Heat Transfer Measurements with Methane in Rocket Nozzle Cooling Channels

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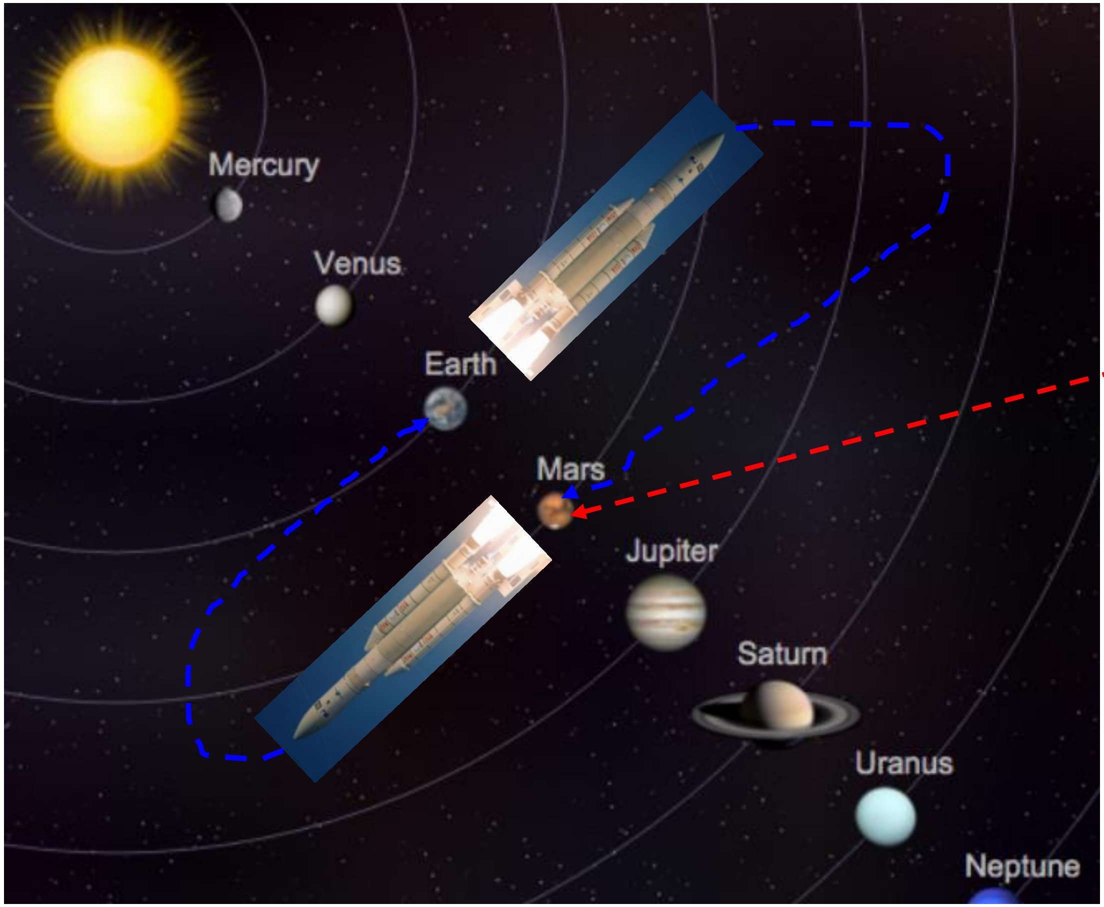
Aerospace Congress 2019, 8-9 Oct 2019

Will we ever explore Mars in the future and how do we come back?

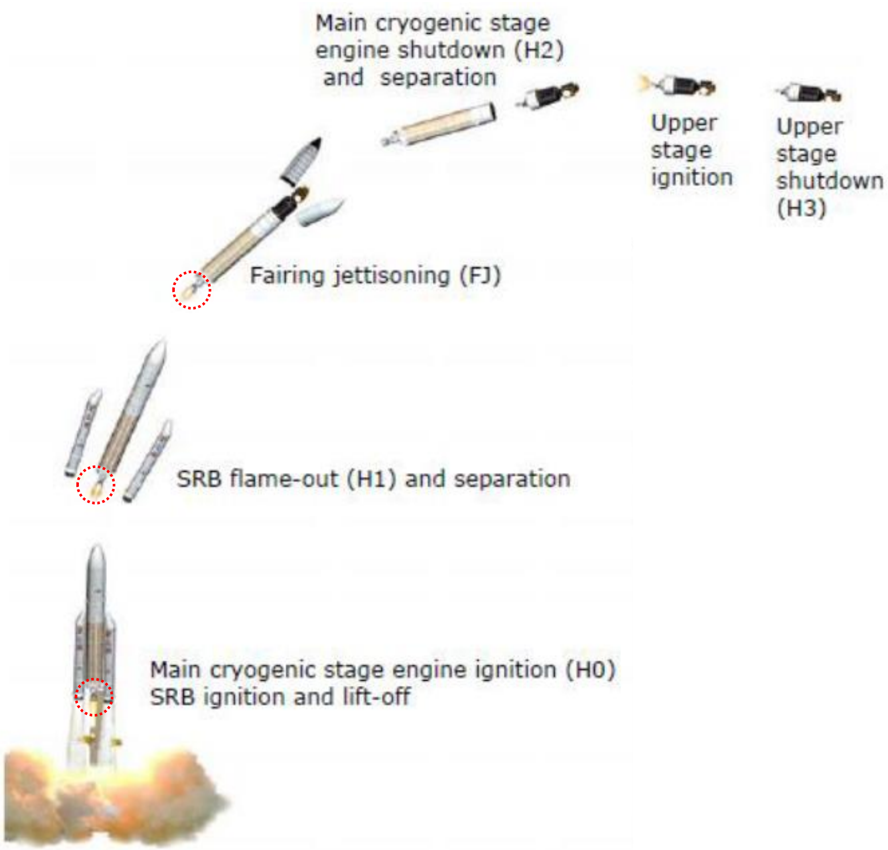


Refuling?
Why methane?

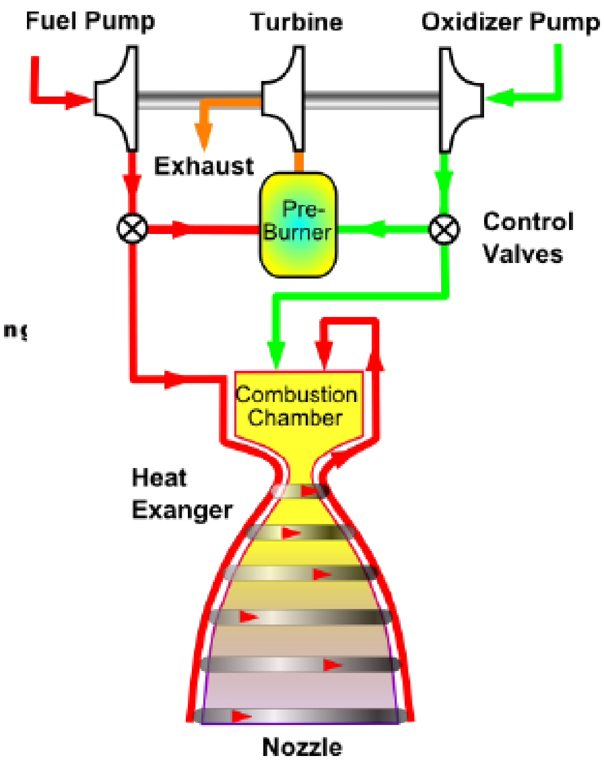
Outline

- Background
- Objectives
- Methodology
- Outcomes
- Summary and future outlooks

Ariane 5 Launch



Gas Generator Cycle with Turbopumps



- Simple integration, simple control
- Relatively high power -> main engine lift-off
- High pressure ratio turbines -> supersonic, impulse type
- High temp turbines
- Exhaust gas losses-> lower ISP than SC

$$I_{SP} = \frac{u_e}{g_0}$$

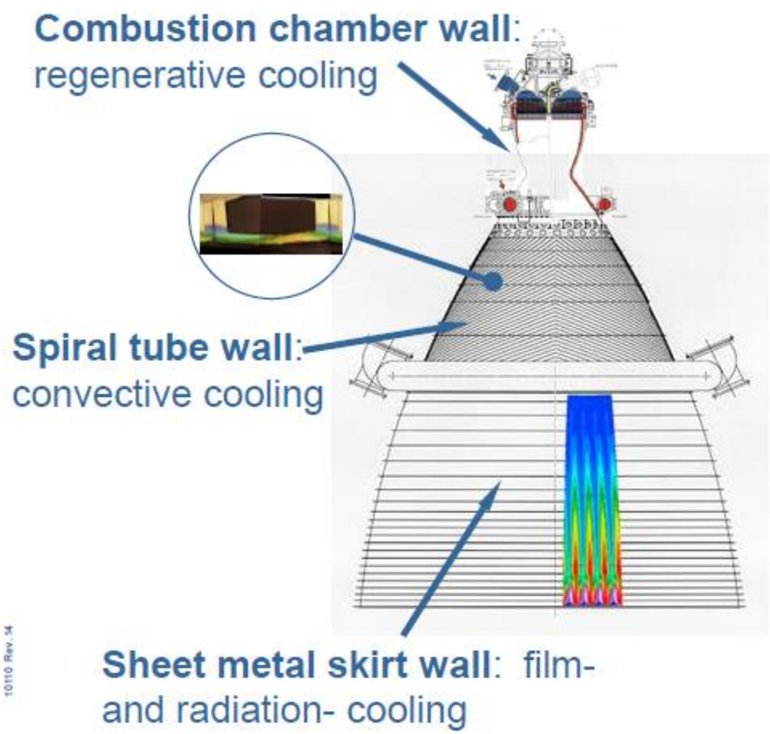
$$F_{thrust} \approx \dot{m} \cdot u_e$$

Vulcain 2 (Ariane 5, main)

- 1st stage main engine, 8% of lift-off power
- Corresponds to 3 Airbus A340s
- 1350 kN Thrust at sea level
- 431s Isp (LOX-H2)
- Mass flow 316 kg/s, turbine exhaust 10kg/s
- Runs 600s
- 1800 kg weight
- 73,6 thrust-to-weight ratio LOX/LH2
- CC pressure 117 bar
- *Expendable*

Heat loads - cooling

- Typical heat transfer rates in rocket propulsion are higher than those in jet engines.
- Combustion temperatures ~*2 the melting point of steel.
- The maximum temperature obtained at nominal/extreme operational conditions dictates the choice of material and also the cooling method/layout that can be used.



Vulcain 2 NE

MERiT - MEthane in Rocket nozzle cooling channels - conjugate heat Transfer measurements

- Propulsion system using hydrocarbons (Methane)
  - grand challenge for today's rocket and space propulsion systems
  - Possibility for re-fulling @ extraterrestrial territories with local assets (Mars… H20 + CO2 + energy, Sabatier process)
  - Good performance indicators for methane
    - good specific thrust (~380 s @ sea level) & cooling charact.
    - low cost, non-toxic, availability & ease of handling/storability
    - Higher density,lower oxi/fuel ratio → smaller tank (comp. to LH2)

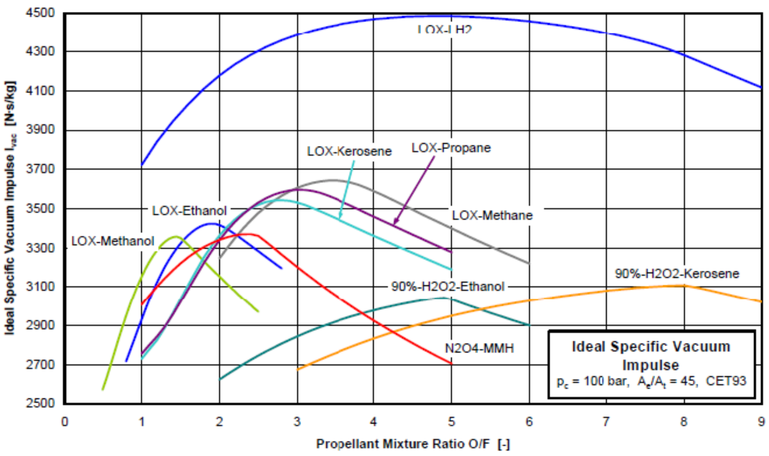
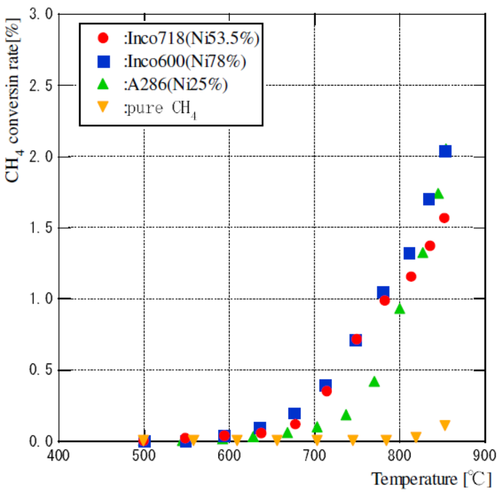


Figure 3: Ideal specific impulse of various propellant combinations

ftp.rta.nato.int/public/PubFullText/RTO/EN/RTO-EN-AVT-150/EN-AVT-150-06.pdf

MERiT - MEthane in Rocket nozzle cooling channels - conjugate heat Transfer measurements



(d) The sweep of temperature experiment increase

Fig.2. Experimental results of CH4 thermal cracking(Ni contents of each material mass level is shown)

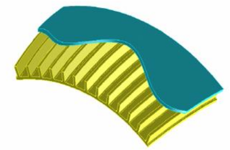
T.Makino and H.Sakaguchi, AIAA 2008-4753

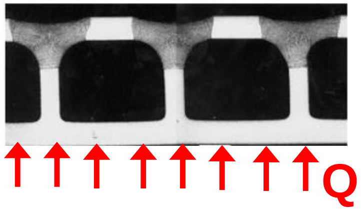
- **Rocket nozzle challenges**
  - Coking in cooling channels due to fuel impurities and/or from thermal decomposition of methane @ high temperatures
  - Degradation of the heat transfer capabilities
  - Increased cooling channel pressure losses
- It is of utter importance for future nozzle designs to quantify the heat transfer characteristics of typical Nickel-based alloy steels used
- Very few places in the world having the infrastructure for heat transfer studies of this type (high temp./press.)
- EGI / ITM / KTH is commissioning a test facility on the EGI lab roof

← SpaceX Raptor Engine Engine tests Feb-19

Starship hopper →

Project Objectives

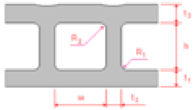




- For a relevant alloy and typical cooling channel geometries, fuel grade and operating conditions determine:
  - heat transfer coefficient (coolant side)
  - degree of coking and corrosion
  - pressure loss

as a function of

  - heat load
  - wall temperature
  - Reynolds number
  - fuel grade
  - pressure level

										
#	Material	Heat flux (MW/m²)	Pressure level (bar)	Inlet temperature (K)	w (-)	h (-)	t_1 (-)	t_2 (-)	t_3 (-)	Length (-)
1	21-6-9 Carpenter 40	~6…7	40…160	270…655	0.16	0.16	0.06	0.1	0.08	0.75
2	21-6-9 Carpenter 40	~3.5…4.5	40…160	270…655	0.16	0.26	0.06	0.1	0.08	1
3	21-6-9 Carpenter 40	~1…2	40…160	270…655	0.3	0.26	0.06	0.1	0.08	1
4	Inco600	~6…7	40 bar	270…655	0.28	0.48	0.06	0.06	0.06	1

Methodology

  - Design and commission a test rig for conjugate heat transfer studies according to specs and perform trials
  - Supported with numerical studies

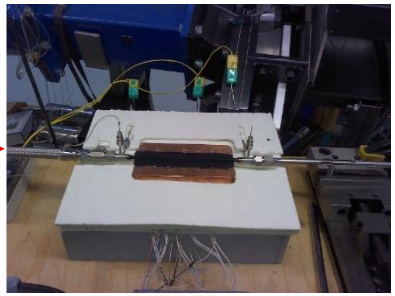
MERiT 1 – inert pre-trials

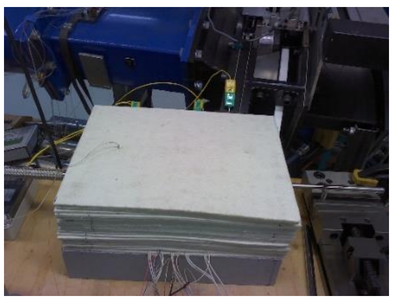
- Air tests: tests are to verify heat transfer estimations (1D, NUM)
- Channel: Inco600
- Heating concept (heater cartridge, 6*400W, current controlled)

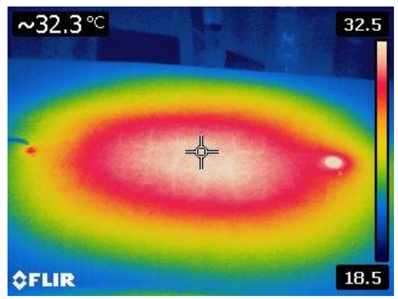
MFC to control/measure fluid flow

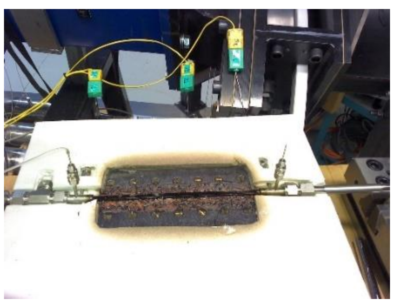
Instrumentation: *bulk gas temperatures, heating power, fluid flow, back pressure*

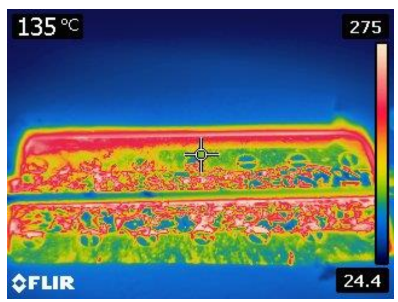
Inlet

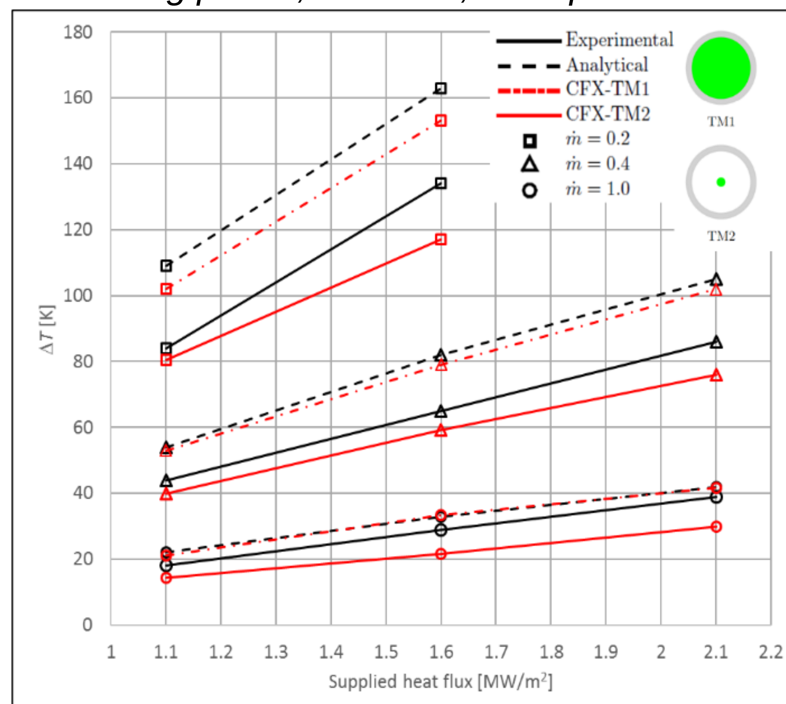




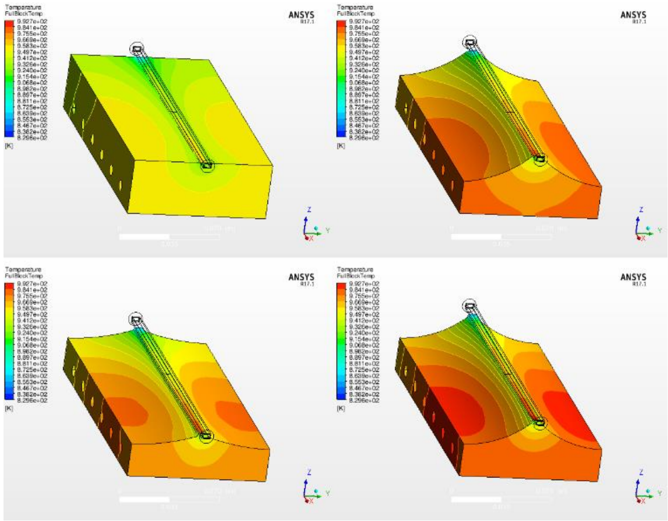


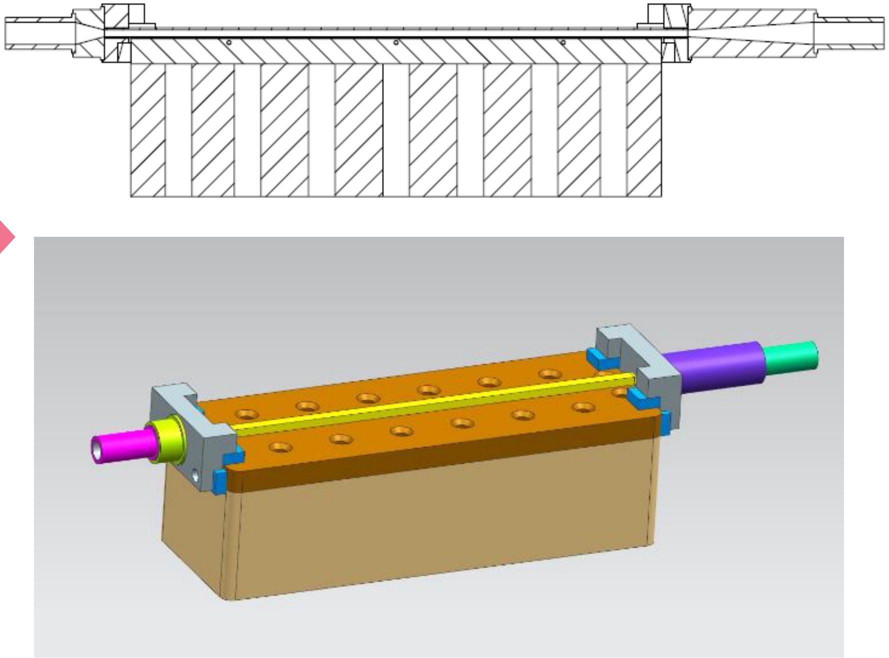






MERiT1 - Final Heater Design

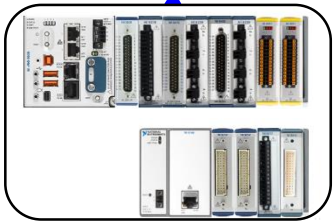


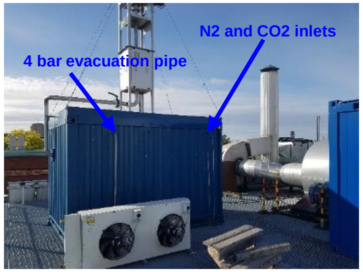


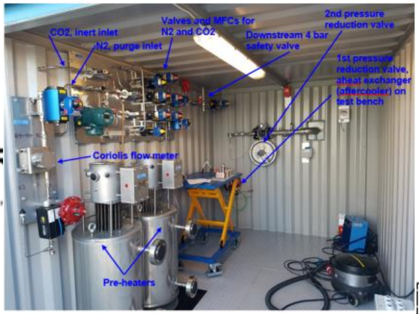
Targets:
Maximize the heat pick-up in fluid
Minimize the maximum block-temperature

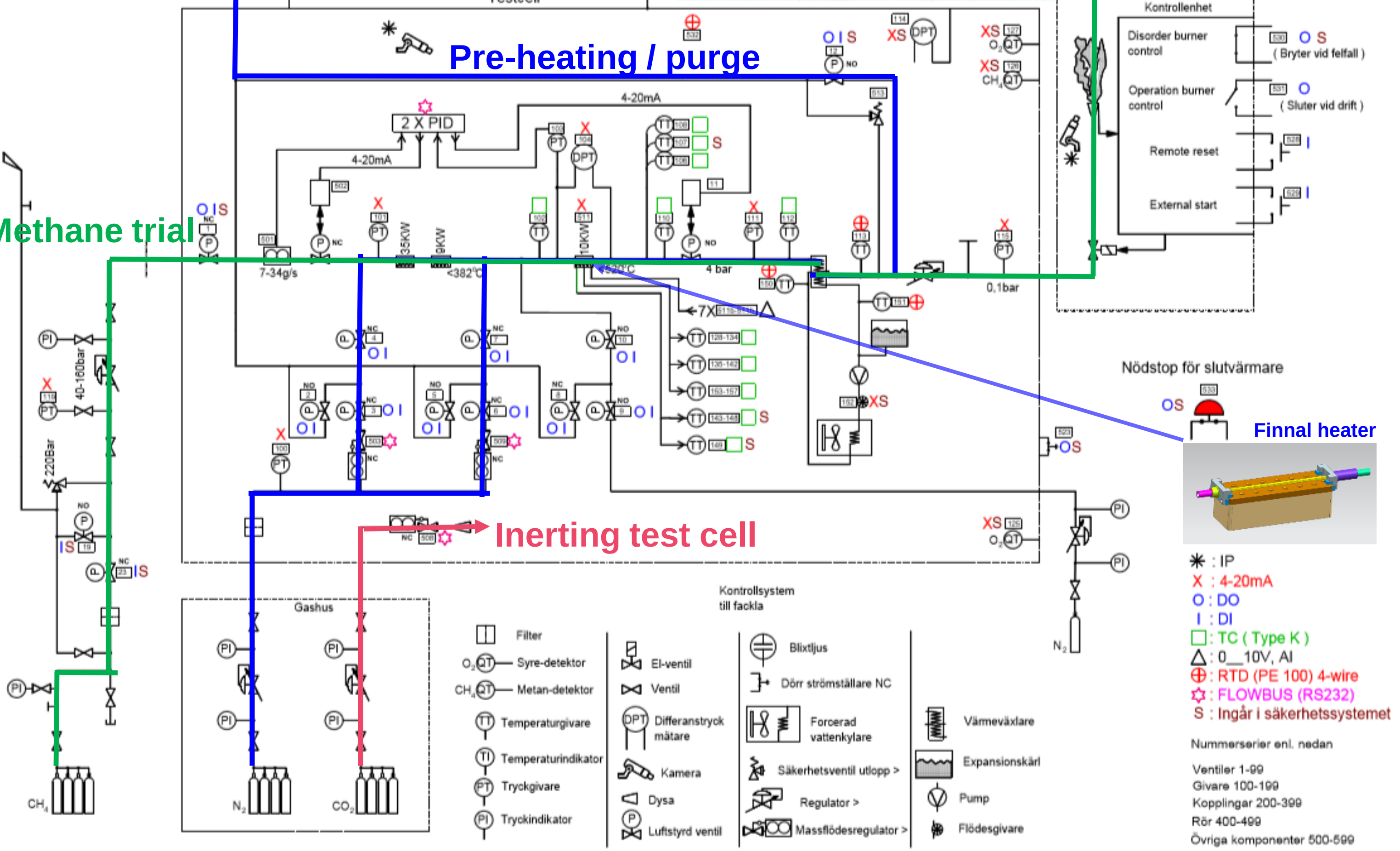
MERiT1 - Infrastructure

NI cRIO: Control & Measurement system



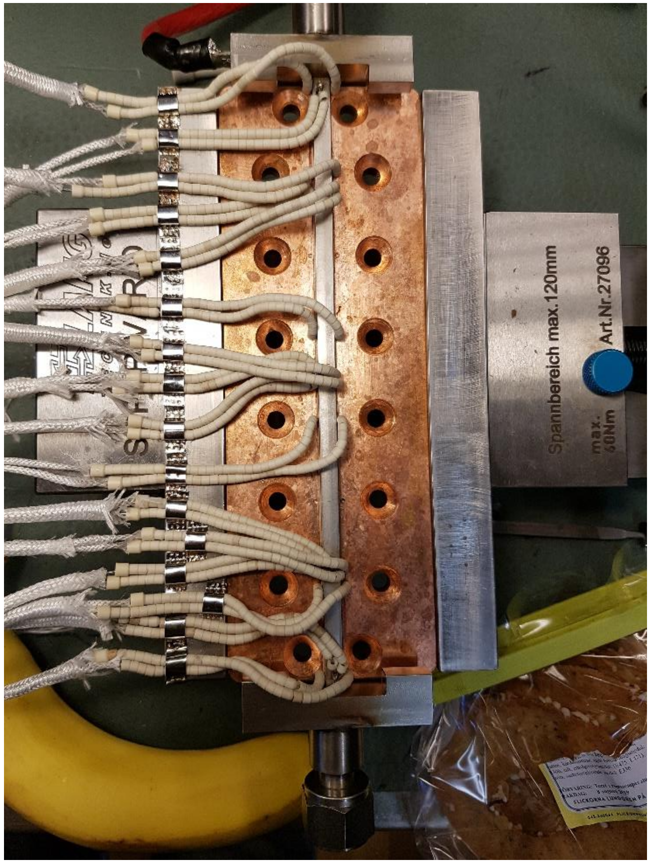






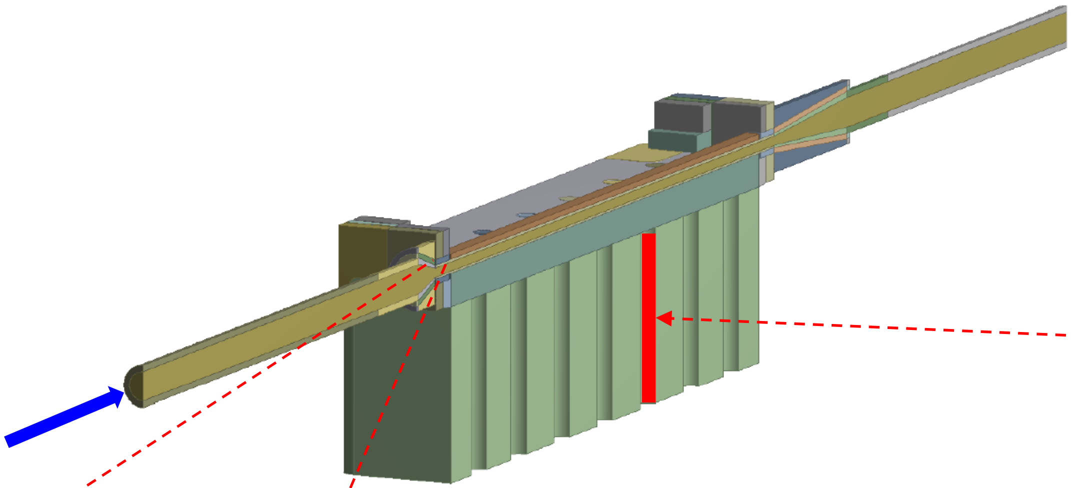
Finnal heater

MERiT 2 - Final heater – meas. setup



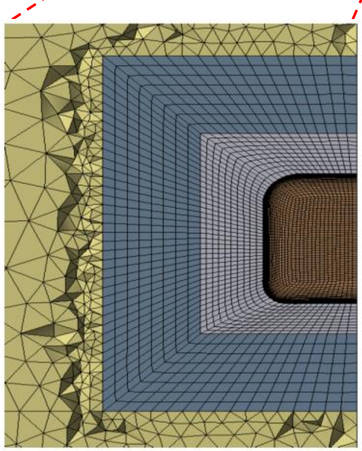
Mature measurement technologies
TC:s, Coriolis flow meter, pressure transducers, gas chromatography
(degree of thermal decomposition)...

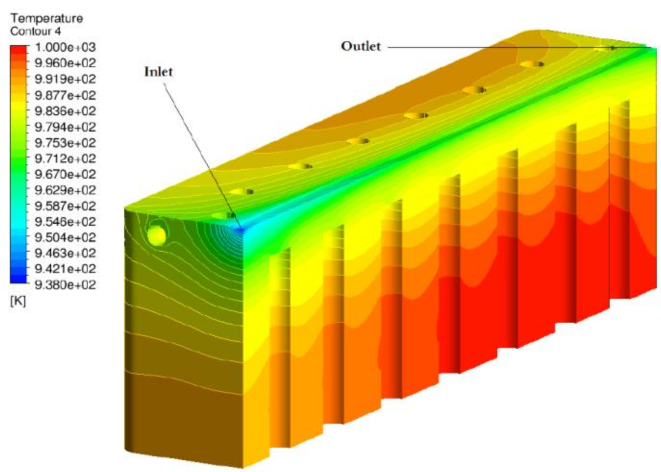
MERiT 2 – NUM



ANSYS modeling suite

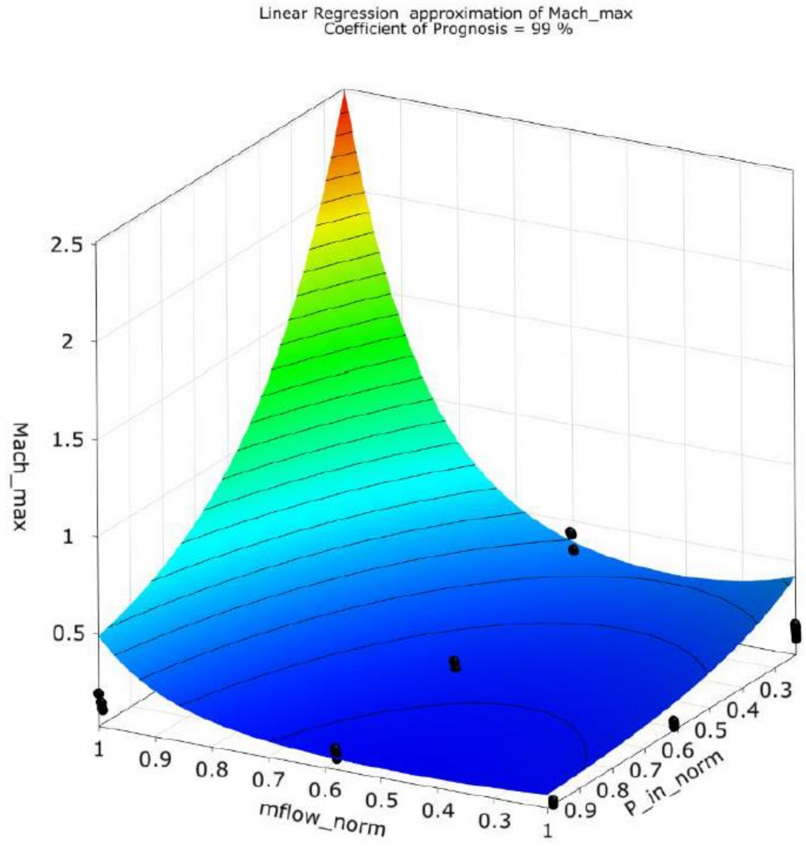
- Fluid: CFX RANS, Total Energy, subsonic, BC_{inlet}: T_{in}, $\dot{m}$, BC_{outlet}: p_{out}
- Material specs. and heat flux at el.cartridges surface, HTC on outer insulation walls (10 W/m^2K)
- Mesh: structured for fluid (H-grid, O-grid), mesh independicy study, y+ < 0.9 along channel walls, structured & unstructured grid for materials
- 6.4 mNodes (~45% in fluid)

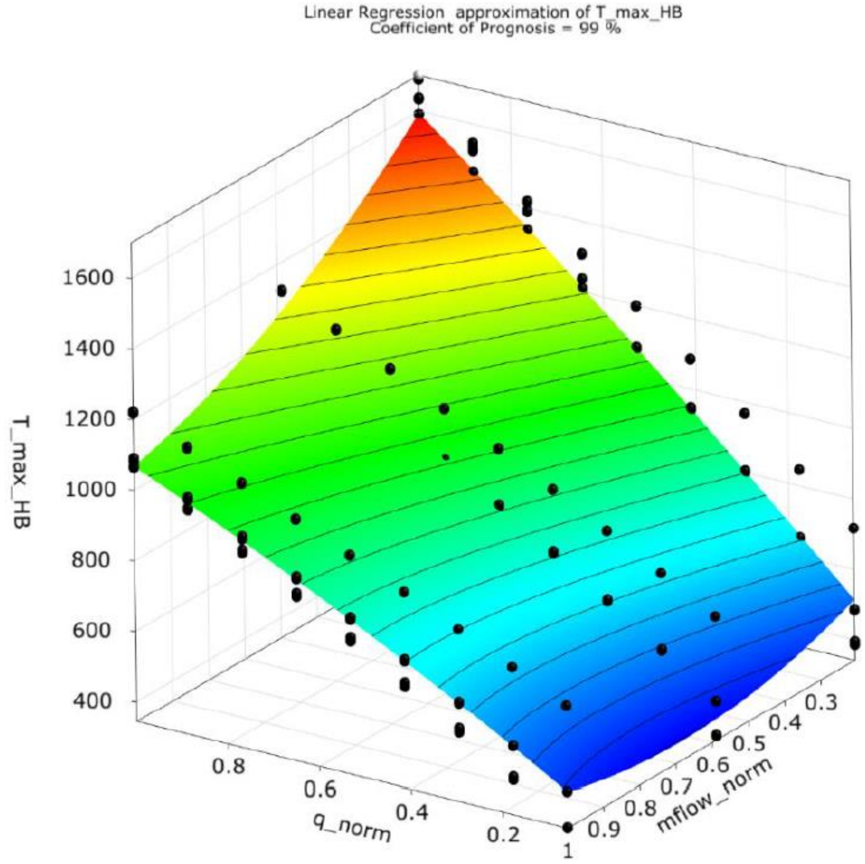




MERiT 2 – NUM

Response surfaces (ANSYS OptiSLang) → identify EXP points of interest

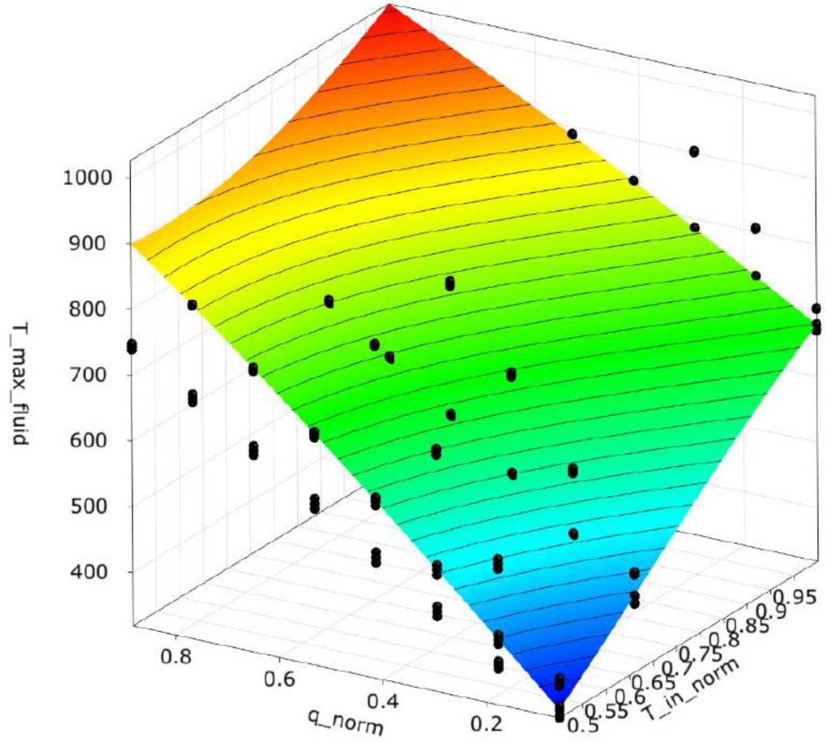


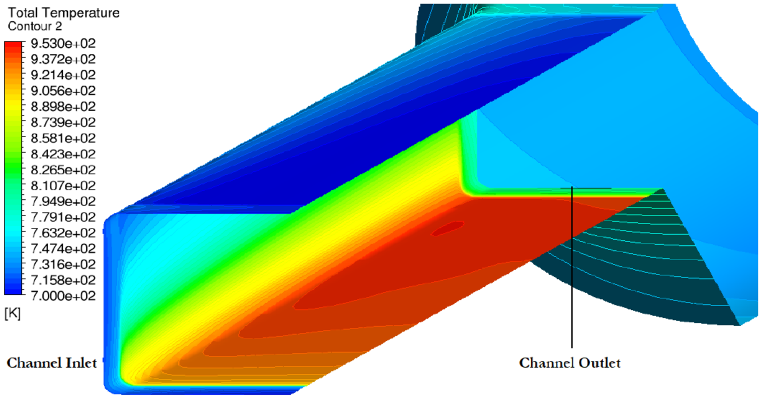


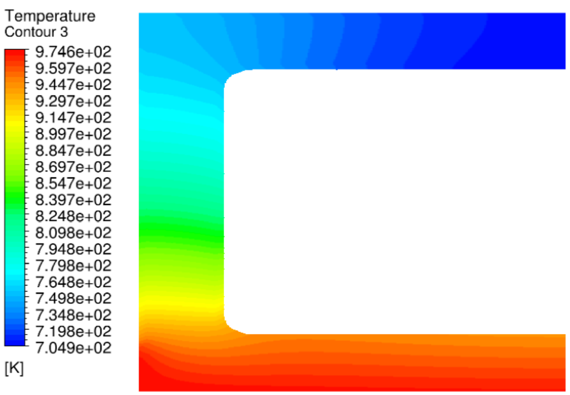
EXP: T_max_HB = 1023 K (limit el. cartridge)

MERiT 2 – NUM

Maximum fluid temp. when temp_HB < 1023 K







CH4 cracking ~above 750 K

Outcomes...

- Test build design
    - Conceptual and design report
    - 2 MSc theses (NUM)
- Infrastructure design
    - Risk assessment report
    - 2 Internships (EXP, NUM)
- Commissioning and Trials
    - Third party audit approval
    - Test and measurement plan report
    - Commissioning report
    - PhD student from Oct 2019
- Conf.paper
    - SP2018
    - AEC2020 (submitted)

Summary / Outlook

Summary

- A world-unique test rig for high pressure (200 bar), high temperatures (1023 K) and fuel thermal power < 1.8 MW heat transfer studies for channels have been designed, manufactured, installed, approved...partly commissioned
- Tight time plan to build a very complex infrastructure (high press, high temp.) → 1.5 years delay compared to the original plan
- Acknowledgements to project funding organizations:
    - Swedish National Space Agency (NRFP3-4)
    - ESA (FLPP)
    - GKN Aerospace Sweden
    - KTH, EGI dept.(KTH)

Outlook

- Final commissioning - athourity approval
- Test readiness review Oct/Nov 2019
- Nov/Dec 2019 initial tests with methane

THE END