Experimental Modelling of Alumina Particulates in Solid Booster

ESA Clean Space Industrial Days

24-26 October 2017, ESTEC, Netherlands

Table of Content

Introduction
Motivation

Ozone depletion of stratosphere

- Heterogeneous reactions, in particular chlorine activation reactions, take place on the surface of alumina particles.
- This mechanism potentially doubles the annually averaged total ozone depletion attributed to the emission of SRMs.
- In literature, there exists a discrepancy in regarding the particle size distribution.
- Research question concerns particle size and to provide benchmark data to describe particle formation processes.

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In Situ Measurement of the Aerosol Size Distribution in Stratospheric Solid Rocket Motor Exhaust Plumes

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Size-resolved particle emission indices in the stratospheric plume of an Athena II rocket

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DLR

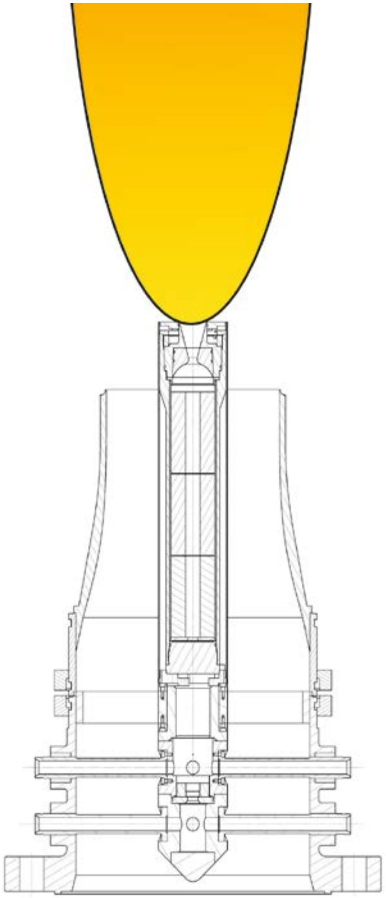
Introduction
Requirements by ESA

Task: Characterize the flow in a representative SRM and in particular the alumina particulate in several planes for <u>code validation</u>, with focus on heat-load computations.

- Alumina properties
    - Size and spatial distribution
    - Agglomeration
    - Temperature
    - Velocity

- Flow properties
    - Temperature
    - Velocity
    - Pressure
    - Species concentration

- Thermal radiation from the plume



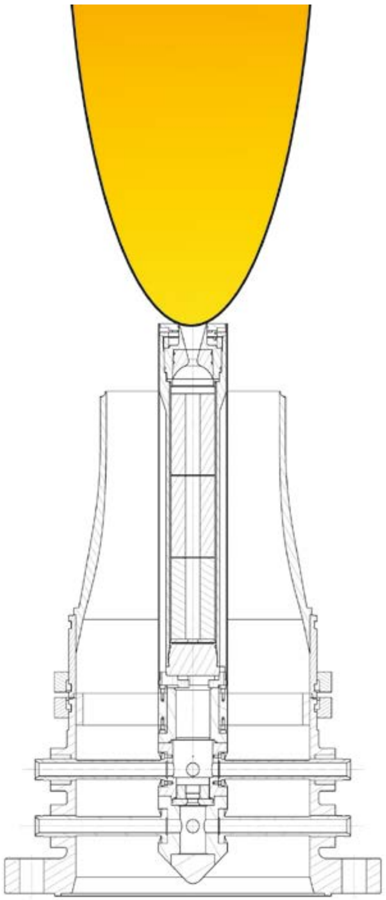
Introduction
Team

- German Aerospace Center
    - Institute of Aerodynamics and Flow Technology
      Supersonic and Hypersonic Technologies Dept.
    - Institute of Propulsion Technology
      Engine Measurement Systems

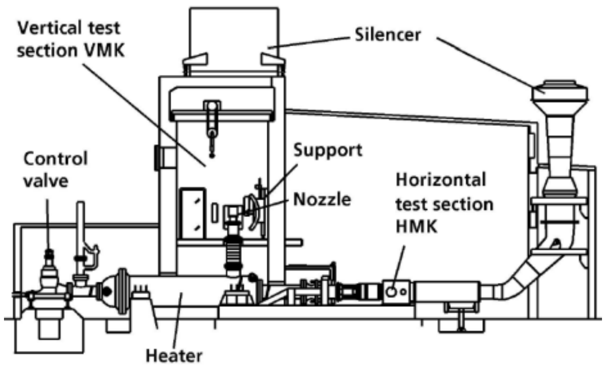
- Politecnico di Milano
  Space Propulsion Laboratory
  Dept. of Aerospace Science and Technology

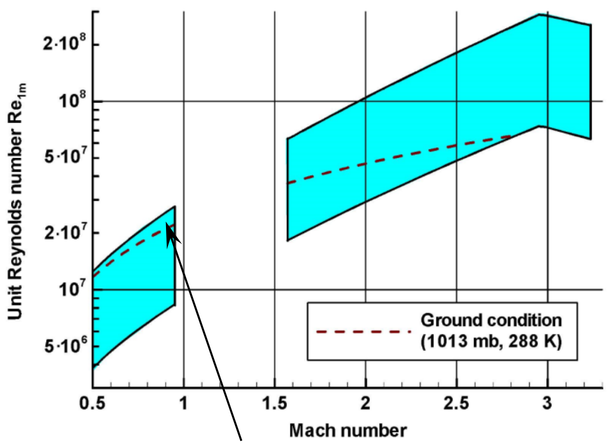
- FOI
  Swedish Defence Research Agency
  Department of Energetic Materials

- ESTEC, TEC-MPA
  European Space Research and Technology Centre
  Aerothermodynamics and Propulsion Analysis Section

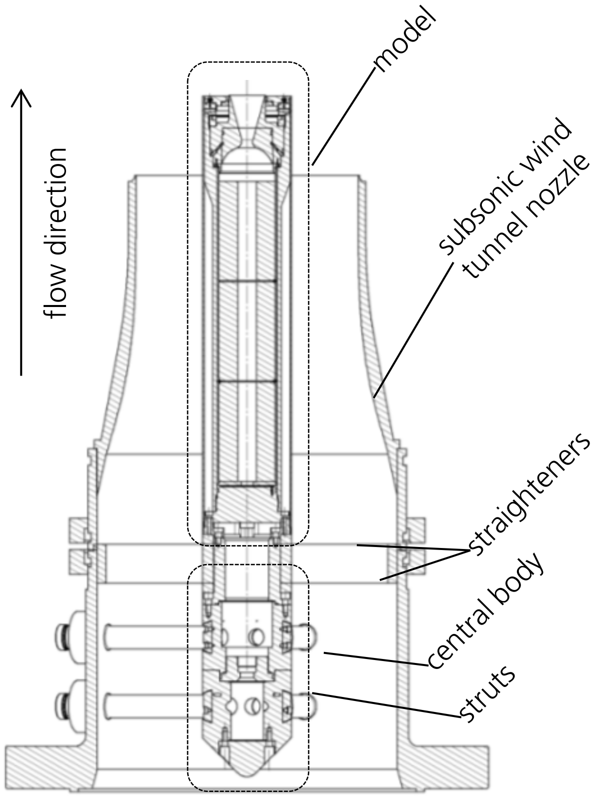


Methods: Test Environment
Vertical Test Section Cologne (VMK)/Wind Tunnel Model





Ma=0,8
ground conditions



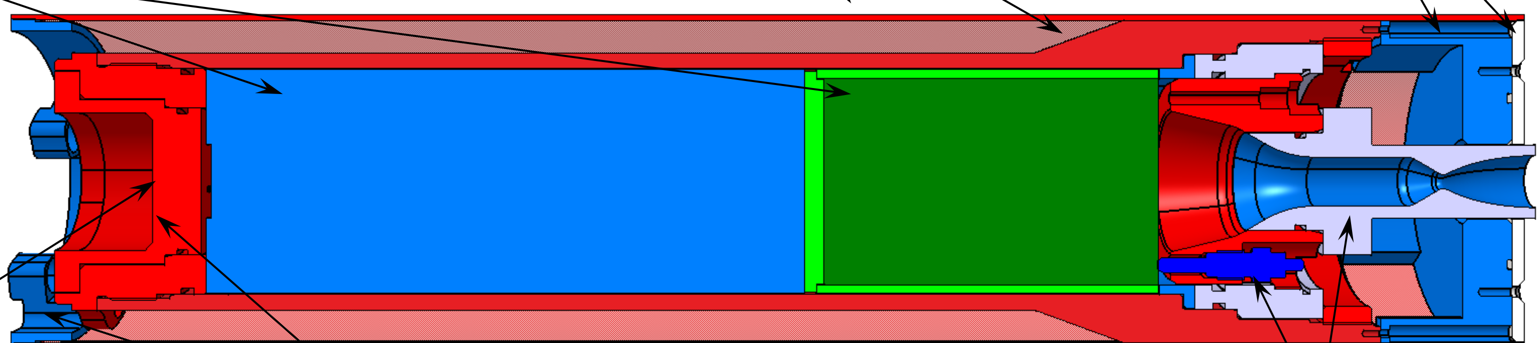
Methods: Test Environment
Model Components

combustion chamber
- *max. 15 MPa*

outer shell
- *double walled version*

spacer
PEEK base plates
- *IR measurements in the base region*

spacer, dummy propellants
- *HTPB/AP/AL*
- *HTPB/AP/MgO*
- *front burner/BATES*



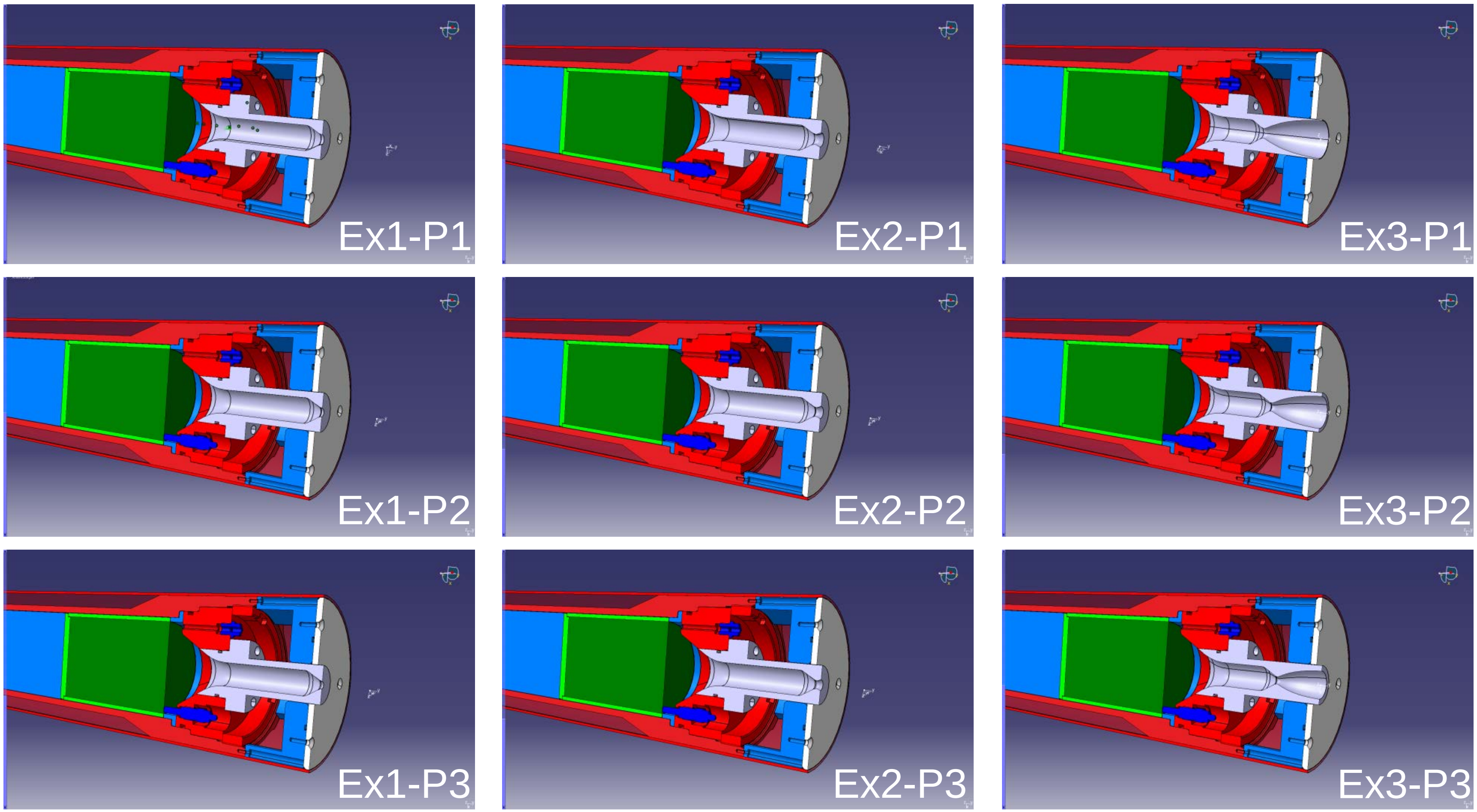
pressure sensors
- *Kulites*
- *high speed*

implemented sensors inside the model bottom

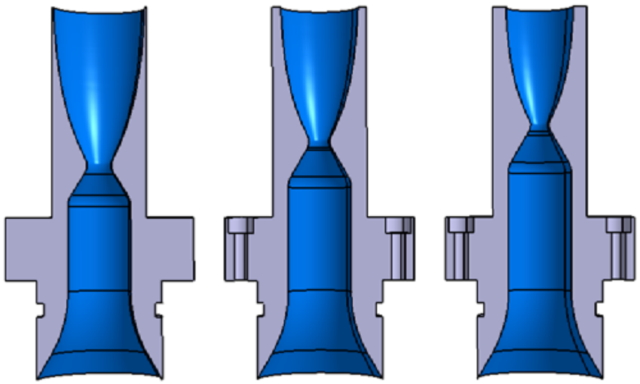
model mount
- *wind tunnel connection*

igniter
safety valves
model nozzle

Results: Test Environment
Nozzle Design/Operation Conditions

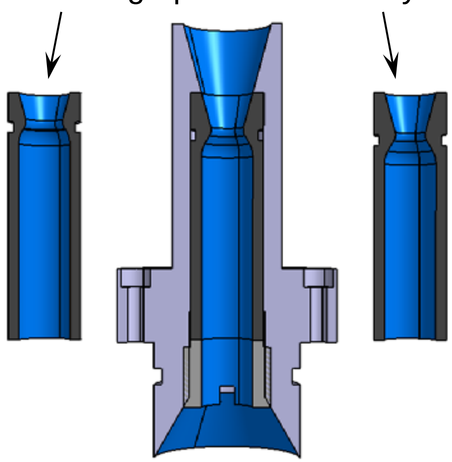


Results: Test Environment
Nozzle Design/Operation Conditions

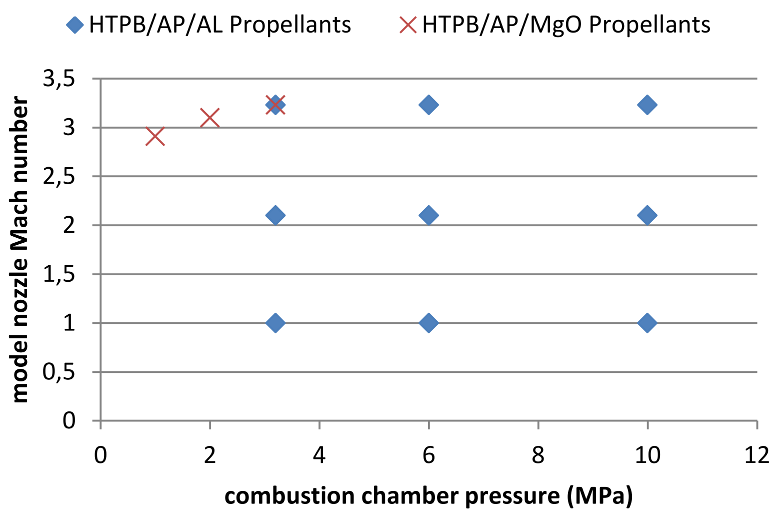


nine contoured tungsten model nozzles

variable graphite nozzle inlays

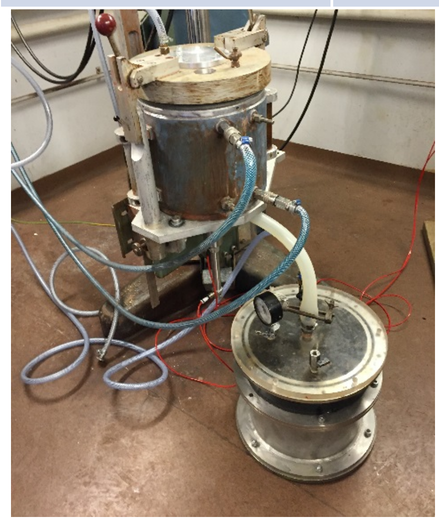


tungsten model nozzle



Methods: Test Environment
Global Solid Propellant Composition

Component	HTPB0015MgO (%)	HTPB0515 (%)	HTPB1814 (%)
HTPB binder	15	15	14
AP	79,5	79,5	67,5
Al	0	5	18
MgO	5	0	0
Fe_2O_3	0,5	0,5	0,5



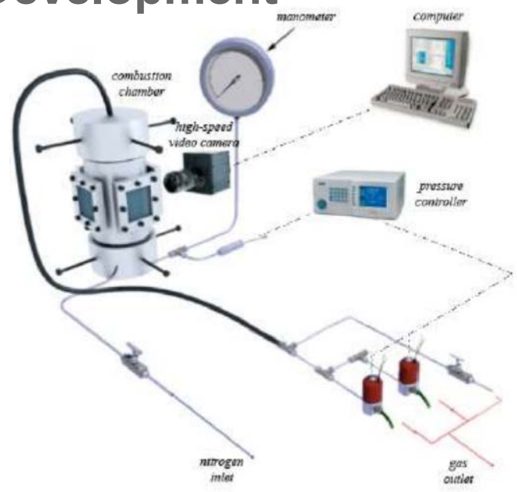
Methods: Test Environment
Lab-Scale Support to Propellant Development

Objectives of the activity

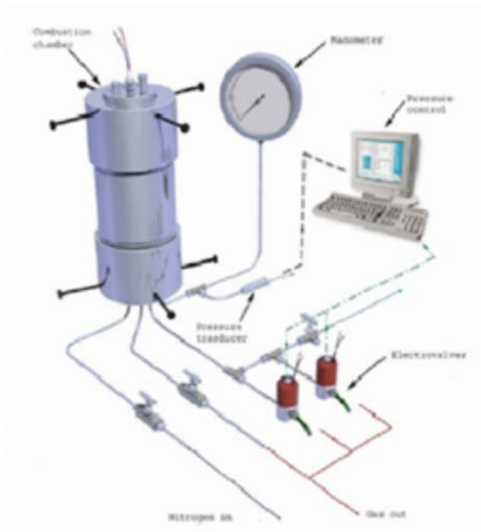
- Support the selection of seeding particles to insert in propellants
- Test the post-collection analysis procedure developed for the probe

Work performed

- Tests in quench bomb at similar pressures
- Burning rate measurement
- Analysis of condensed combustion products

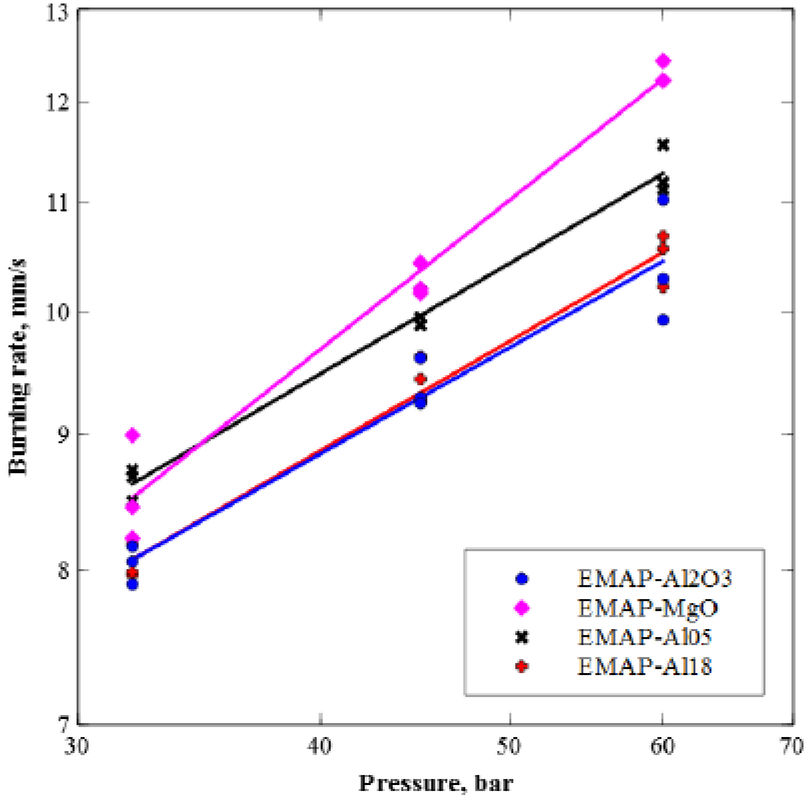


Burning rate experimental rig

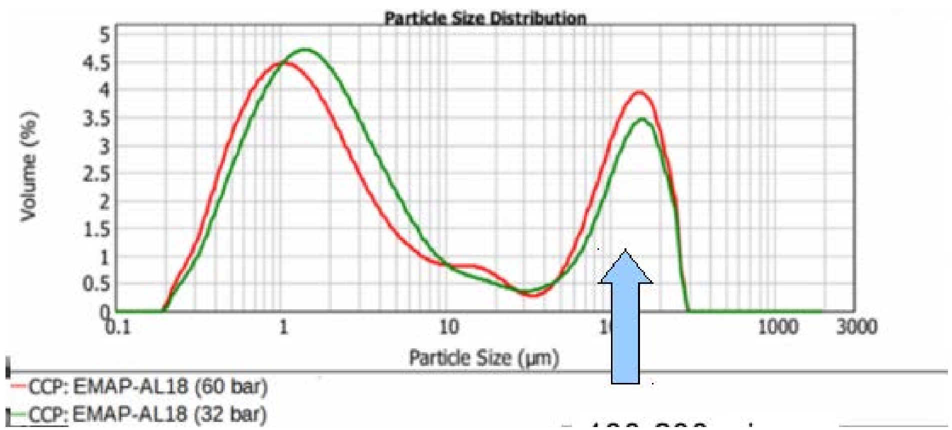


Experimental rig for collection of condensed products

Results: Solid Propellant Testings
Lab-Scale Support to Propellant Development

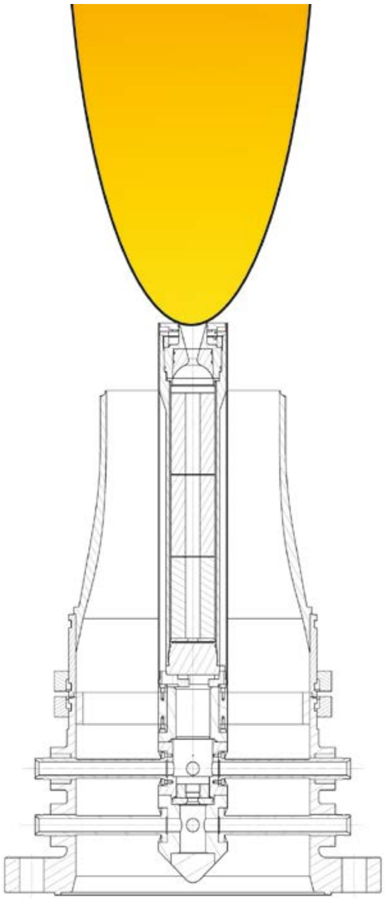


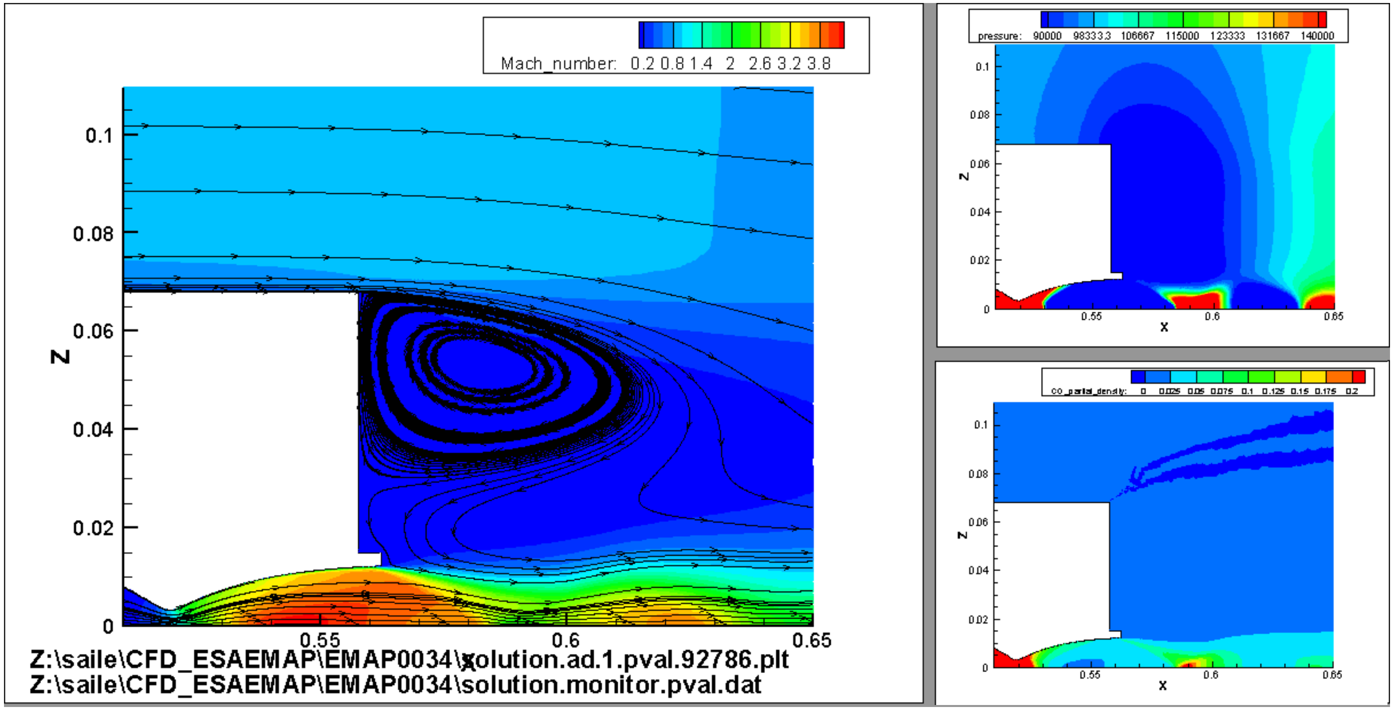
Typical burning rate results for the tested propellants



Condensed products for a AP/Al/HTPB propellant containing 18% of aluminum

Results: Measurement Concept
Flow Topology



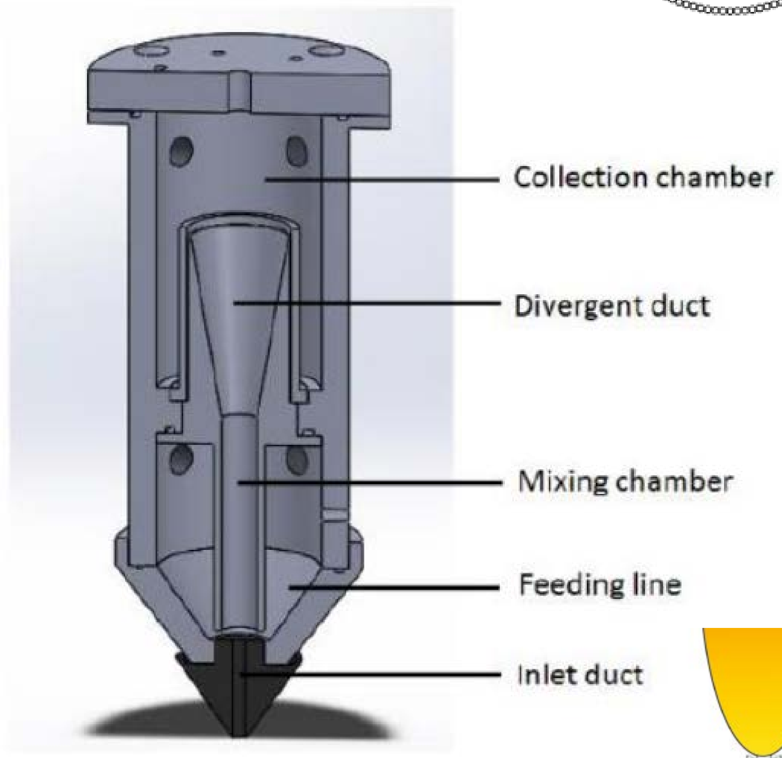


Results: Measurement Concept

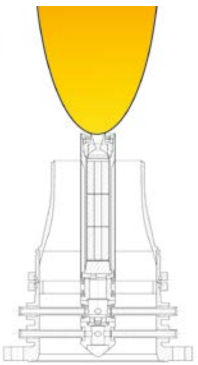
Supersonic Probe for Particle Collection

- **Main requirements**
- Collect particles inside the plume of a solid propellant rocket motor
- Operational time 0,5-1 second
- Fast reconditioning
- Enable particle post-collection analysis
- Nominal inlet Mach: 3.2

- **Features**
- Supersonic flow inlet, progressively cooled and slowed down
- Thermal management: passive (thermal protections + heat sink)
- Liquid quenching for collection of particles



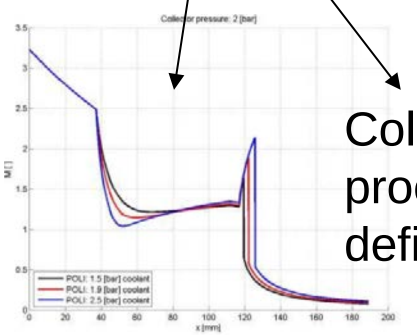
Incoming hot plume



Results: Measurement Concept

The Roadmap to Supersonic Probe Operations

Concept and preliminary design → Thermal structural development → Production → Cold flow validation → Fire tests

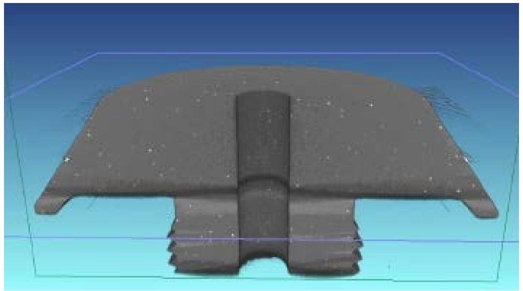


POLIRocket tool for quasi 1D flow design based on Shapiro approach

Collection procedure definition

Tests under relevant conditions for high-temperature material selection

Non destructive tomographic tests for graphite tip assessment



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Results: Measurement Concept
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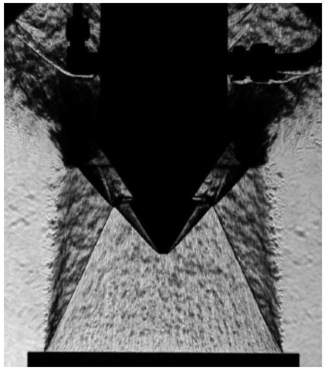
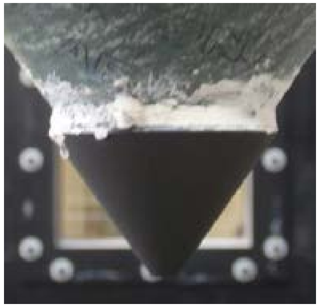
Concept and preliminary design → Thermal structural development → Manufacturing Integration in VMK facility → Cold flow validation → Fire tests



Validation of the internal gas dynamic design



Validation of materials in high Mach flow and of collection concept

Results: Measurement Concept
Plume Collection Probe Flow Simulation

- <u>Simulation Goals:</u>

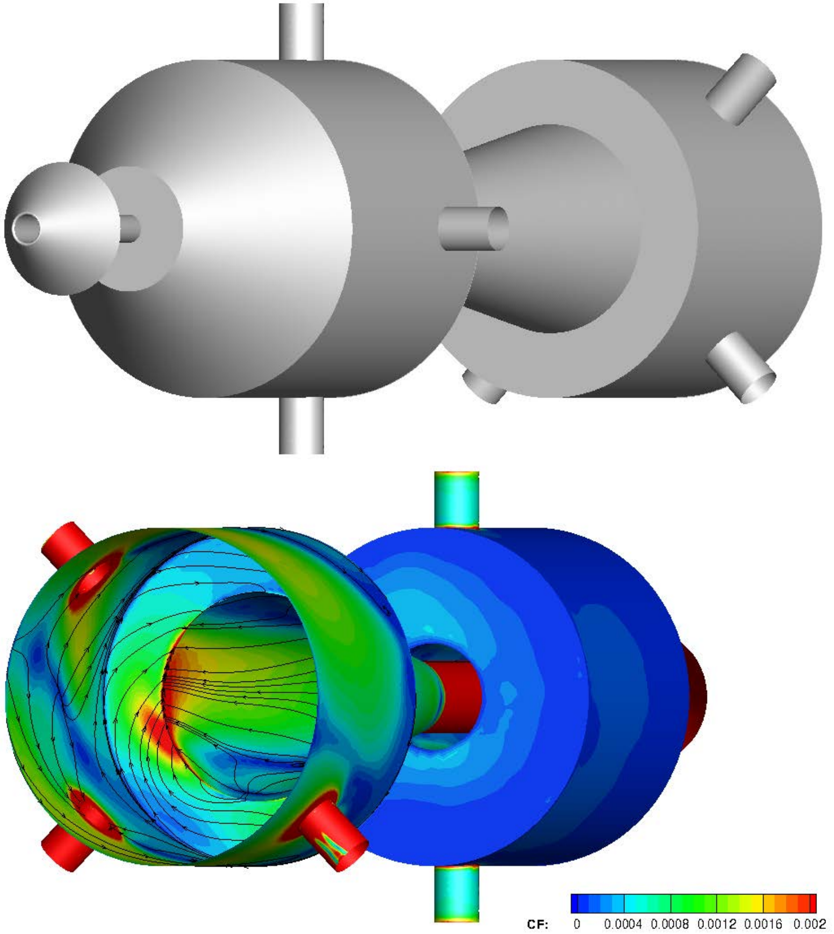
➢ Investigation of supersonic and subsonic internal multi-species flow in the particle probe to verify the concept of particle deceleration and flow cooling

➢ Ensure that sufficient cooling of alumina particles before transition to subsonic flow occurs → avoid particle breakup in order to preserve size distribution as found within SRM plume

➢ Provide design guidelines to POLIMI

Complex internal Geometry warrants computationally intensive 3D flow simulation

- DLR's TAU solver used
- Simulation on TEC-MPA's computational cluster



Top: Overview of computational domain

Bottom: Skin-friction coefficient plot on inner probe surfaces

Results: Measurement Concept
Plume Collection Probe Flow Simulation

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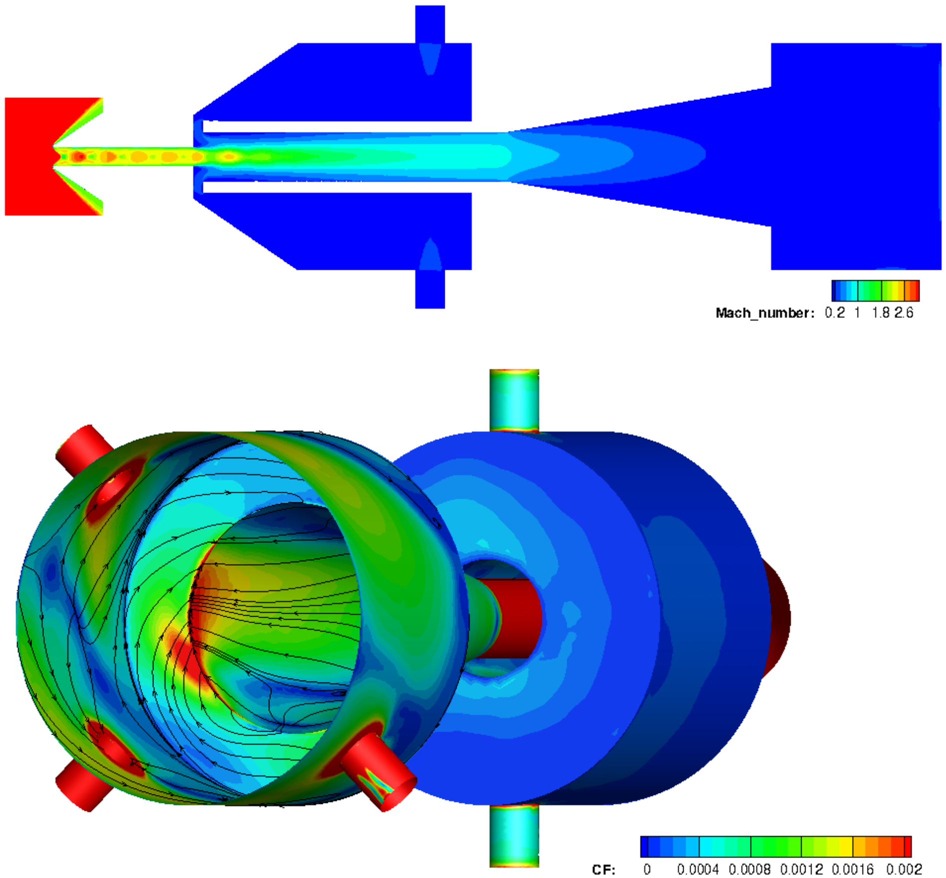
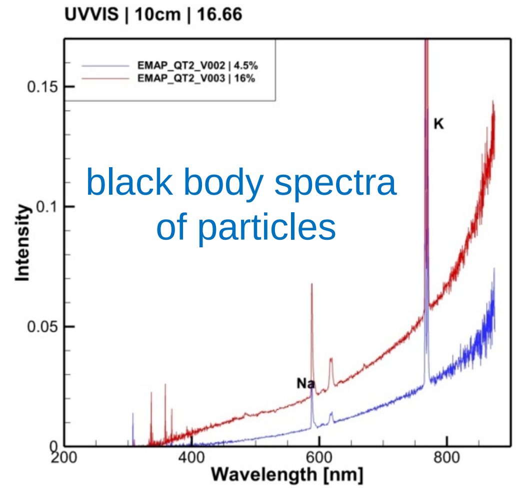
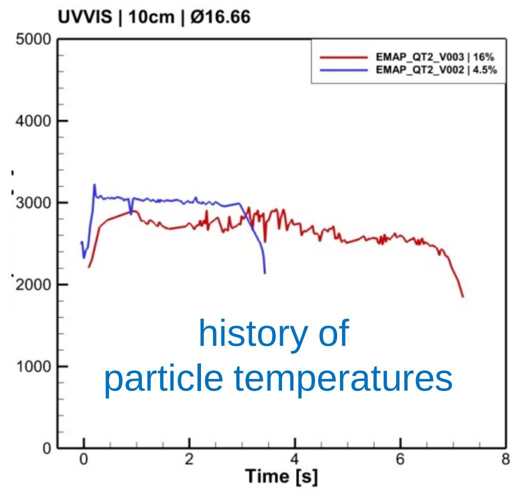
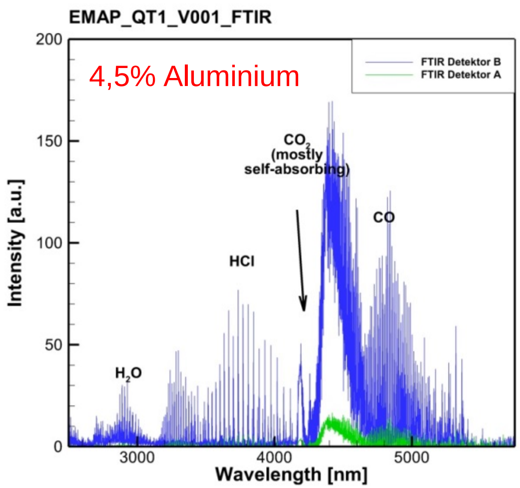


Top: Mach number contour plot on probe symmetry plane
Bottom: Skin-friction coefficient plot on inner probe surfaces

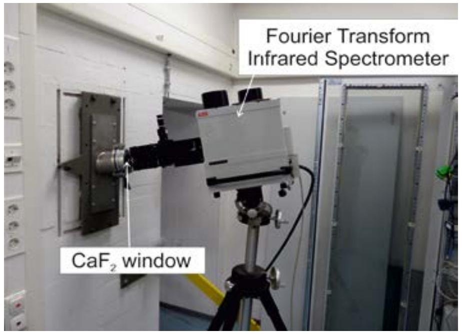
Results: Measurement Concept
UV-VIS & FTIR - Emission Spectroscopy







- species identification
- gas temperatures



Results: Measurement Concept
Alumina Emission Measurements (AEM)

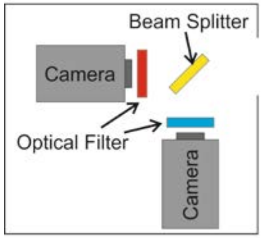
Determination of particle temperature (position dependend 2-color pyrometer)

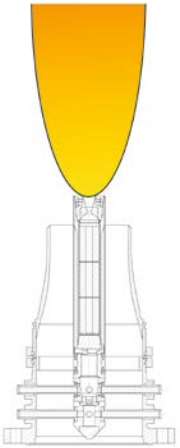
- Measurement of the ratio of the spectral exitances at to wavelengths

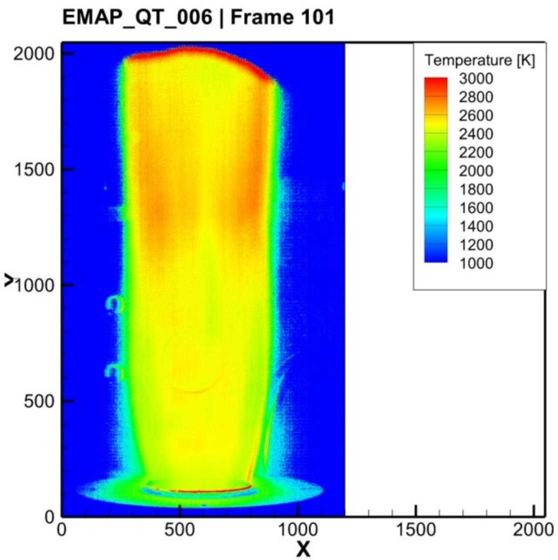
$$\frac{M_2(T)}{M_1(T)} = \frac{\epsilon_2(T)}{\epsilon_1(T)} \cdot \frac{{\lambda_1}^5}{{\lambda_2}^5} \frac{e^{\frac{hc}{\lambda_1 k_B T}} - 1}{e^{\frac{hc}{\lambda_2 k_B T}} - 1}$$

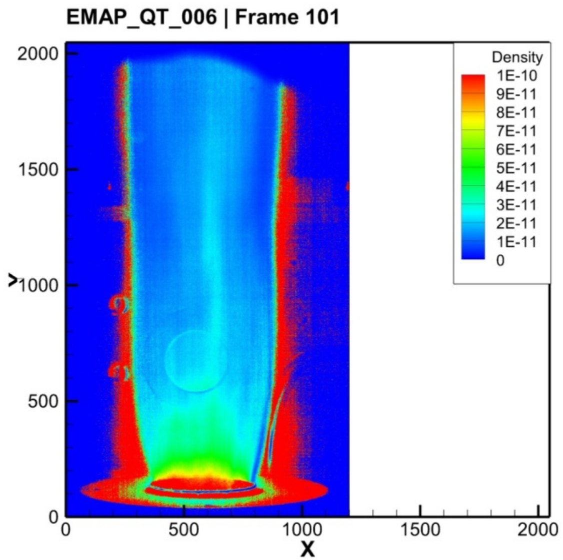
ratio of emissivities (literature values)

ratio of blackbody spectral exitances









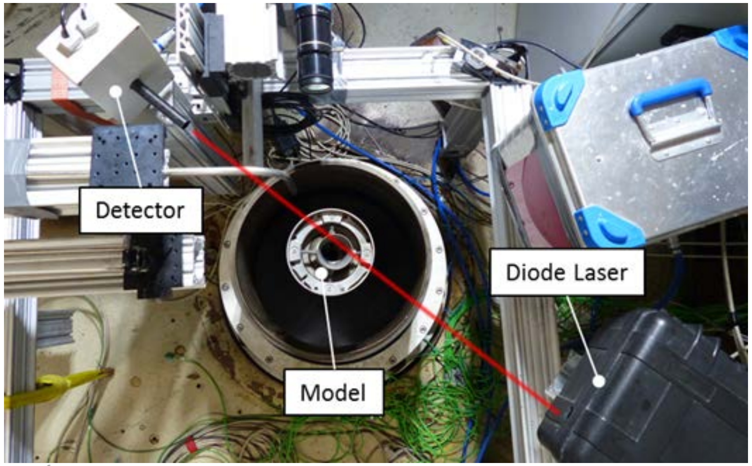
Results: Measurement Concept
Diode Laser Absorption Spectroscopy (DLAS)
Infrared Thermography (IR-Thermo)

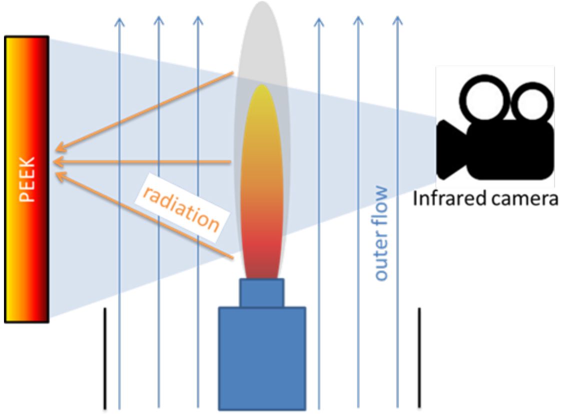
Diode **L**aser **A**bsorption **S**pectroscopy of carbon monoxide (CO-DLAS)

Precise measurement of the shape of a rotational absorption line of carbon monoxide at 2329.1nm and determination of CO rotational temperatures and CO partial concentration

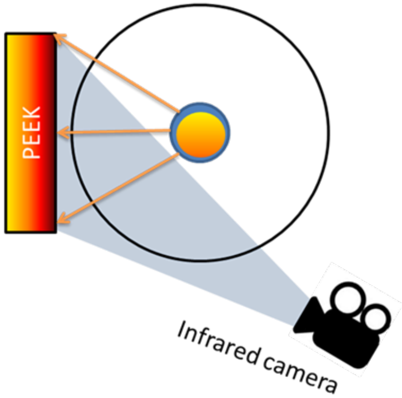
Infra**r**ed Thermography (IR-Thermo)

Measurement of the heating of an PEEK radiation absorber in the vicinity of the plume with an infrared camera in order to determine the radiative heat flux emitted by the hot flow





(a) Side View

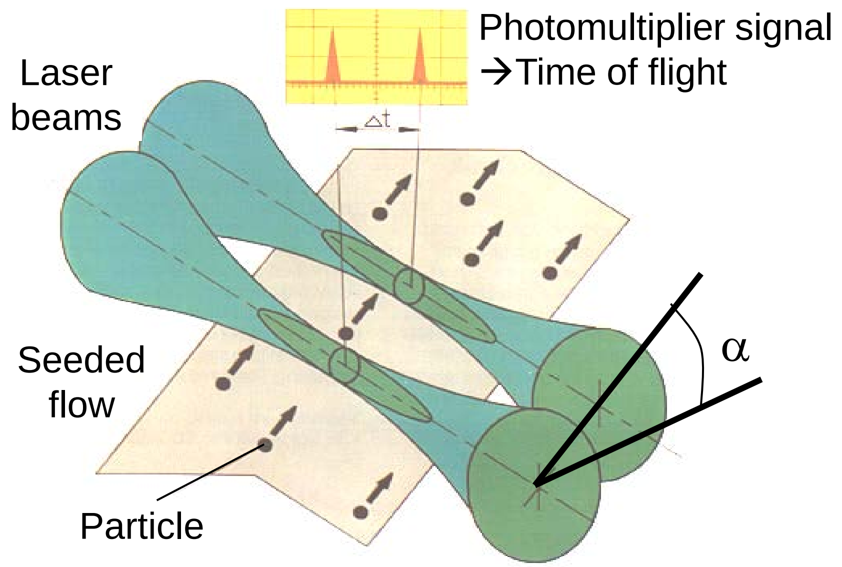


(b) Top View

Results: Measurement Concept

L2F Principle (2-component measurements)

- Time-of-flight (ToF) measurement of small particles convected with the flow (dia.: 0.3 … 1.0 µm)
- Flow velocity is determined by the focal distance of two parallel laser beams (D ≈0.2 … 0.5 mm)
- Flow direction is determined by turning the beam pair repeating the ToF measurement for different angles α
- For turbulent flows a statistical evaluation of multiple ToF readings is performed
- Evaluation of mean flow parameters (U_{mean}, flow angle, Tu)



Results: Measurement Concept

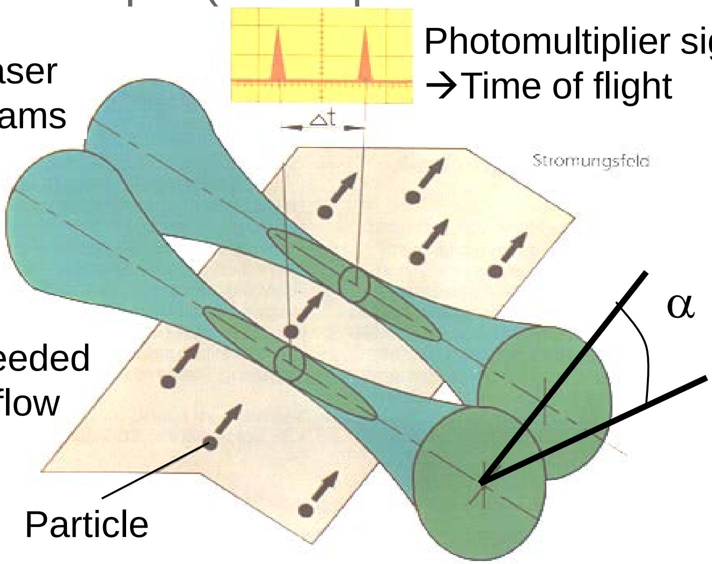
L2F Principle (2-component measurements)

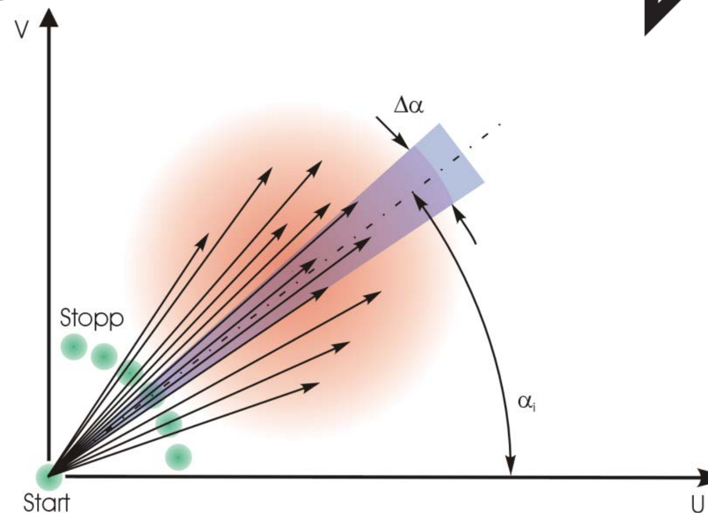
Photomultiplier signal
→Time of flight

Laser beams

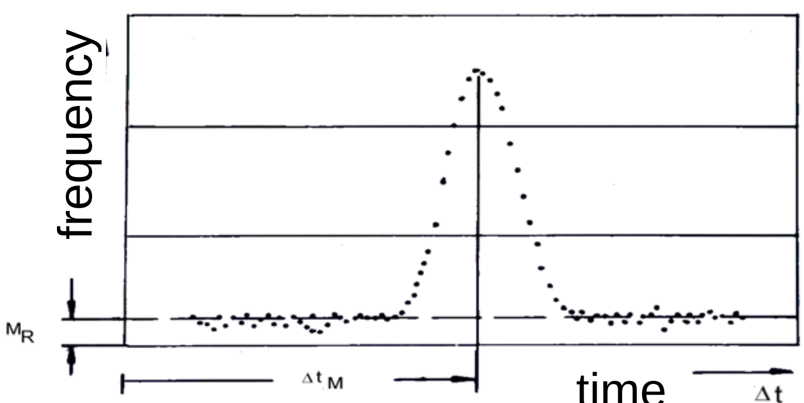
Seeded flow

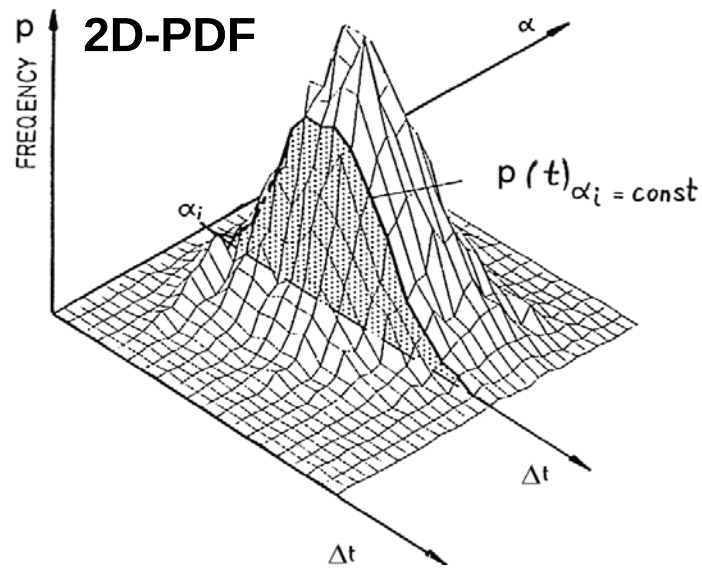
Particle





PDF for given angle α





Measurement Techniques
High-Speed Schlieren and POD of HSS

Short description of measurement principle

- Light deviation caused by differences in the length of an optical path through a medium with density gradients.

Setup details wrt the test environment

- See image

Expected results

- Temporally and spatially highly resolved visualization of the flow topology
- Sampling frequency: ~ 12 to 20 kHz

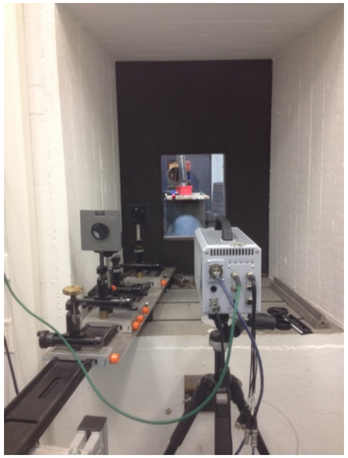
Literature references/comparable investigations

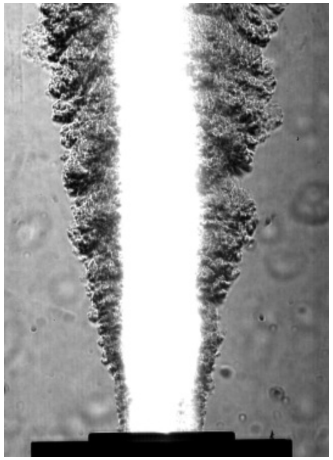
- See image**Complexity, uncertainties and risks**
- None

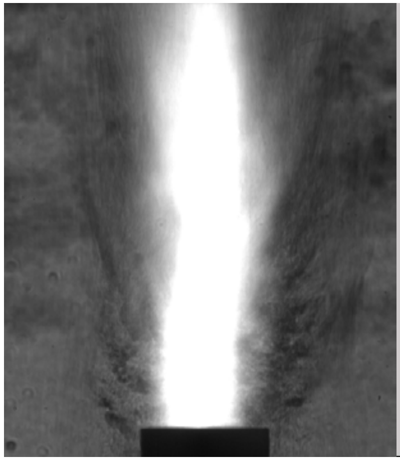
Cost-benefit analysis

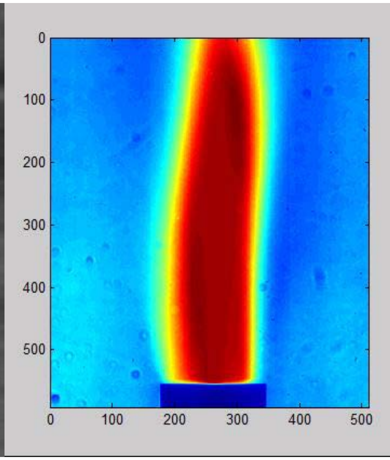
- Well-established, non-intrusive, line-of-sight, imaging measurement technique, straight forward setup

Measurement method will be applied for all experimental configurations.









Measurement Techniques

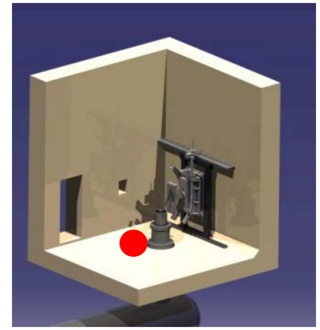
Particle Image Velocimetry

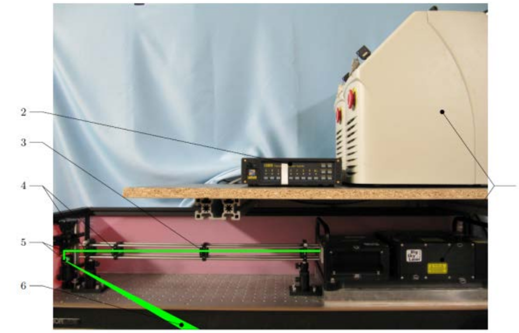
Short description of measurement principle

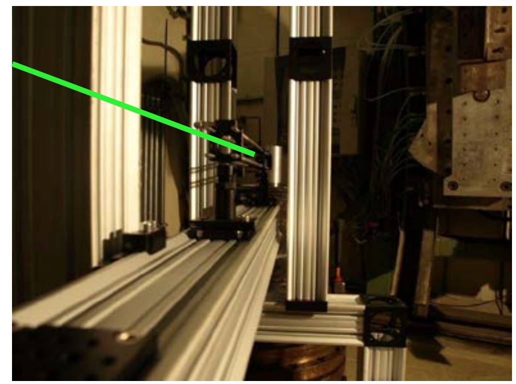
- Here: crosscorrelation of particle images. Intrinsic particles of solid propellants are used to track the particle velocity.
- Measurement equipment:
  - Camera PCO1600:
    - Resolution: 1600 x 1200 px, 7.4 um pixel size
    - Cooled 14 bit dynamic range
  - Ultra CFR Nd:YAG Laser, Big Sky/ Quantel
    - 190 mJ per pulse
- Sampling frequency: 15 Hz

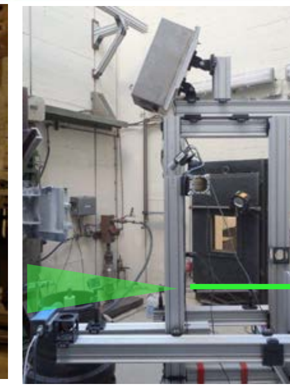
Setup details wrt the test environment

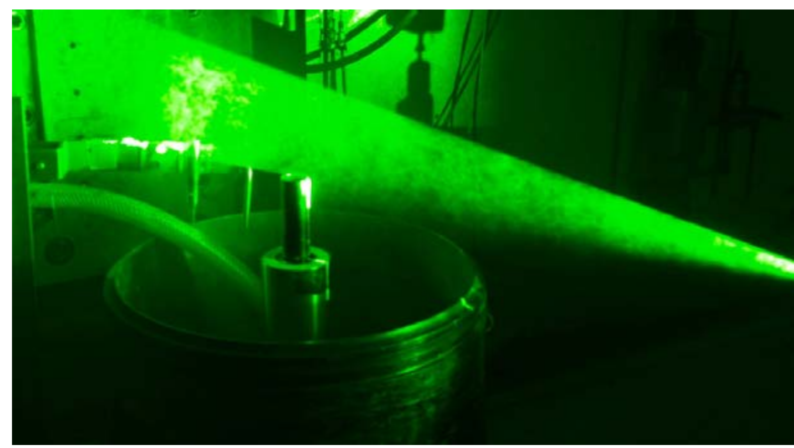
- See images



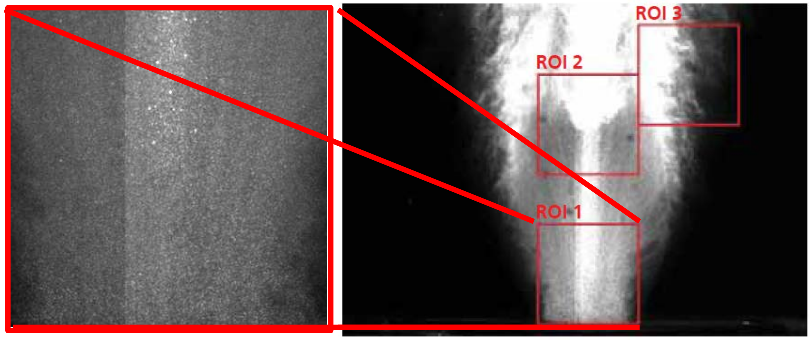








Measurement Techniques
Particle Image Velocimetry

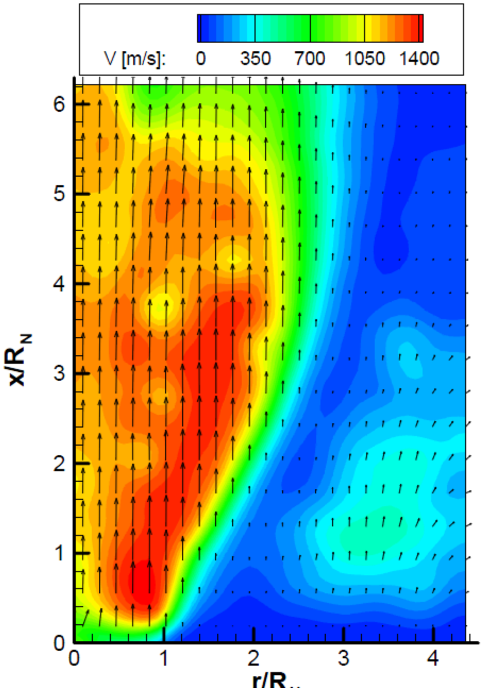


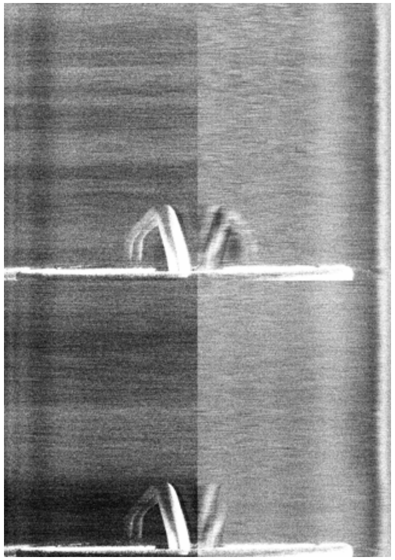
Complexity, uncertainties and risks

- Small region of interest
- Very high gas velocities, particle velocity is difficult to predict, setting of interframing time is done after calibration with COTS solid propellants
- No transmittance due to high optical density for HTPB1814 → not applicable
- High density gradients cause a deflection of the optical path
- Nominal case: For 2700 m/s (!gas velocity!) + time delay: Δ t = 120 ns → Δs = 0.324 mm → ~1.3 mm/vector

Cost-benefit analysis

- More sensitive setup, small ROI, most likely only applicable for HTPB0515, uncertainties wrt distortions (optical path)
- Non-intrusive, imaging measurement technique
- Data wrt to particle distribution, particle size distribution and velocity





Measurement method will only be applied for particle-loaded propellants; for HTPB0015: free stream could be seeded, but has not been discussed and is not part of the objective; for HTPB1814: no data is expected

Results: Measurement Concept

Requirements & Measurement Techniques

- Experiments are very challenging! In some cases, more experience must be gained while running the experiments.

- Experiments marked in
  - Green: confident wrt results
  - Orange: output requires precursor tests/will show capabilities „on the go“

L2F	Laser-2-Focus
PIV	Particle Image Velocimetry
FTIR	Fourier Transformed Infrared Spectrometer
UV/Vis.	Emission Spectroscopy
Schlieren	Schlieren and Shadow Technique
IA	Incipient agglomeration
RPC	Rocket plume collection
AEM	Alumina Emission Measurement
MWI	Microwave Interferometry
P.Trans.	Pressure Transducer
IR	Infrared-Thermography

			CC	**Jet**		
				Method 1	Method 2	Method 3
Alumina	**Size and spatial distribution**	required	IA	RPC		
	Phase state	additional	na	AEM		
	Agglomeration	required	IA	RPC	PIV	
	Temperature	required	na	IR	UV/Vis.	FTIR
	Velocity	required	na	PIV	L2F	
Flow properties	**Temperature**	required	na	CO-DLAS		
	Velocity	required	na	CO-DLAS	MWI	
	Pressure	required	P.Trans.	P.Trans.		
	Species concentration	required	na	CO-DLAS		
	Species identification	additional	na	UV/Vis.	FTIR	
	Density gradient	additional	na	Schlieren		
Thermal radiation	**Surface temperature**	required	na	IR		

Conclusion

- Test environment was selected.
- Wind tunnel model has been developed.
- CFD data has been generated regarding an approximation of the wake flow and
- Numerous measurement techniques have been
  - considered,
  - selected and
  - tested/qualified in validation tests for hot gas tests.
- Numerical data has been generated to validate the design of the rocket plume collector.

- Tests will start end of January 2017

End

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• Team	1 slide	D. Saile
• Motivation	1 slide	D. Saile
• ESA requirements	1 slide	D. Saile
• Concept	1 slide	D. Saile
• Flow topology CFD	1 slide	C. Groll/D. Saile
• Wind tunnel & model	1-2 slides	V. Kühl
• Solid propellant (dev./man.)	1-2 slides	N. Wingborg
• Solid propellant (characterization)	1-2 slides	F. Maggi/S. Carlotti
• Measurement techniques		
• Plume Collection Probe	1-2 slides	F. Maggi/S. Carlotti
• Plume Collection Probe CFD	1 slide	C. Groll
• Spectroscopic methods	2 slides	L. Steffens
• DIPSD	1 slide	D. Kerkhoff
• IR-thermography+DLAS	1 slide	J. Riehmer
• L2F	1 slide	C. Willert
• APS+PIV+HSS	2 slide	V. Kühl
• Conclusion/Outlook/Scheduling	1 slide	D. Saile