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ESA, Technical Centre ESTEC

ID : 3125302

Title : Challenges on modelling fluid-dynamic problems of space propulsion systems. Overview of selected programmatic efforts at the European Space Agency

Theme :

Attached documents :

Abstract submission-JLongo.pdf

Resume :

Current and expected developments in space transportation have led to growing interest in new solutions for the design of propulsion systems. These new solutions require essential improvements over current one in order to ensure economic viability and to fulfil mission and safety constraints. The size and complexity of this problem has led to growing importance of numerical tools for design and optimization involving the coupling of many disciplines as well as the optimal use numerical techniques and computer resources. The high design sensitivities for new spacecraft and the small payload fractions for launcher vehicles make necessary new development and test approaches, with numerical multi-disciplinary simulation and optimization as well as experimental vehicles playing a deciding role.

This paper presents the current programmatic efforts at the European Space Agency in order to facilitate the solution of some of those issues. The status of the physical modelling and code development issues such as numerical algorithms, grid generation and validation strategies are addressed. The problem to obtain adequate data for code validation is discussed. The strong need to validate the computer codes by comparison with experiments is for high enthalpy flows not an easy task due to the wide spectrum of physical conditions to be reproduced in the experiments. Measurement techniques, sensors, ground facilities and in-flight experimentation are addressed and discussed. While viscous, high enthalpy unsteady flows are still restricted to simple problems due to a strong demand in computer resources, computational fluid dynamics (CFD) based multidisciplinary analysis is emerging as a key element in aerospace design. Supported by a continuous, almost linear, growth in computer capacity and performance, this new procedure to conduct design and analysis is paying off. However, the effective use of CFD to more complex applications, require more sophisticated algorithms, since one of the key problems here is the treatment of multiple space and time scales. These arise particularly for combustion problems, where chemically reacting flows, flame fronts, turbulent flows and plasma dynamics need to be simultaneously accounted.

The paper addresses a number of selected problems of multidisciplinary character with complex high enthalpy physics like transient flow problems with cryogenic fuels like sloshing, priming, chilldown; but also problems like buffeting, acoustic, plume impingement and contamination.

Challenges on modelling fluid-dynamic problems of space propulsion systems at ESA
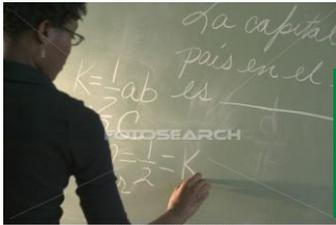
Overview of selected programmatic efforts (2013-2017)

J.M.A. Longo
European Space Agency

Space Propulsion 2016
Rome, Italy, May 2 to 6, 2016
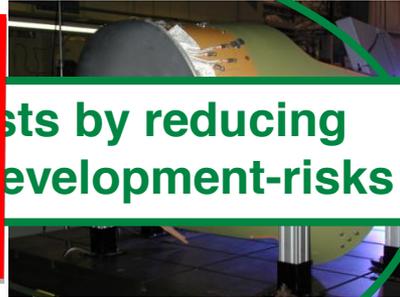
European Space Agency

1. Idea

2. Fundamental Research
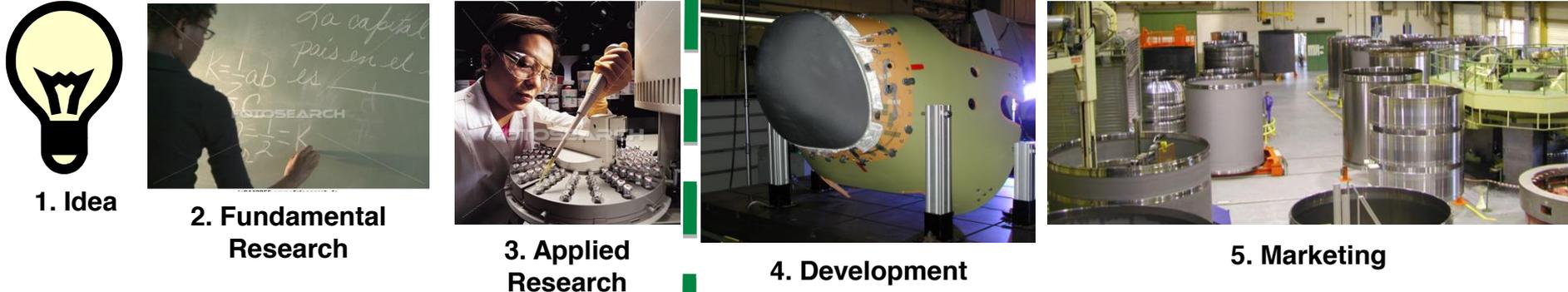
3. Applied Research

4. Development

5. Marketing

reduce costs by reducing drastically development-risks

Virtual Product

The long term objective of ESA in Aerothermodynamics is to provide tools for a virtual product, here defined as the philosophy of providing a reasonable estimate with maximum possible errors in the predicted performances, to certify the system prior the first flight.
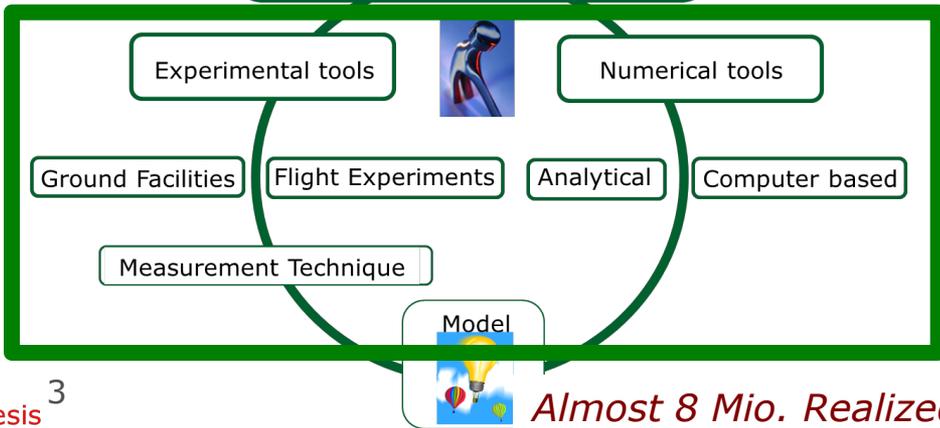
1. Idea

2. Fundamental Research

3. Applied Research

4. Development

5. Marketing

TEC ← **TRL ~ 5** → **FLPP, LEE, …, ARTES, CV, EO**

security margin

uncertainty

ATD is a predictive engineering science *provide reasonable estimates with* **maximum possible errors**

Experimental tools

Numerical tools

Ground Facilities

Flight Experiments

Analytical

Computer based

building blocks approach

Measurement Technique

Model

hypothesis

3

Almost 8 Mio. Realized since 2013

European Space Agency

Contents

- **Propellant feedlines**
- **Propellant tanks**
- **Rocket plume**
- **Intake flows**

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Characterization of a cryogenic propulsion valve (TechSpace-Aero, BE):
Characteristic relationship between the volumetric flow rate and pressure drop across the valve for liquid nitrogen and water. For the cryogenic tests, temperature measurements at the valve inlet and outlet are also presented, as well as visualizations of the flow upstream the test section. The experimental results show that the valve flow coefficient is identical for both liquid nitrogen and water in normal flow regime.
*L. Peveroni et al. Experimental and numerical study of the flow characteristics in a cryogenic valve with liquid nitrogen and water. Proceedings of the 8th European symposium on aerothermodynamics for space vehicles, March 2015, Lisbon, Portugal.*
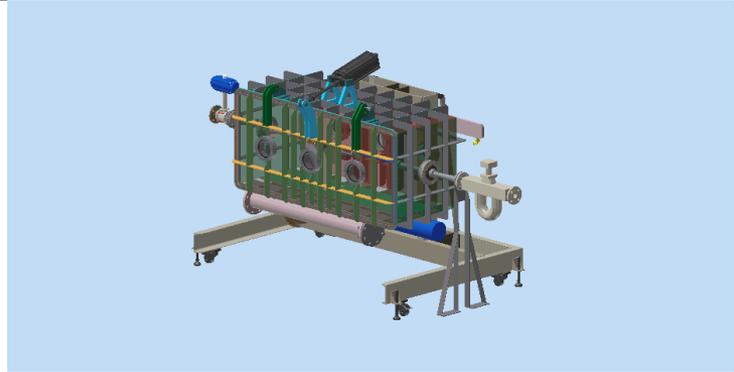
CryoLine vacuum chamber and test section (VKI)

Comparison between numerical and experimental results obtained in the cryogenic valve.
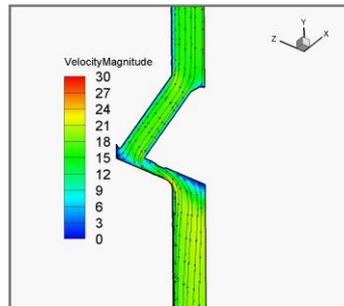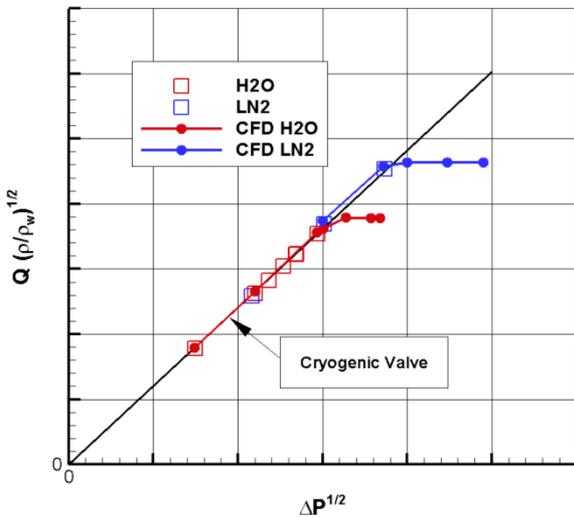
Velocity magnitude and streamlines along a 2D section of the Cryogenic valve (VKI)

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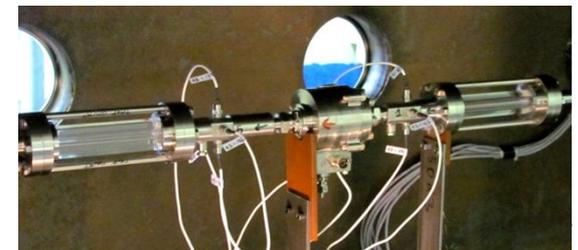
Sapphire window, cryogenic valve and pressure temperature modules (VKI)

**Modelling of chill down two-phase flow phenomena (ET GmbH, DE):**
Measurement of pressure and temperature during the transient phenomena; high speed visualisation of the liquid two-phase flow; determination of the two phase flow characteristics (bubble velocity, bubble shape,…).
Experimental investigation of cryogenic two phase flow. Energie Technologie GmbH (DE), ESA Contract no. 4000111616/14/NL/PA. S. also Session 46 SP2016.
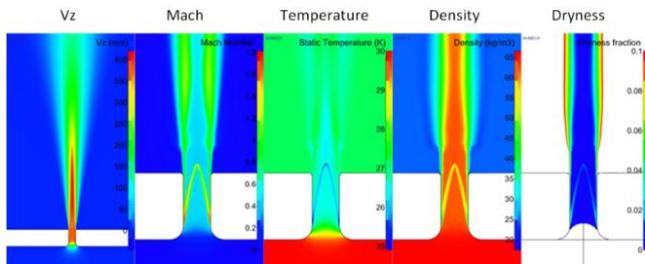
Example of Pipeline chilldown

CHIEF vacuum chamber and measurement section (VKI)
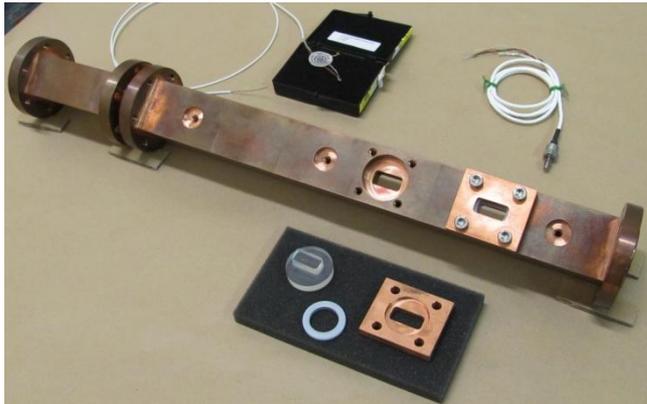
CHIEF measurement section representative of a real engine cooling channel (VKI)

Cryogenic pressure transducer (VKI)

Numerical simulation flow through orifice (NUMECA)

Cryogenic temperature transducer (VKI)

Fluid Hammer Facility (VKI, BE):
A dedicated facility representative of the priming process in a satellite propulsion system to create a reliable experimental database. The facility integrates the elements affecting the fluid hammer occurrence, i.e., the pressurized liquid reservoir, the fast opening valve (FOV) and the propellant line with a closed end. These elements are clamped on a vertical rigid structure.
J-B. Gouriet et al. Multiphase fluid hammer with non-cryogenic and cryogenic fluids. Proceedings of the 8th European symposium on aerothermodynamics for space vehicles, March 2015, Lisbon, Portugal.
S. also Session 46 SP2016.
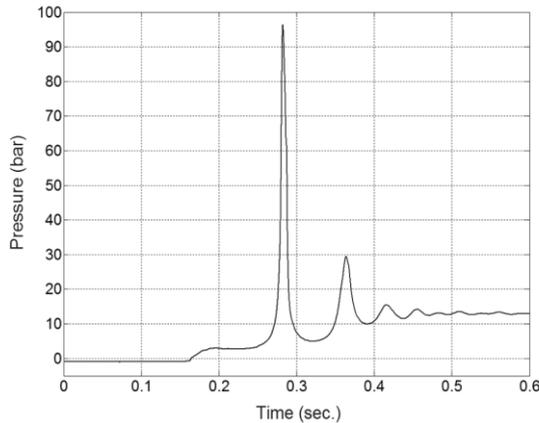
Typical pressure surge measured at impact location (transducer P3)
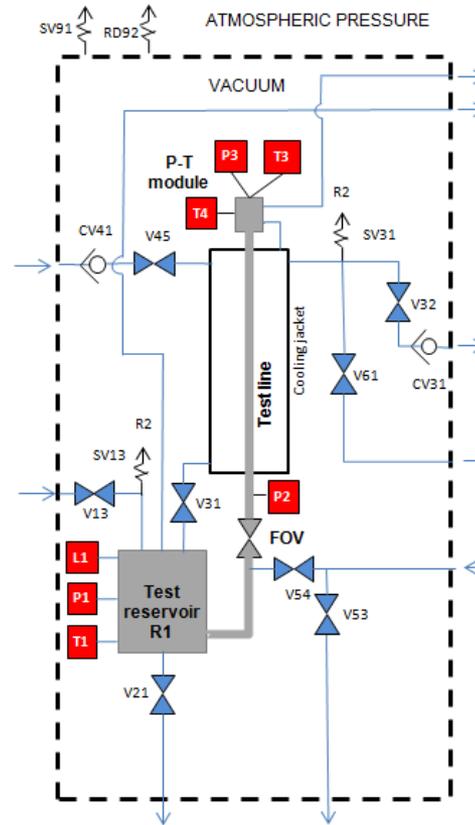
Piping & Instrumentation Diagram of the Fluid Hammer Facility

Fluid Hammer Facility (VKI) Top: chamber closed; bottom: chamber open.

European Space Propulsion Simulation System ESPSS (Empresarios Agrupados, ES):
a propulsion system library capable of modelling various kinds of dynamic systems: modelling & simulation of spacecraft and rocket propulsion systems; design and Analysis of steady state condition able to reproduce all rocket engine cycles; simulation of all possible transient phases from start-up to shut-down; simulation of in-orbit conditions of spacecraft propulsion systems (including flight dynamic forces as a function of attitude and orbit); simulation of subcomponents interaction like solar arrays, reaction wheels, gravity booms, and tanks.

M. Leonardi et al. A zooming approach to investigate heat transfer in liquid rocket engines with ESPSS propulsion simulation tool. Proceedings of the 8th European symposium on aerothermo-dynamics for space vehicles, March 2015, Lisbon, Portugal.
S. also Session 69 SP2016 and the Poster exhibition.
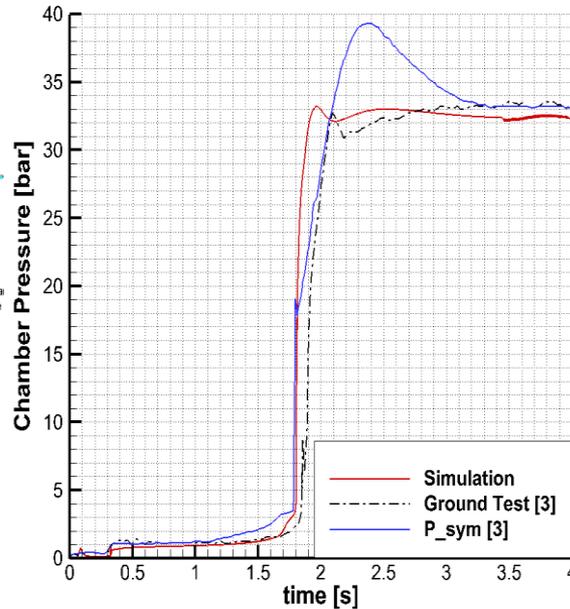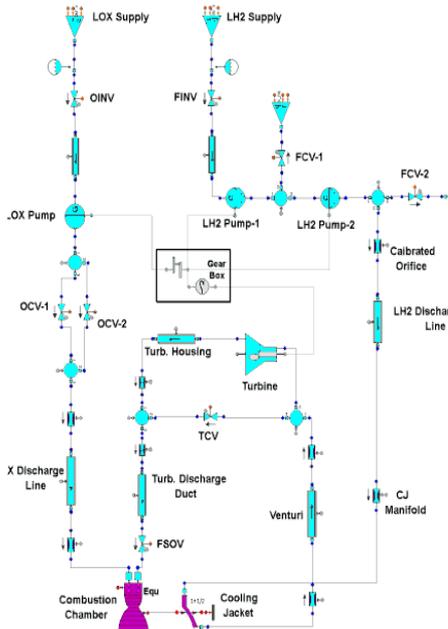
RL-10 start-up: ESPSS(red), TEST(black), NASA(blue). AIAA-2011-6032
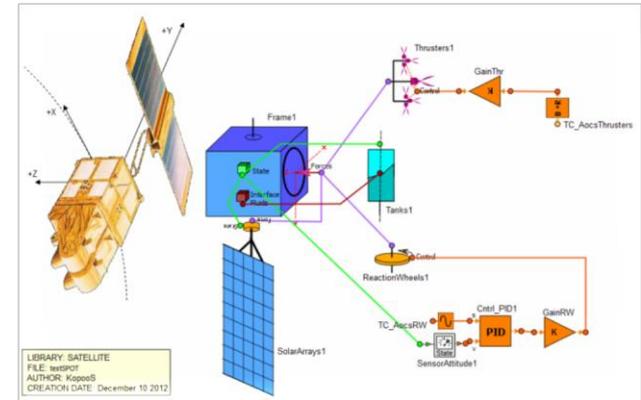
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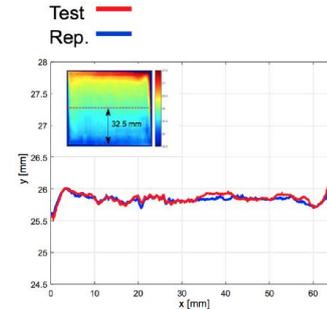- **Propellant tanks**
- Rocket plume
- Intake flows

**Prediction methods for propellant management devices (NUMECA, BE):**

Accurate description of propellant phenomena like linear and non-linear sloshing, thermal stratification, ullage pressure variation, liquid settling, chill down and boiling for the development and validation of CFD methods for the design and verification of tanks and the related Propellant Management Devices (PMD) for conventional and cryogenic propellants during all phases of a typical mission of a space vehicle.

C. Dinescu et al. A verification an validation approach for eulerian modelling of sloshing flows. Proceedings of the 8th European symposium on aerothermodynamics for space vehicles, March 2015, Lisbon, Portugal.
S. also Session 30 SP2016.
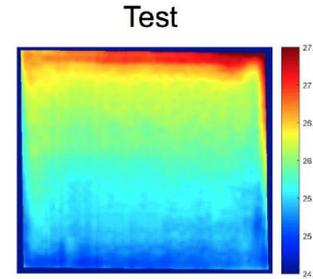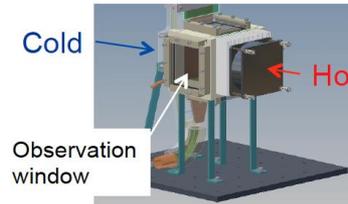
Experimental detection of thermal stratification using LIF (VKI)
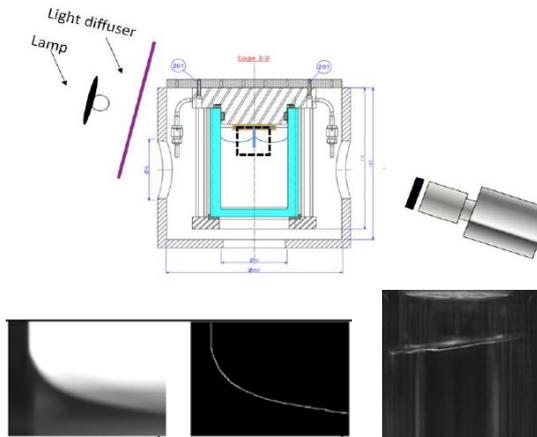
Experimental detection of wall angles and free surface topology (VKI)

Experimental facility for boiling tests(VKI)

Characterization of sloshing with cryogenic fuels (DLR, DE):
Bubble detection and surface topology measurements using ultrasound tomography; nuclear magnetic resonance tomography; computed X-ray tomography; time-of-flight camera; optical tomography; Electrical tomography; microwave tomography; cavity perturbation method; particle velocimetry; wire-mesh sensors and fibre optic.

Advanced measurement techniques for validation of CFD for cryogenic flows in reduced gravity. DLR (DE), ESTEC/Contract no. 4000109332/13/NL/Cbi.
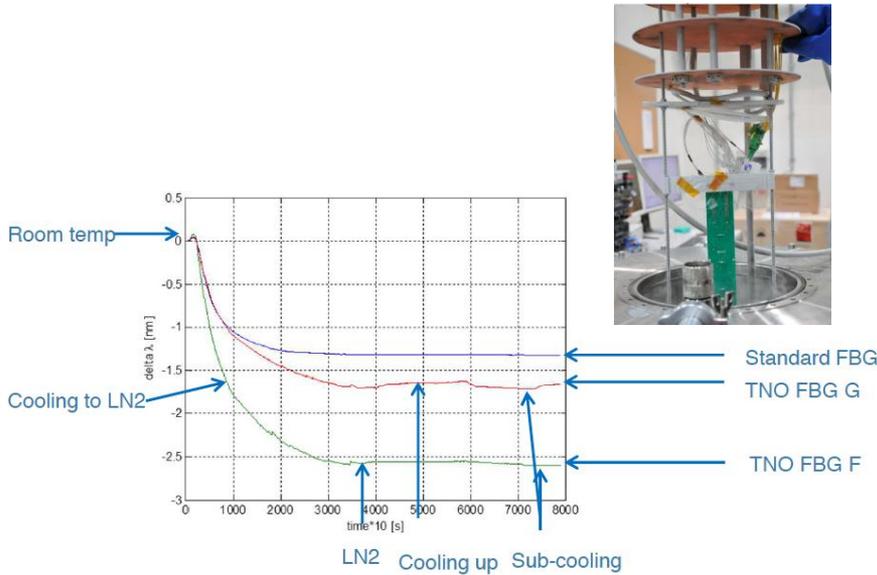
TNO fibre optic test performance at DLR facility

European Space Agency

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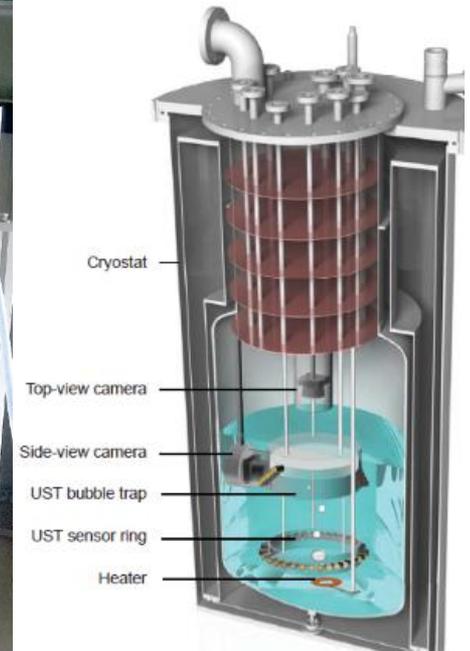
Fibre optic, ultrasound tomography array and test facility (DLR)

Diaphragm design

Numerical modelling tool for evaluation of sloshing-reaction control system coupling (NUMA, IR):
Design and validation of a ground based experiment to simulate non-linear sloshing phenomena in tanks of spacecraft. Enhanced comprehension of the effects of non-linear slosh dynamics on spacecraft stability by extrapolation of experimental results to flight conditions.
Numerical modelling tool for evaluation of sloshing-reaction control system coupling (SI). NUMA Engineering Services Ltd., ESA Contract no. 400011493/14/NL/PA.
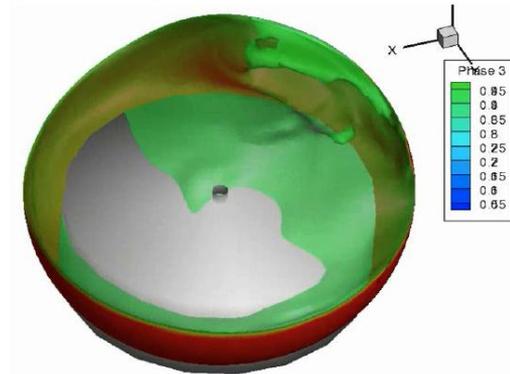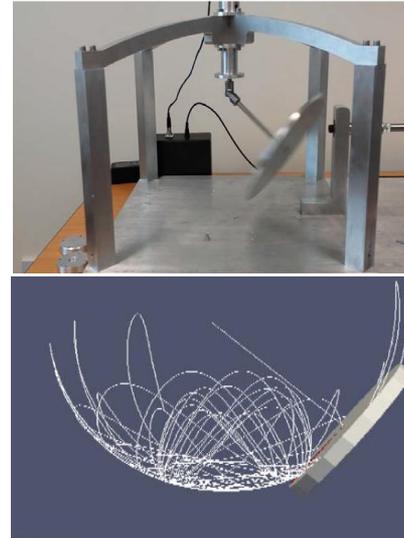
Comparison of gyroscopic and fluid motion under spin and linear acceleration (NUMA)

Verification of diaphragm analysis (MT Aerospace, DE):
Experimental simulation of membrane tank filling/draining and lateral sloshing. Provide with models to estimate the impact of numerically non-resolved effects as history and scatter on folding and damping properties. Implementation into FSI tools in form of, e.g. adapted uncertainty margins for the numerical prediction.
Verification of Diaphragm Analysis. MT Aerospace AG, ESA Contract no. 4000114567/15/NL/KML.
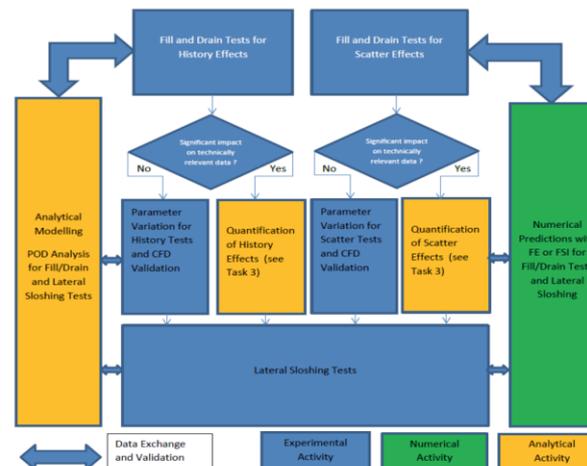
Work Logic (MT Aerospace)

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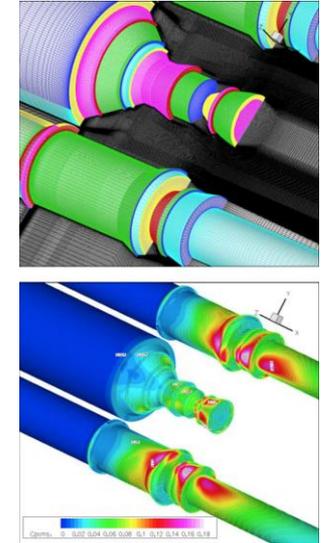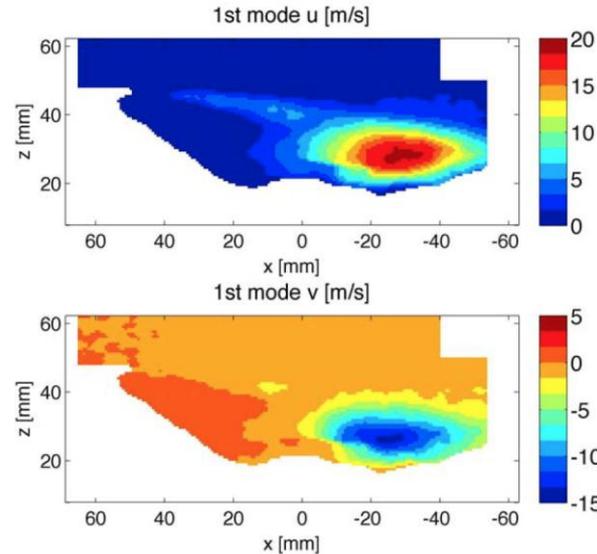- **Intake flows**

Base flow:
Characterization of the gas dynamical flow phenomena and their interactions, e.g. compression shocks, shear layers, expansion fans, in the base region of an expendable launcher vehicle by means of experimental data recorded with high-speed PIV measurements and reduced using proper orthogonal decomposition methods. Provide detailed knowledge on the status of CFD methods for rebuilding such type of flows.
K. Hannemann et al. Launch vehicle base buffeting-recent experimental and numerical investigations. Proceedings of the 7th European symposium on aerothermodynamics for space vehicles, May 2011, Brugge, Belgium.
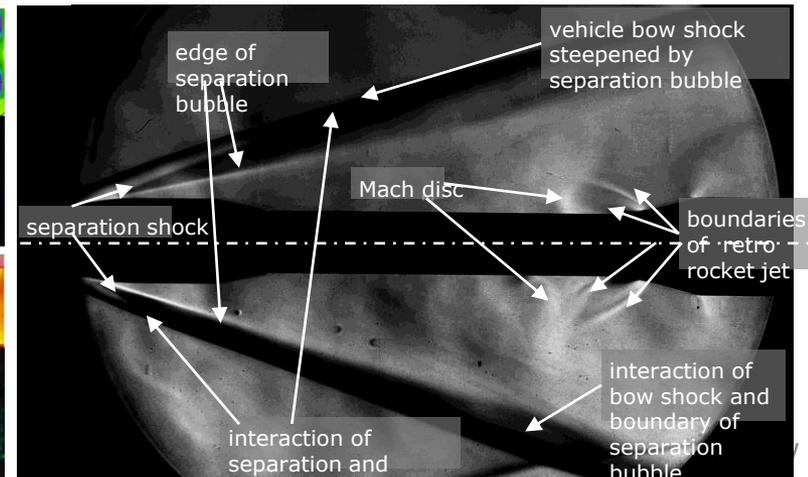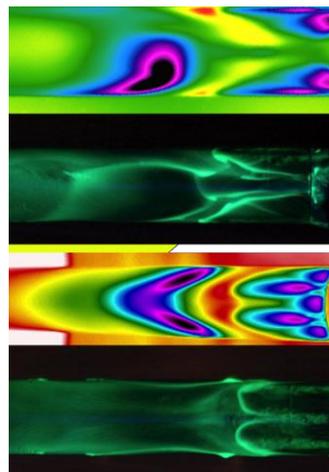
Stage separation:
Reconstruction of the complex flowfield that occurs during serial stage separation when the plumes of retro rockets interact with the freestream flow creating asymmetric, unsteady, events on the upper stages.
Launcher stage separation and plume interaction validation. DLR (DE), ESA Contract no. 4000102454/10/NL/NA.

Retro-rocket deceleration:
Upgrade a rarefied gas facility and its associated measurement techniques to verify the performances of a RCS capable to control and guide an entry probe for Mars landing.
Mars Robotic Exploration Program-2. ESA/Prog. Ref. E918-008MP.
S. also Poster exhibition SP2016

POD results (TU Delft) and Numerical simulation (ONERA)

edge of separation bubble

vehicle bow shock steepened by separation bubble

Mach disc

separation shock

boundaries of retro rocket jet

interaction of separation and

interaction of bow shock and boundary of separation bubble

Experimental surface and flow visualization (DLR)

Plume and soil testing facility (Uni. Glasgow, UK):
a vacuum facility in which it is possible to carry out different measurements on flows with dust particles and fulfil the following detailed objectives:

assessment of scaling phenomena, vacuum effects and pulsing of rockets; erosion effect of the plume impingement on the planet surface (airless bodies and Martian conditions); lateral extent and depth of regolith contamination due to rocket plumes; impact of the plume/regolith interaction on the spacecraft (forces and moments); effect of the regolith liberated by the rocket plume impingement on the spacecraft forces and moments and particularly on the engine and engine-nozzle during lunar/planetary landing operations; brown out due to plumes and surface dust.

As secondary objective the facility will be capable of allowing small, controlled blasts to initially assess the fragmentation of structures in reduced atmospheres.

Effect of a regolith liberated by a rocket plume impingement. FGE (UK), ESA Contract no. 4000115469/15/NL/KML.

Plume-soil interaction characterization (FGE, UK):
Characterization of the thruster exhaust plume in vacuum conditions, by collecting the species distribution and thermodynamic data in the plume at a number of streamwise locations downstream of the nozzle; and by determining the sticking coefficients of the thrusters species on the regolith surface.

Phobos sample return. ESA/IPC(2015)135.
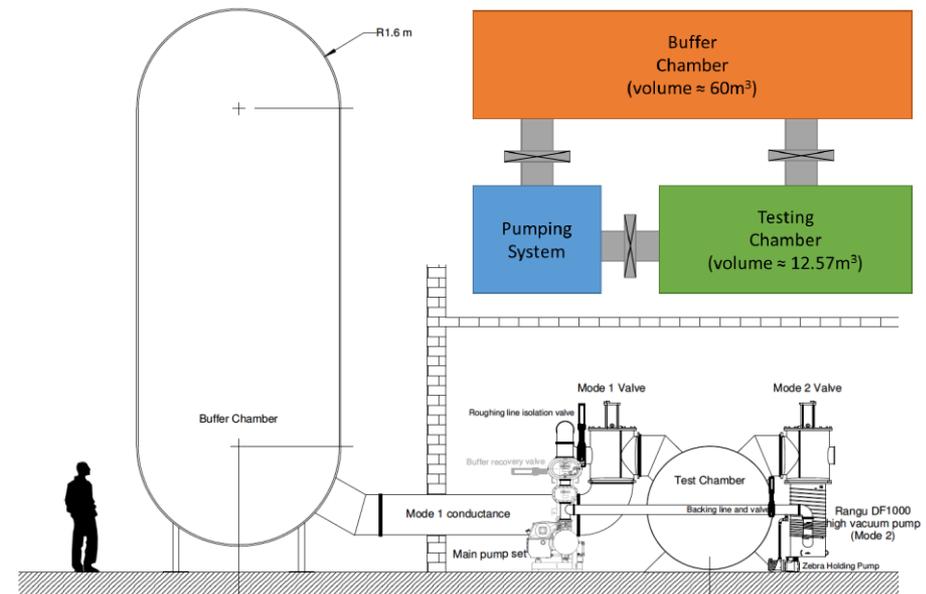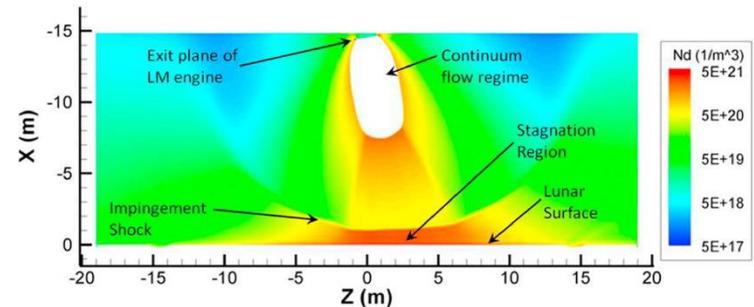
Experimental modelling (DLR, DE):
Experimental characterization of the flow of a representative solid rocket motor. In particular the alumina particulate in several planes starting upstream of the nozzle inlet until downstream of the nozzle exit. Measurement of the plume thermal radiation.
Experimental modelling of alumina particulate in solid booster. DLR (DE), ESA Contract no. 4000114698/15/NL/SFe.

Numerical modelling (CFS, CH):
Upgrade existing numerical tools for the computation of hot plumes from solid rocket boosters, by implementing chemistry and radiation models for solid particles.
Modelling of hot plumes with particles for improved launcher applications. CFS (CH), ESA Contract no. 4000115215/15/NL/SFe.

In flight measurement (CNES, FR):
Conduct a flight test through the plume of an ESA launcher at French Guiana. The science campaign focuses on the determination of the alumina particulate size distribution and chemical concentrations through the plume of the launcher.

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Assessment of key aerothermodynamics element for a RAM-EP concept (SITAEL, IT):
Experimental demonstration of the feasibility of a ram-Electric Propulsion system concept by performing an end-to-end test in a ground facility: particle flow generator, hall effect thruster for RAM application, integrated RAM-EP system composed by the RAM-HET and the intake/collector assembly, measurement technique.
*G. Cifali et al. Experimental validation of a RAM-EP concept based on hall effect thruster technology. Proceedings of the Space Propulsion 2016, May 2016, Rome, Italy.*
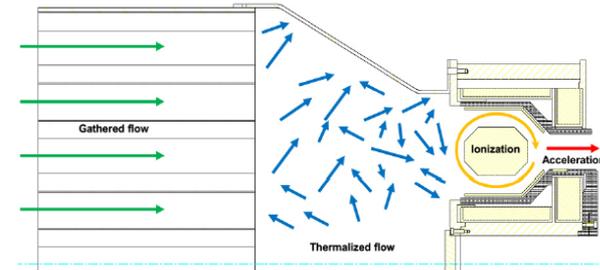
Flow generator and diagnostic system (SITAEL)

collector   thruster

intake
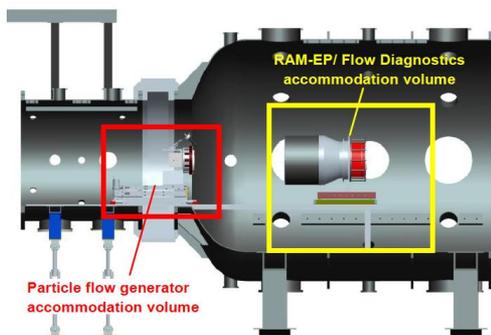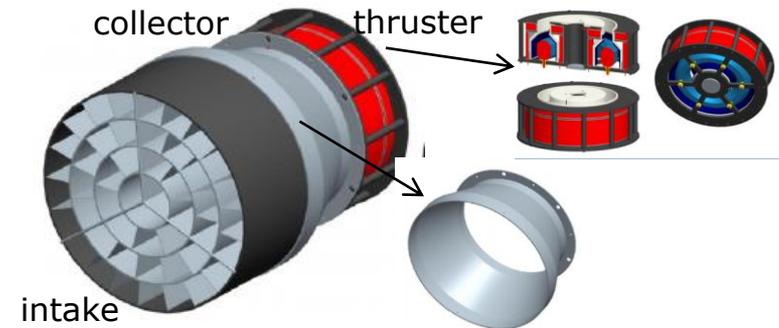
|	Flight condition	Ground test @ 500 mm far from the source
Number density [1/m³]	1.16E+16	7.25E+16
Flow velocity [km/s]	7.8	9.1
Flow field shape	parallel	conical
Incoming MFR [mg/s]	4.26	3.05
MFR to the thruster [mg/s]	1.27	1.2
Drag area [m²]	1.1	0.125
Cd	2.2	2
Drag force [mN]	40.52	35
RAM-EP Thrust [mN]	45	23
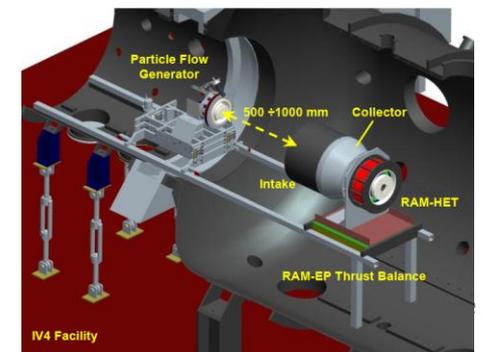
Close Remarks

The long term objective of ESA in Aerothermodynamics is to provide tools for a virtual product, here defined as the philosophy of providing a reasonable estimate with maximum possible errors in the predicted performances, to certify the system prior the first flight.

Within this context, in all the flight phases there are large number of problems involving fluid dynamics still waiting to be modeled and solved.

Most of them require in addition to aerothermodynamics, the involvement of other disciplines, like physics of materials, chemistry, optic, quantum physics, to mention some of them.

Further, in the majority of the cases, the problems take place during unsteady conditions, either transient phases or dynamic phases of the vehicle motion. Thus, their solution demand huge amount of computational resources, advanced mathematical solvers, sophisticated measurement techniques as well as dedicated facilities and specific flight experiments.
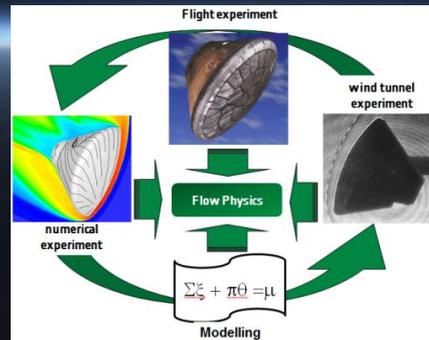
ESA will be striving for increased international co-operation in aerothermodynamics with the classical partners like US, Russia, Japan and Australia but also Worldwide in the frame of Fundamentals Sciences for Hypersonic.

Thank you