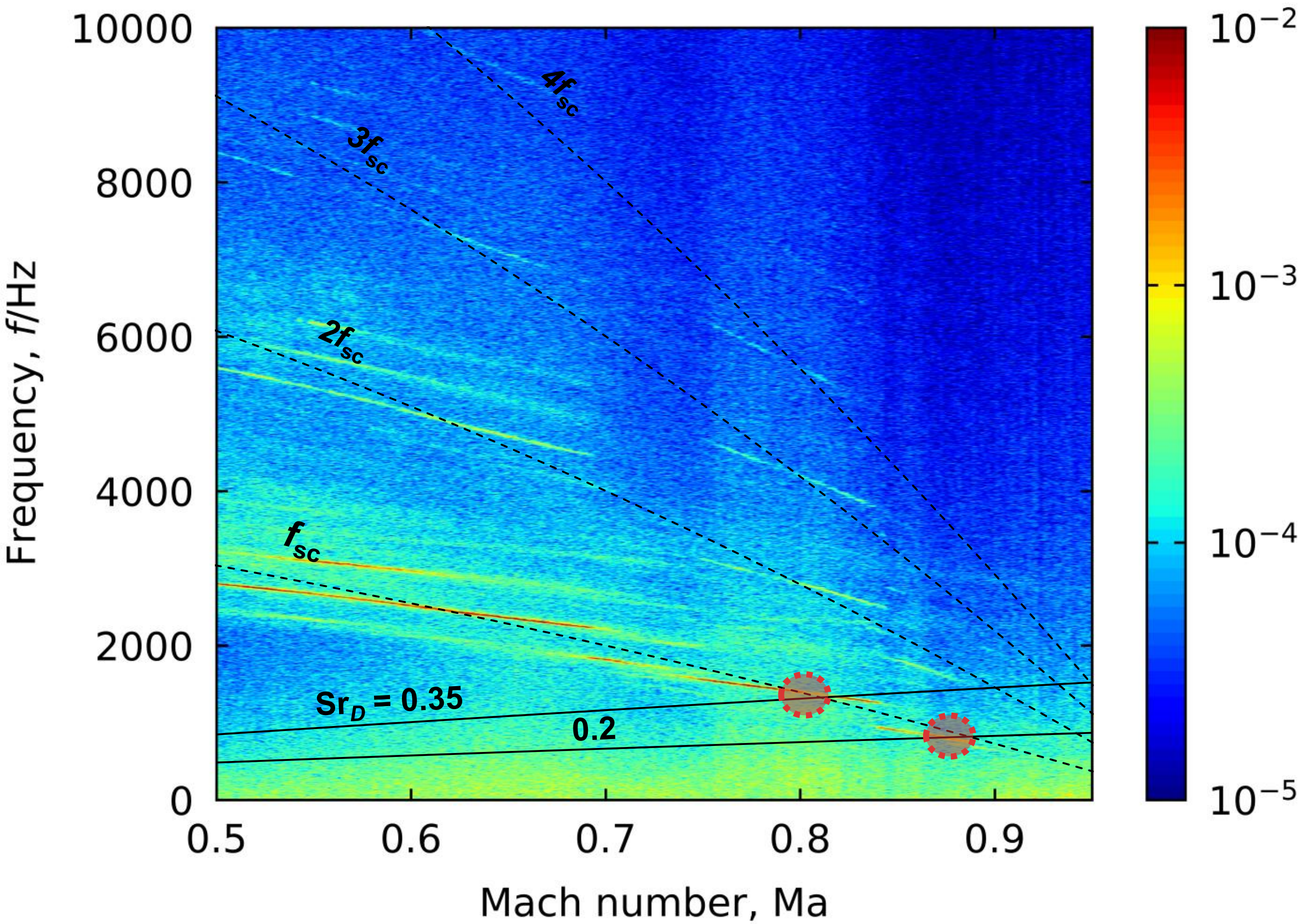


[8] Saile, D.: Experimental Analysis on Near-Wake Flows of Space Transportation Systems. Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen. Ph.D. Thesis (2019).

Mach Number Variation

- Continuous variation of the ambient freestream Mach number (45s)
- ➢ Spectrogram from high-frequency base pressure measurements



- Estimated screeching and shear layer frequencies intersect at excited frequency bands

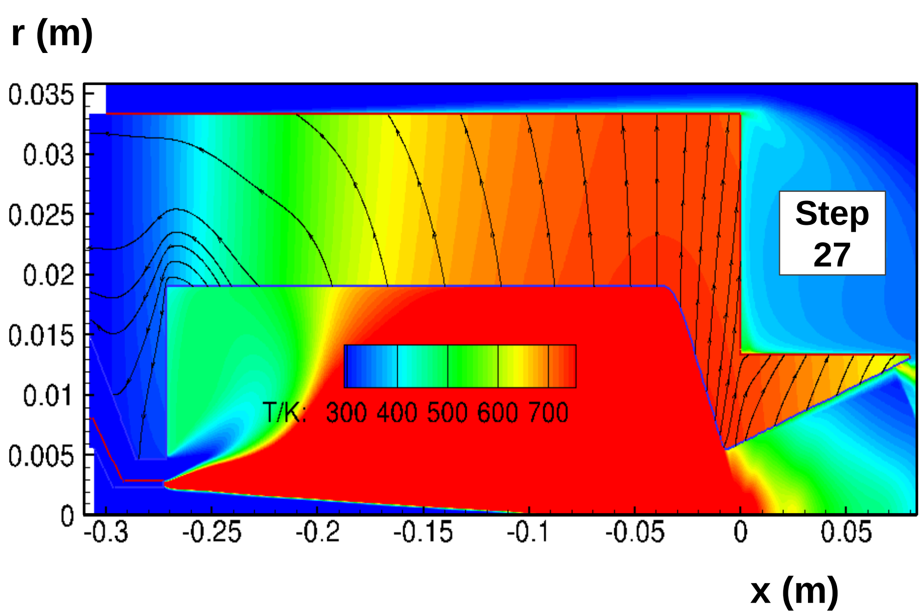
- ➢ Verification for SAILE's hypothesis
- ➢ Found locking mechanism for coupling with different flow motions

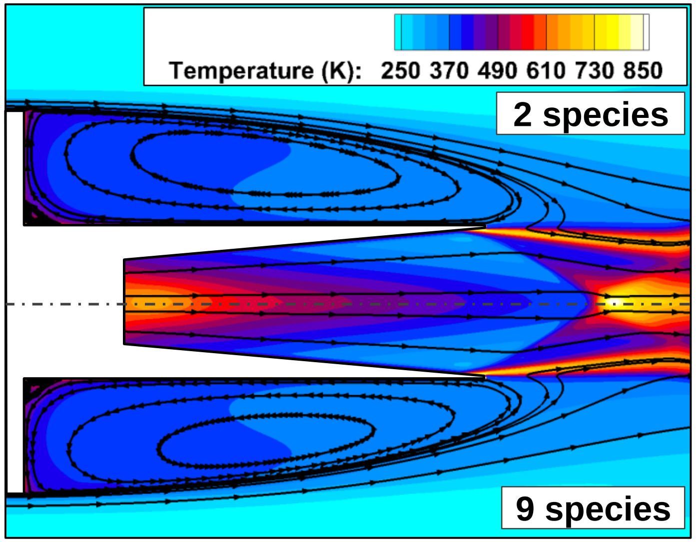
Results

HOT PLUME TEST CASE

Thermally Coupled Simulations

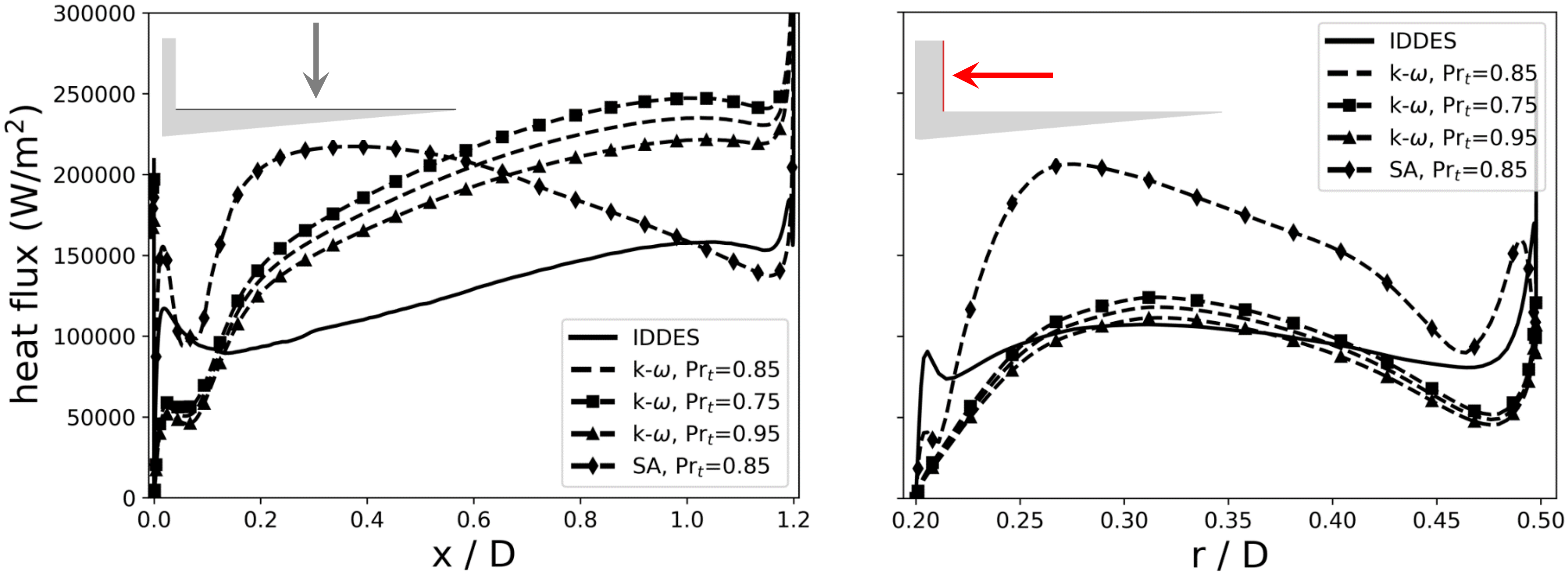
- Combustion chamber and structure conditions at OFR = 0.7
  - $T_{cc,max}$ = 3550K, $T_{cc,avg}$ = 900K, p_{cc} = 21.5bar
  - T_{th} = 743K, T_{corner} = 730K
- Aft-body RANS flow field
  - Comparison between 2 species/no chemistry ↔ 9 species/finite rate chemistry
  - Similar results without post combustion





Heat Flux Data (IDDES)

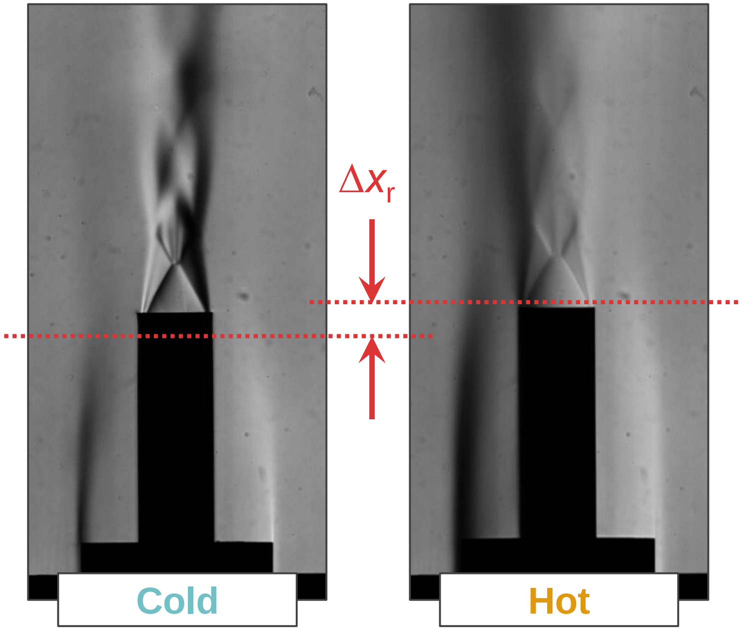
- Large discrepancies in heat flux prediction between RANS and IDDES
  - Partially due to mean flow field changes
    (e.g. earlier reattachment for SA-RANS)

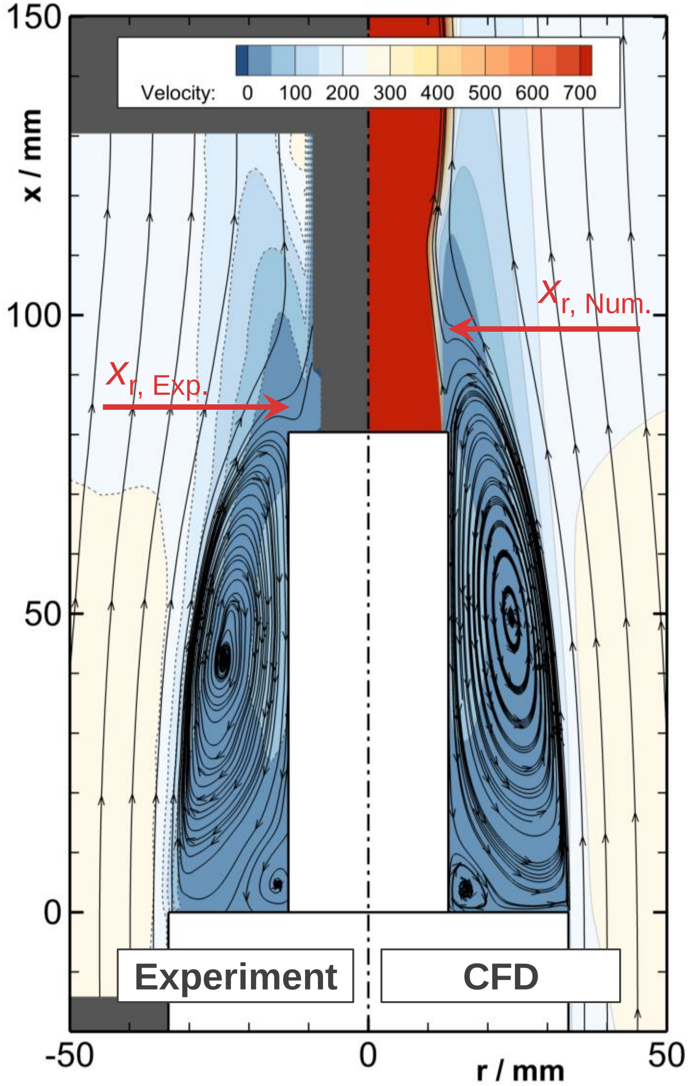


HOT PLUME TEST CASE

Impact on Mean Flow Field

- Comparison between PIV and CFD
  - Reattachment location about 20% farther downstream in the CFD
- Hot plume impact on the mean flow field
  - Reattachment location shifted approx. 22% downstream compared to the cold plume case

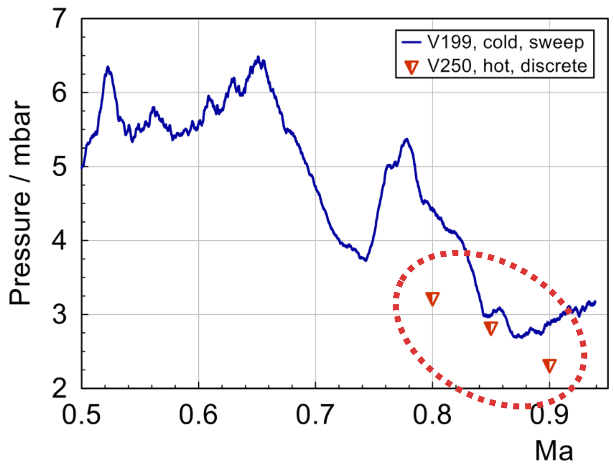


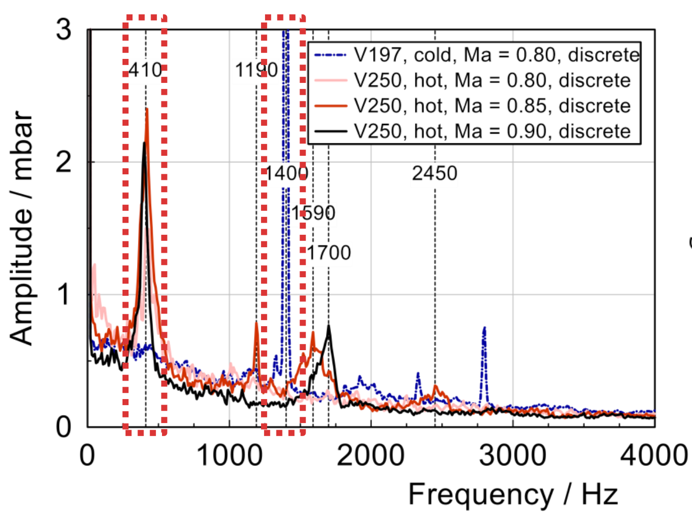


HOT PLUME TEST CASE

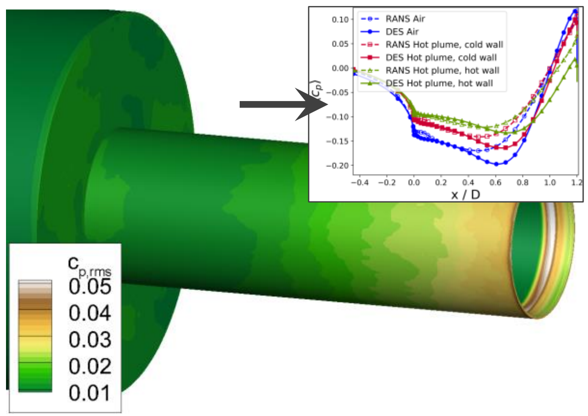
Impact on Base Pressure

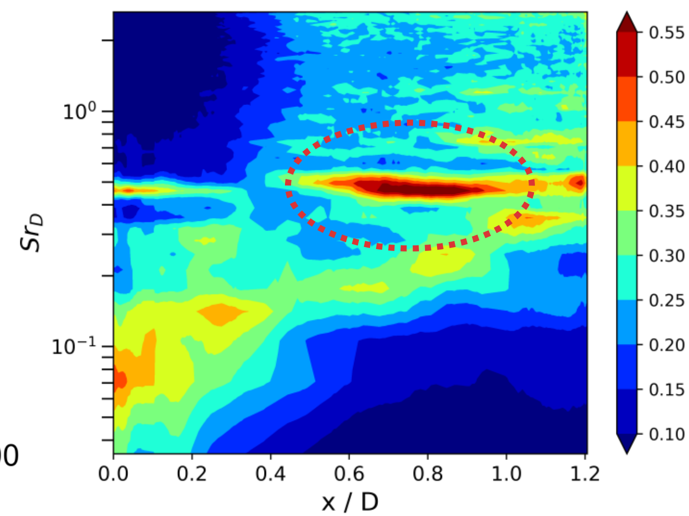
Experiment





CFD



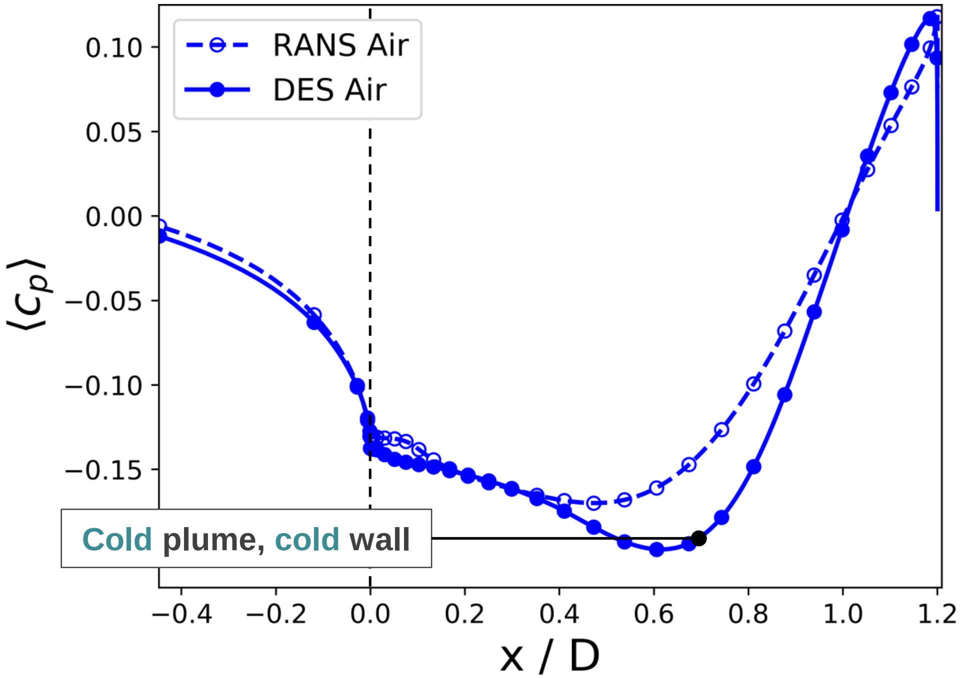


- Pressure level and pressure fluctuation level reduced for the hot plume case in WTT and CFD results
- Impact on the base pressure spectrum
- Additional frequency peak at 2/3 of the nozzle length

➢ Various effects on the pressure visible in WTT and CFD results

Impact on Base Pressure (IDDES)

- Significant changes in flow field and pressure distribution when comparing cold/cold, hot/cold, and hot/hot cases



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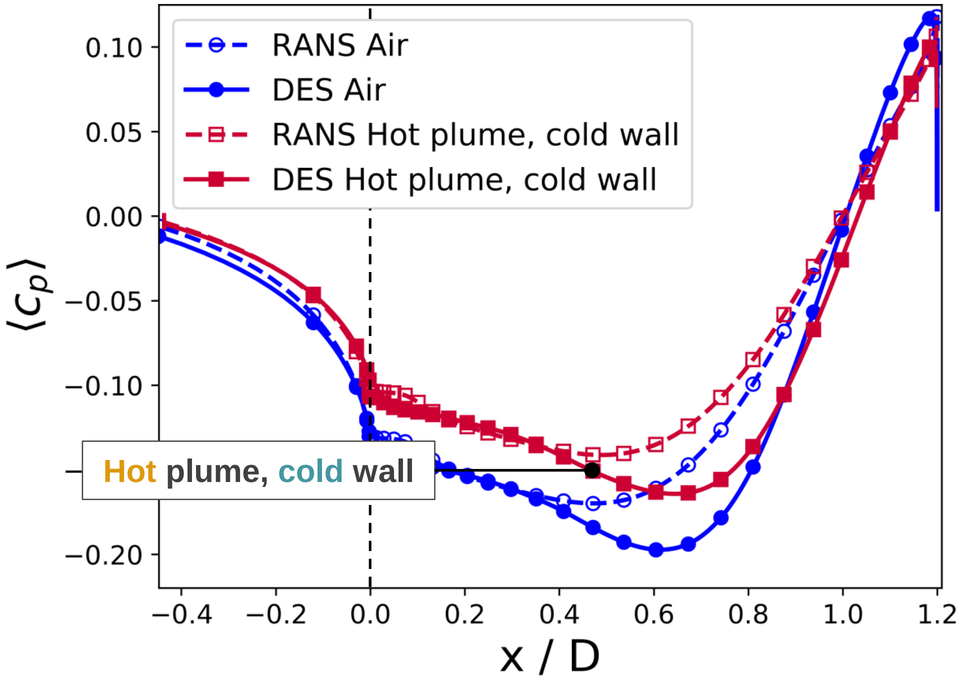

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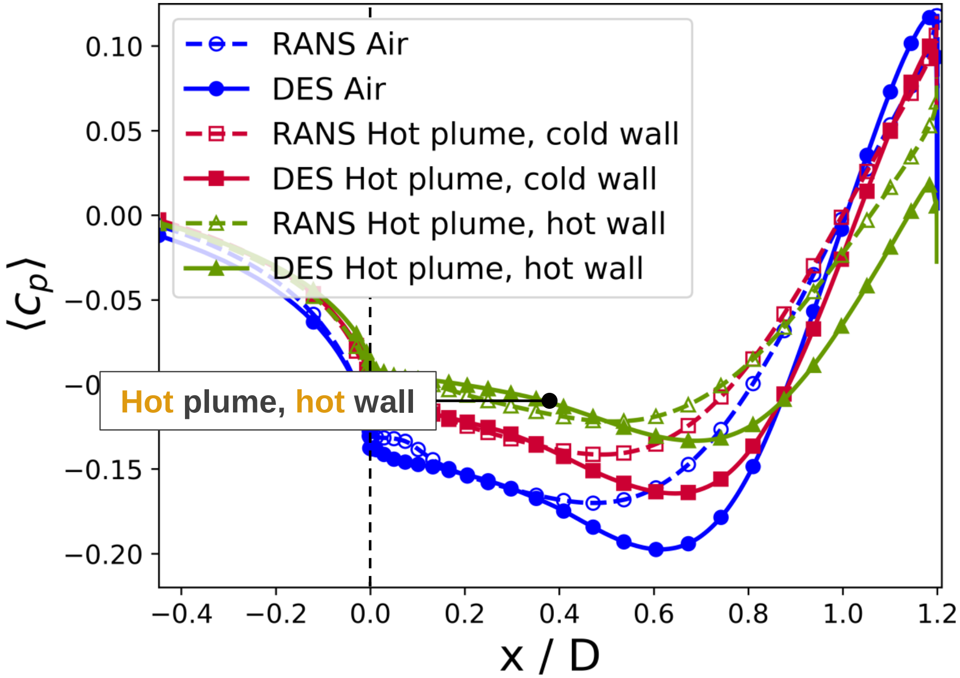
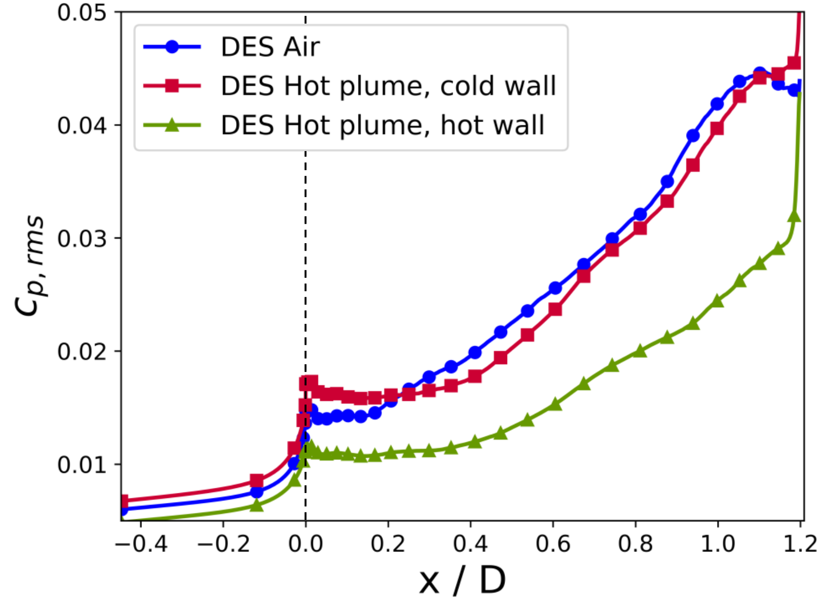
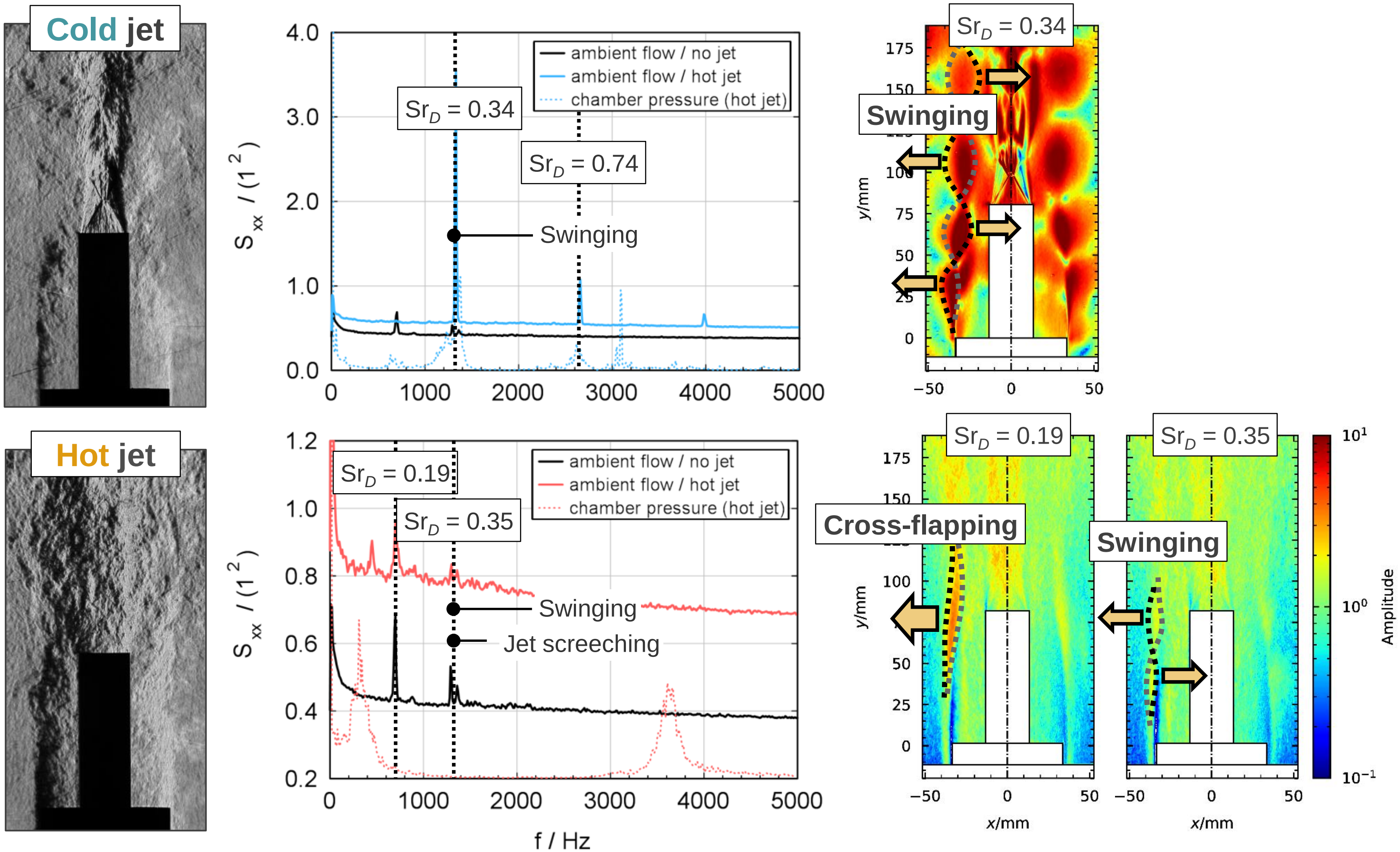




➢ Pressure fluctuations on the nozzle wall are significantly reduced in the hot plume case with hot walls.

HOT PLUME TEST CASE

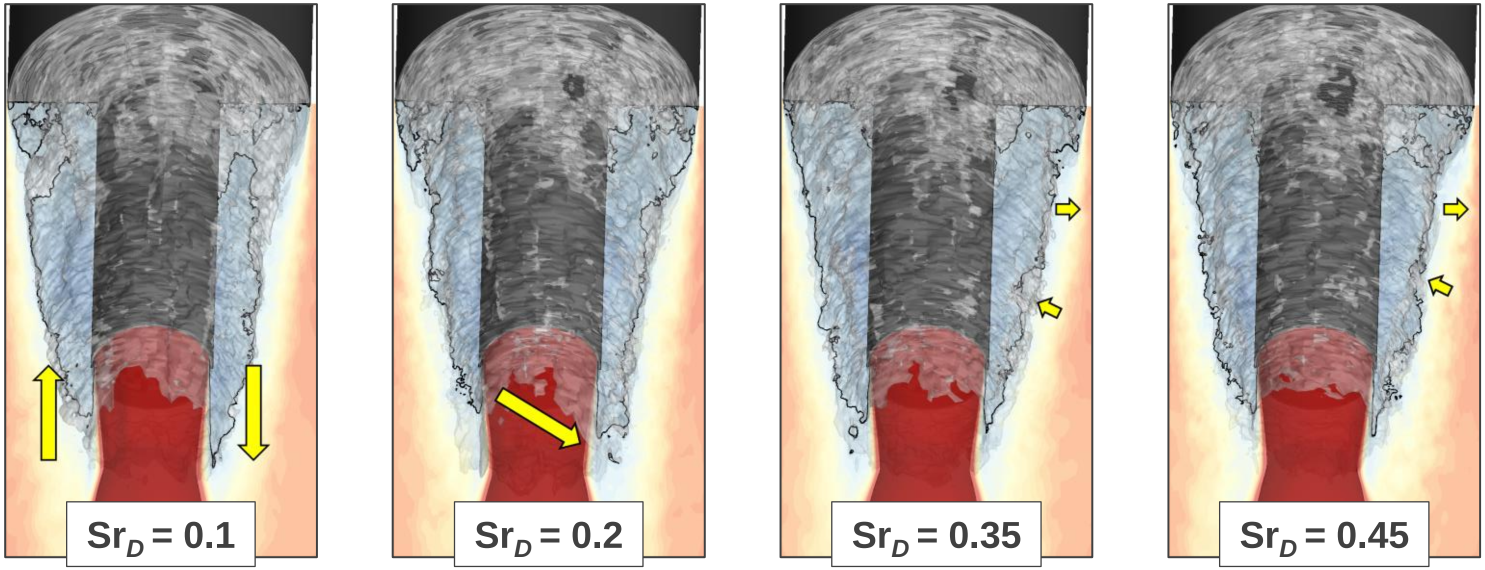
Impact on Wake Flow Dynamics



- No excitation of one of the shear layer modes in the hot plume case. The dominant movement corresponds to the case without plume

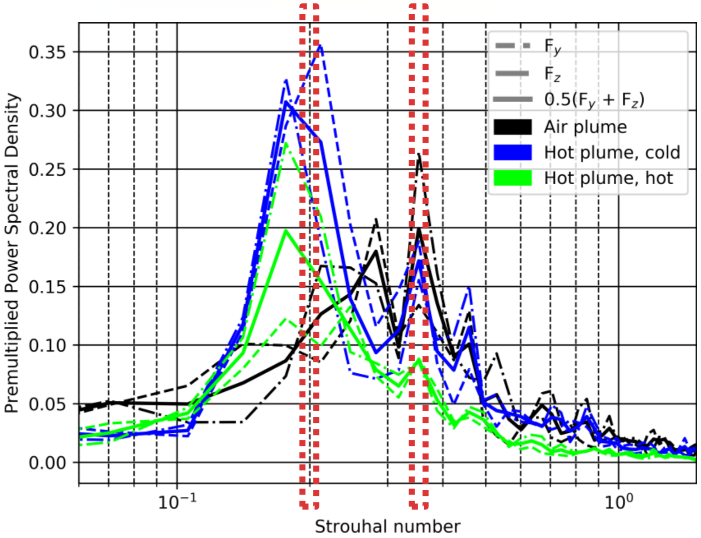
Dynamic Mode Decomposition (IDDES)

- Similar mode frequencies and mode shapes for all cases
  - $Sr_D = 0.1$ (symmetric, *longitudinal cross-pumping*)
  - $Sr_D = 0.2$ (asymmetric, *flapping*)
  - $Sr_D = 0.35$ (asymmetric, *swinging*)
- Additional mode at $Sr_D \approx 0.45$ (symmetric, *swinging*)
  - Appears related to an interaction between the shear layer movement and a nozzle flow separation

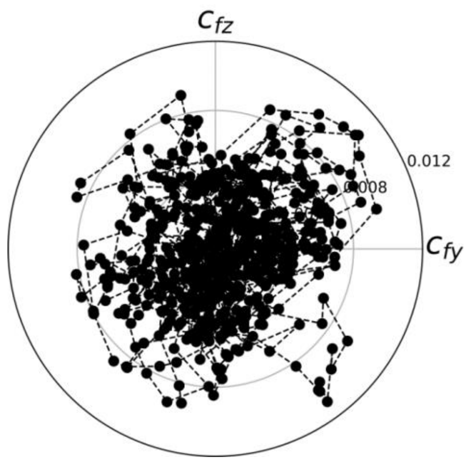


Impact on Nozzle Forces (IDDES)

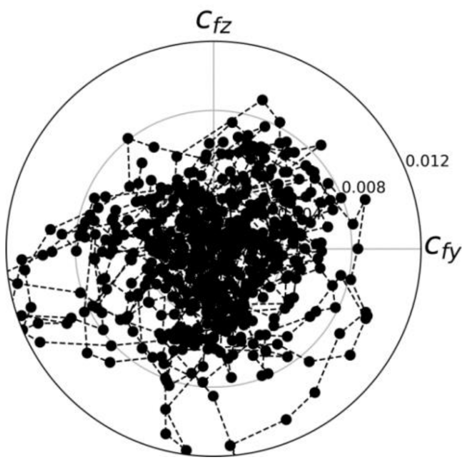
- Nozzle forces dominated by $Sr_D = 0.2$ and $Sr_D = 0.35$ peaks for the hot exhaust plume
- Reduced amplitude of forces for the hot wall case (~20%)



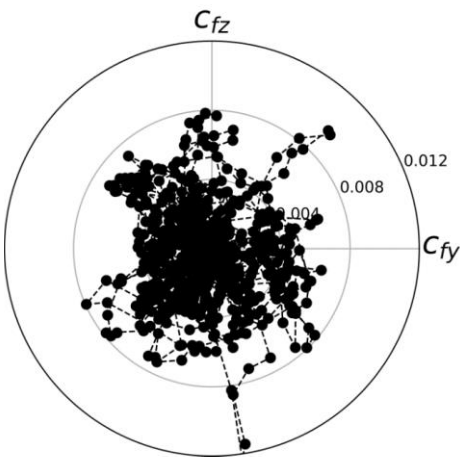
Cold plume, cold wall



Hot plume, cold wall



Hot plume, hot wall



Conclusion

Conclusion

- **INVESTIGATION OF PLUME INTERACTION WITH AMBIENT FLOW**
  for cases with cold and hot exhaust jets using wind tunnel tests and CFD

- **CHARACTERIZATION OF THE COLD PLUME INTERACTION**
  test case in terms of: mean flow features, base pressure, wake flow dynamics

- **COMPARISON OF THE COLD AND HOT PLUME INTERACTION**
  test cases indicates significant impacts from hot plumes and higher
  wall temperatures on the near wake flow of a launcher

- **RELEVANT DATA SETS ARE PROVIDED**
  about the experimental and numerical results of the main test cases
  (listed at the end of the presentation)

APPENDIX

Provided Data Sets

Experimental

Description	Mach	Plume	L/D	Tw	Stored data
No plume	0.8	No plume	1.2	N/K	$p_b(t)$, HSS, PIV
Cold plume	0.8	Air (~288K, ~20bar)	1.2	N/K	$p_b(t)$, HSS, PIV
Hot plume	0.8	O/F=0.7 (~900K, ~20bar)	1.2	N/K	$p_b(t)$, HSS, PIV

*an updated list with an increased number of test cases might be available after final evaluation of all data

Numerical

Description	Mach	Plume	L/D	Tw	Stored data
Cold plume	0.8	Air (300K, 22bar)	1.2	300K	$p_w(x,t)$
Hot plume, cold	0.8	O/F=0.7 (~900K, 22bar)	1.2	300K	$p_w(x,t)$
Hot plume, hot	0.8	O/F=0.7 (~900K, 22bar)	1.2	~700K	$p_w(x,t)$ & $T_w(x)$
Short, cold	0.8	O/F=6 (~3000K, 22bar)	0.4	300K	$p_w(x,t)$
Short, hot	0.8	O/F=6 (~3000K, 22bar)	0.4	~1100K	$p_w(x,t)$ & $T_w(x)$