Appendix N

VEGA Launch Vehicle
Improved Fluidic Thermal Prediction Model

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Abstract

The VEGA Launch Vehicle Thermal Prediction Model is introduced and its latest improvements described. With increased availability of sensor data from successfully performed flights it was possible to highlight the need for higher predictive accuracy, both in temperature trends and values, in some specific but crucial elements, in particular the 4^{th} stage liquid propulsion system main engine. It is in fact one of the most critical component due to the long mission requirements with respect to other stages engines, with complex attitude profiles in space environment and multiple re-ignitions.

In an upper Stage Assy, as the VEGA LV A4, the major concern is the propellant temperature, especially in the moments just before engine start-up, being related with combustion instabilities and performances. For this reason, ESATAN FHTS library capabilities were studied and fluidic network representing the engine feeding lines introduced in the Thermal Model.

Propellants properties are taken from available literature and dedicated libraries are developed to fit ESATAN required format.

Thrust Chamber cooling system is also included and complex heat exchanges between hot gases and engine structure accounted. Simulations temperature trends are compared with flight sensor data for previous flights resulting in a very good correlation.

The whole model is finally optimized in order to minimize impacts on runtime due to the new solution loop. Further improvements are foreseen both in fluid properties and model details.

VEGA LAUNCH VEHICLE:
Improved fluidic thermal prediction model

Noordwijk, October 2016

Introduction

Scope of this work is to present the latest improvements introduced in the VEGA **T**hermal **M**athematical **M**odel (**TMM**) concerning the 4th stage **L**iquid **P**ropulsion **S**ystem (**LPS**). The content of the presentation is:

- Thermal activities performed by AVIO
- Objectives of the improvements and background in the **L**aunch **V**ehicle (**LV**) **TMM**
- New Geometrical Mathematical Model of the **LPS** feeding lines (4th stage)
- Improvements in the **LPS** Thrust Chamber nodal definition
- Our experience with *ESATAN-TMS* fluidic networks capabilities
- Application to the VEGA **LV** 4th Stage **LPS** Assy
- Correlation with respect to reference documentation
- Model verification with respect to flight data
- New information available from the improved model

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1

Thermal Activities for VEGA Launch Vehicle

- Reference software is *ESATAN-TMS*
- Thermal Activities can be divided in three groups:

Development
(once for launch vehicle qualification…)

- Thermal Model development
- Definition of design, qualification and operative limits at System Level
- Design of System Components (*i.e. Thermal Protections*) and feedbacks to Sub-System Components (*i.e. Equipment positions*)

Recurrent Operations
(for every launch campaign…)

- **C**oupled **L**oad **A**nalysis (**CLA**)
  - **P**ay**L**oad (**PL**) + **LV**
  - **S**tand **B**y **O**n **G**round (**SBOG**) + Flight
- System Predictions
  - Temperatures of structures and equipment within operative limits
- Sub-System Predictions
  - **LPS**
  - **R**oll and **A**ttitude **C**ontrol **S**ystem (**RACS**)

Improvements

- Changes of requirements
- <u>General improvements of the **TMM**</u>

VEGA** & **VEGA C ***VEGA***

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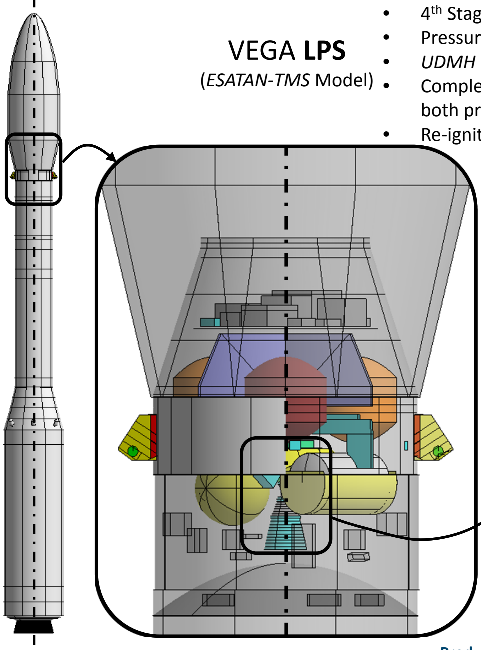
VEGA Thermal Model Improvements

The main goal of the performed activities was to improve the model accuracy of the **LPS TMM** in order to answer at questions arose during VEGA flights preparation.

VEGA **LPS**
(*ESATAN-TMS* Model)

- 4^{th} Stage (*AVUM*)
- Pressure Feed (*He*)
- *UDMH* + N_2O_4 propellants
- Complex cooling system using both propellants
- Re-ignitable up to 5 times



Impact of Hardware Temperature on Propellants, mainly at engine start-up, which is linked to important performance issues such as *HF* combustion instabilities and *NTO* freezing point

Legacy
Main **E**ngine **A**ssy (**MEA**)
(*ESATAN-TMS* Model without piping and components, dated 2014)

Three steps have been followed to achieve the objective:

- add needed geometry
- improve structural nodes definition
- introduce fluid nodes and relevant fluid/structure interaction

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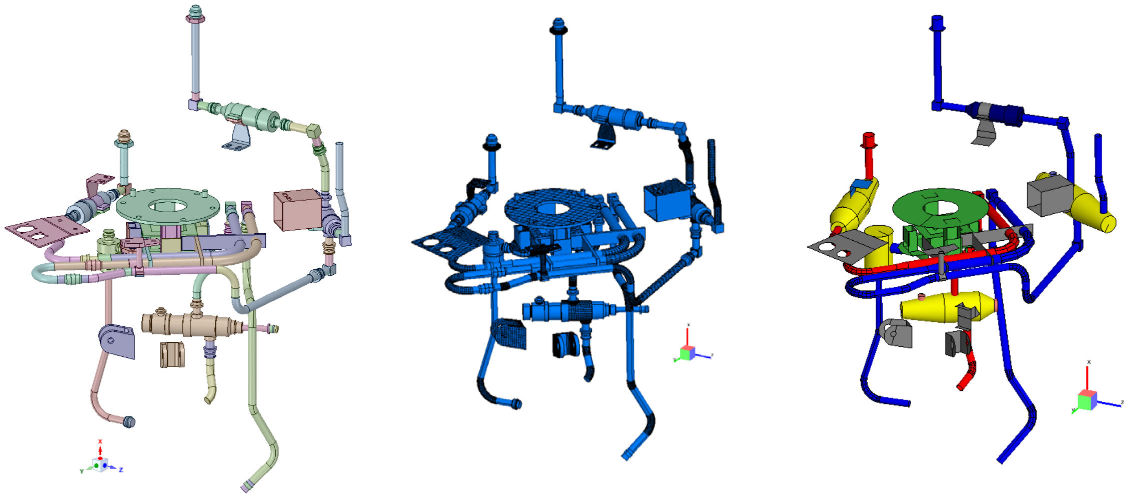
New geometry included in the Thermal Model



Relevant geometry imported from .step to *CADBench* → Conversion to *ESATAN-TMS* .erg geometry format → Geometry simplification and improvements in *ESATAN-TMS*

- The simplification process reduced the overall number of faces from 113396 to 1228 resulting in low expected impact on radiative cases computation times (comparable to average **PL**).
- Attention to small size faces…

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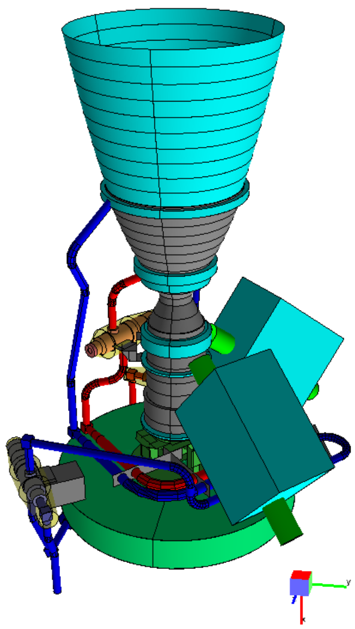
Geometry comparison with real hardware (1)



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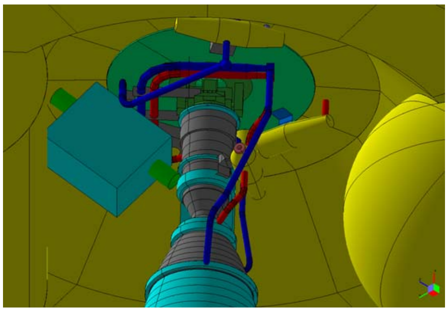
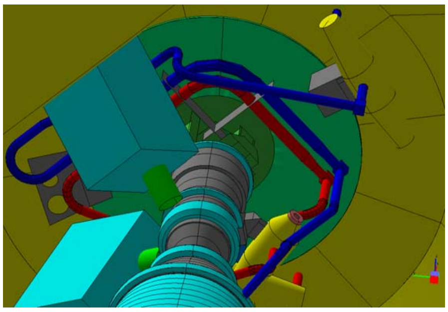
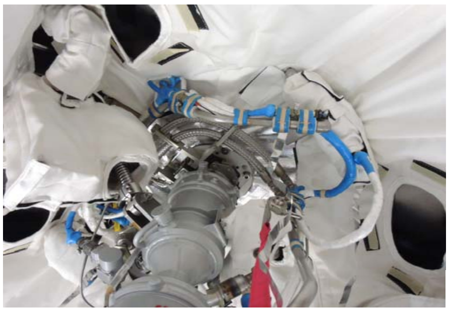
Geometry comparison with real hardware (2)







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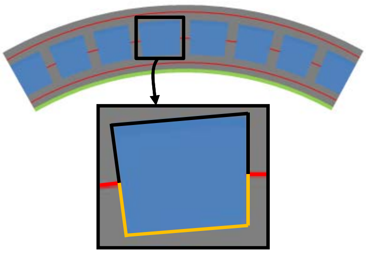
6

Structural Nodes overview

Detailed thickness discretization of the **T**hrust **C**hamber (**TC**) was needed to properly reproduce steep temperature gradients across engine walls and interaction with cooling propellants

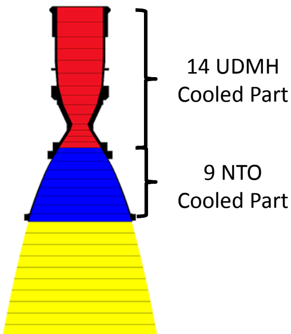
Radial Direction
(thickness)

4+1 nodes



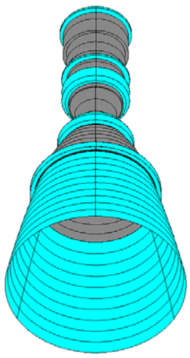
Longitudinal Direction
(**LV** axis)

33 nodes



Circumferential Direction

3 nodes (@120°)



Nodes interfaces
Coating material node (only for NTO cooled)
Fluid node
Structural node

External node/fluid contact area
Internal node/fluid contact area

The two areas are approximately equals
(this allows to use * option for GLs…)

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7

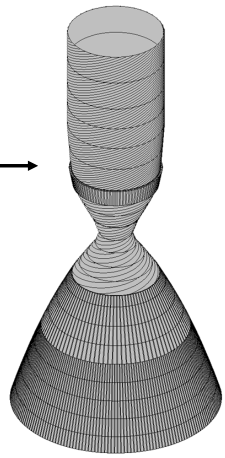
Structural Nodes properties calculation

A total of *363* nodes are used for the **TC** with ≈1000 *GLs*

Nodes and *GLs* have different averaged properties for each **TC** longitudinal section and for each radial position, depending on:

MATLAB is used to generate definitions in ESATAN-TMS format

- longitudinal position
- radius
- walls thicknesses
- cooling channels heights, widths, number, *swirling angle*



The total mass of computed nodes is compared with the expected engine mass resulting in an error of ≈ $\mathbf{0.05\ kg}$

In this phase also the properties of fluidic nodes for cooling channels are computed (hydraulic diameters, flow areas, lengths, heat exchange areas)

→ 1 fluidic node for each longitudinal node

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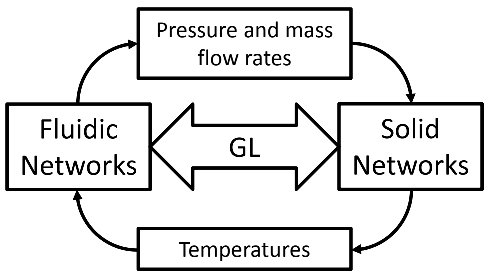
ESATAN-TMS Fluid Networks overview

ESATAN-TMS allows to model fluidic networks interacting with solid nodes (FHTS)

- 1D Fluid models
- steady/transient
- single/two phases



The overall complexity of a thermal model coupled with a fluidic model is higher both in number of required inputs and solution time

- Fluid definition
- Network definition
- Coupling definition

Two solutions routines requiring two different coupled convergences

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Fluid Definition overview

- Default fluids source codes in *ESATAN-TMS* are stored in ***"flpDefs"*** folder as *.flp* ASCII files (***Fl***uid ***P***roperties)
- Before being used, any fluid must to be precompiled to a Fortran library .a through dedicated *ESATAN-TMS* procedure
- The library must to be included in Analysis Case definition in order to be linked by *ESATAN-TMS* during preprocessing to the solution *.exe*
- The default fluid library is distributed with *ESATAN-TMS* in the ***"bin"*** folder named as *flpobj.a* and it is automatically linked to any model with fluid networks if no other is specified
- A single library can contain more fluids which may or may not be used in the studied model: the default library include **AIR**, **AIRW**, **AMMONIA**, **R11**, **R12**, **R21**, **R22**, **R114**, **R502** and **WATER**

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Fluid Definition properties

- A fluid properties file defines the thermodynamic and transport properties for the fluid:

• Density	$RHO	kg/m^3
• Specific heat (at constant pressure)	$CP	J/kgK
• Thermal conductivity	$COND	W/mK
• Dynamic viscosity	$VISC	kg/ms
• Surface tension	$SIG	N/m
• Specific enthalpy	$ENTH	J/kg
• Temperature	$TEMP	$°C$
• Pressure	$PRES	Pa
• Joule-Thompson coefficient	$JT	K/Pa
• Isothermal compressibility	$KT	$1/Pa$

- For each property values have to be provided in different states:

• Liquid	$LIQUID	
• Saturated liquid	$SAT_LIQ	
• Two-phase	$TWO_PHASE	→ $SAT
• Saturated vapor	$SAT_VAP	
• Vapor	$VAPOUR	

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Fluidic Network overview

- *ESATAN-TMS* fluid model are best suited to simulate closed-loop circuits such as satellites thermal control systems (it is not possible to “deactivate” a fluidic node to account, in example, for the emptying of a pipe)
- Fluid nodes are defined by the letter **F**
- Open-loops can be simulated by imposing two boundaries at the inlet and outlet:
  - Pressure-Pressure
  - Pressure-Mass Flow
- Boundary types are:
  - **J** user prescribed pressure
  - **K** user prescribed temperature
  - **R** user prescribed pressure and temperature
  - **H** arithmetic node

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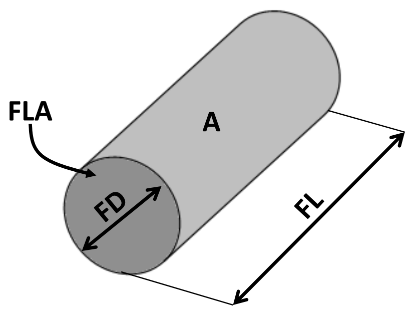
Fluidic Network nodal properties

- *ESATAN-TMS* fluid nodes have the following main properties:

A	heat transfer area	m^2
FD	hydraulic diameter	m
FL	length	m
P	static pressure	Pa
T	temperature	°C
FF	wall surface roughness	m
FQ	internal heat source	W
FM	mass source rate	kg/s
FT	fluid type	
VQ	vapor quality	
FLA	flow area	m^2



- **P** and **T** have to be specified only on boundary nodes, for fluid nodes they are used as initial condition

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Fluidic Network nodes connections

- The network topography is defined by Mass-Flow links (type **M**)
- The value is computed automatically by *ESATAN-TMS* during solution time as result of the pressure drops balance in the network and fluid properties: the initial value is useful only to reach quickly the first convergence to numerical solution value of Mass-Flow.
- For each **M** link, a **GP** link is automatically created representing the conductance between the linked nodes.

$$GP = \frac{\rho u^2}{2\Delta p} = \frac{\dot{m}^2}{2\rho A^2 \Delta p}$$

- A dedicate function is created to handle conductance links:

$$\texttt{CORRGP(NODE, MASS FLOW, }\underbrace{\texttt{PRESSURE DROP}}_{bar}\texttt{);}$$

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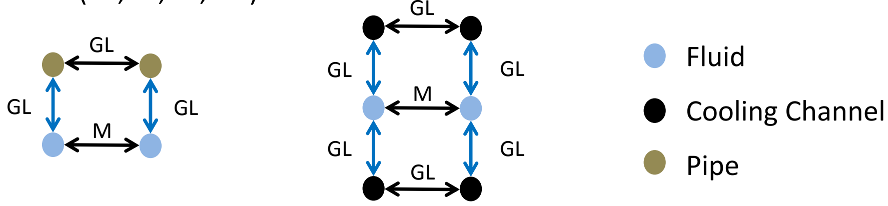
Fluid-Solid Coupling Definition

- *ESATAN-TMS* allows an automatic calculation of Heat Exchange coefficient (HTC) for a Fluid Node interacting with a Solid Node

```
GL(FLUID, SOLID) = *;
```

- The reference parameter *ESATAN-TMS* uses for calculation is the Hydraulic Diameter
- Natural and forced convection are accounted (for natural convection, horizontal pipes are the reference)
- Single Phase and Two Phase (boiling or condensing fluid) are taken into account with relevant equations (*Re*, *Pr*, *Gr*, *Nu*)



- Detailed explanation in *ESATAN-TMS* User Manual Appendix K

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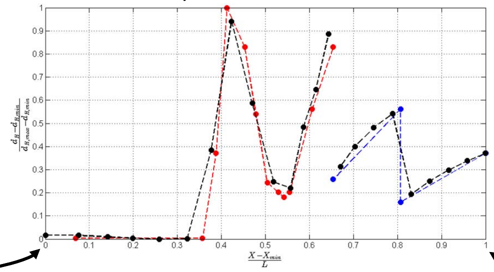
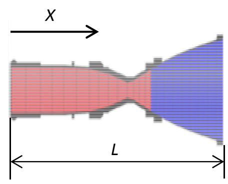
Fluidic Nodes properties check

Computed fluidic properties such as Hydraulic Diameter and Flow Area are verified with respect to reference documentation.

- Documentation values are in ***RED*** for UDMH and ***BLUE*** for NTO
- *ESATAN-TMS* model is in ***BLACK***
- Dots are nodes positions

Hydraulic Diameter

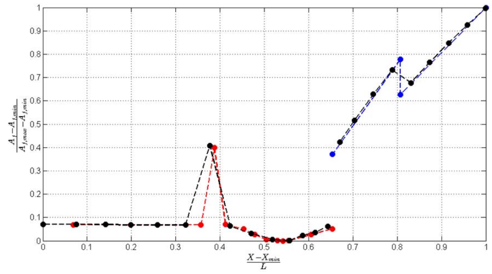




End of UDMH cooled part of ***TC***

Start of NTO cooled part of ***TC***

Flow Area



To be noted that position of documentation nodes may differ from position of *ESATAN-TMS* nodes explaining the difference in punctual values

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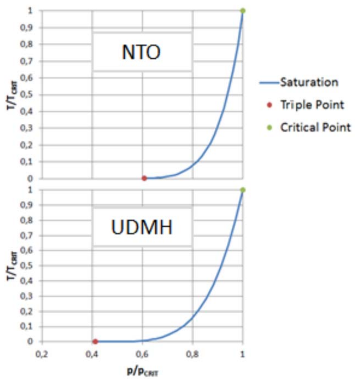
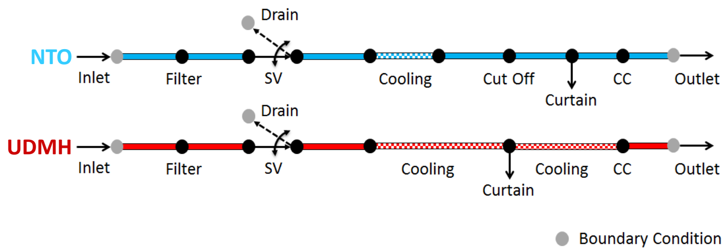
16

Fluid properties and Fluidic Network application

Propellant libraries in *ESATAN-TMS* formats are created from available literature

Feeding lines are implemented with fluidic nodes linked through *Ms*, *GPs* and *GLs*





- Boundary conditions *R* and *J* to simulate open circuit
- Pressure drops from hydraulic tests
- Curtain coolant mass flow extracted through negative *FM*

Several custom outputs are implemented such as density, mass, Prandtl, Reynolds and velocity to crosscheck against reference documentations

To correctly model cooling system, heat flux is applied as boundary to ***TC*** hot gas side

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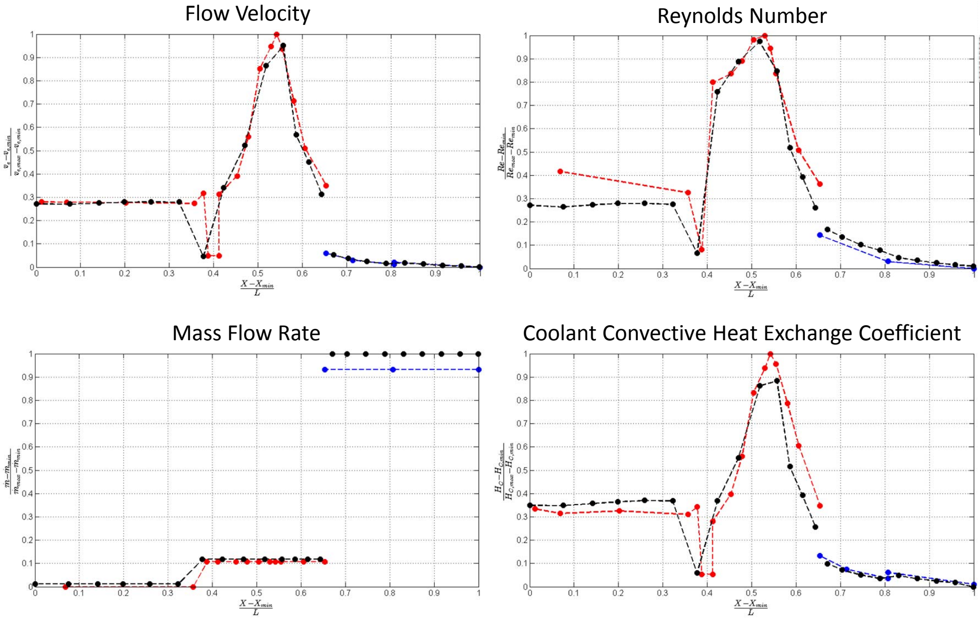
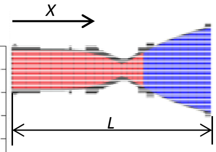
17

Fluidic Network Properties Check

Comparison of Fluidic Network properties with respect to reference documentation at engine nominal operative condition and steady state





- Documentation values are in ***RED*** for UDMH and ***BLUE*** for NTO
- Documentation values are verified through test campaign during **TC** design
- *ESATAN-TMS* model is in ***BLACK***
- Dots are nodes positions

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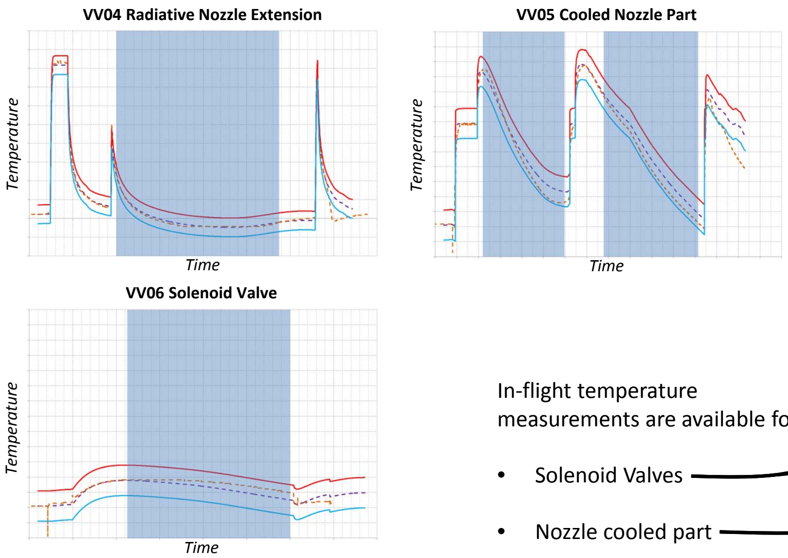
18

Flight verification of model improvements

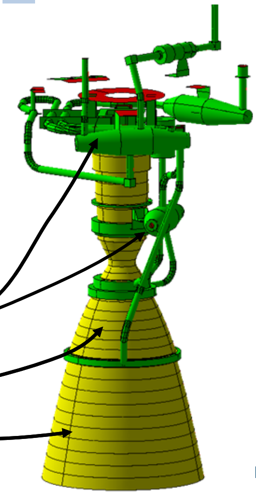
The model was verified with flight data from VV04, VV05 and VV06 missions revealing a good agreement between sensor data and predictions. The improved model has been used also for VV07 mission (sensor data currently under exploitation)



Best accuracy where the trajectory data were fully available

In-flight temperature measurements are available for:

- Solenoid Valves
- Nozzle cooled part
- Nozzle radiative extension



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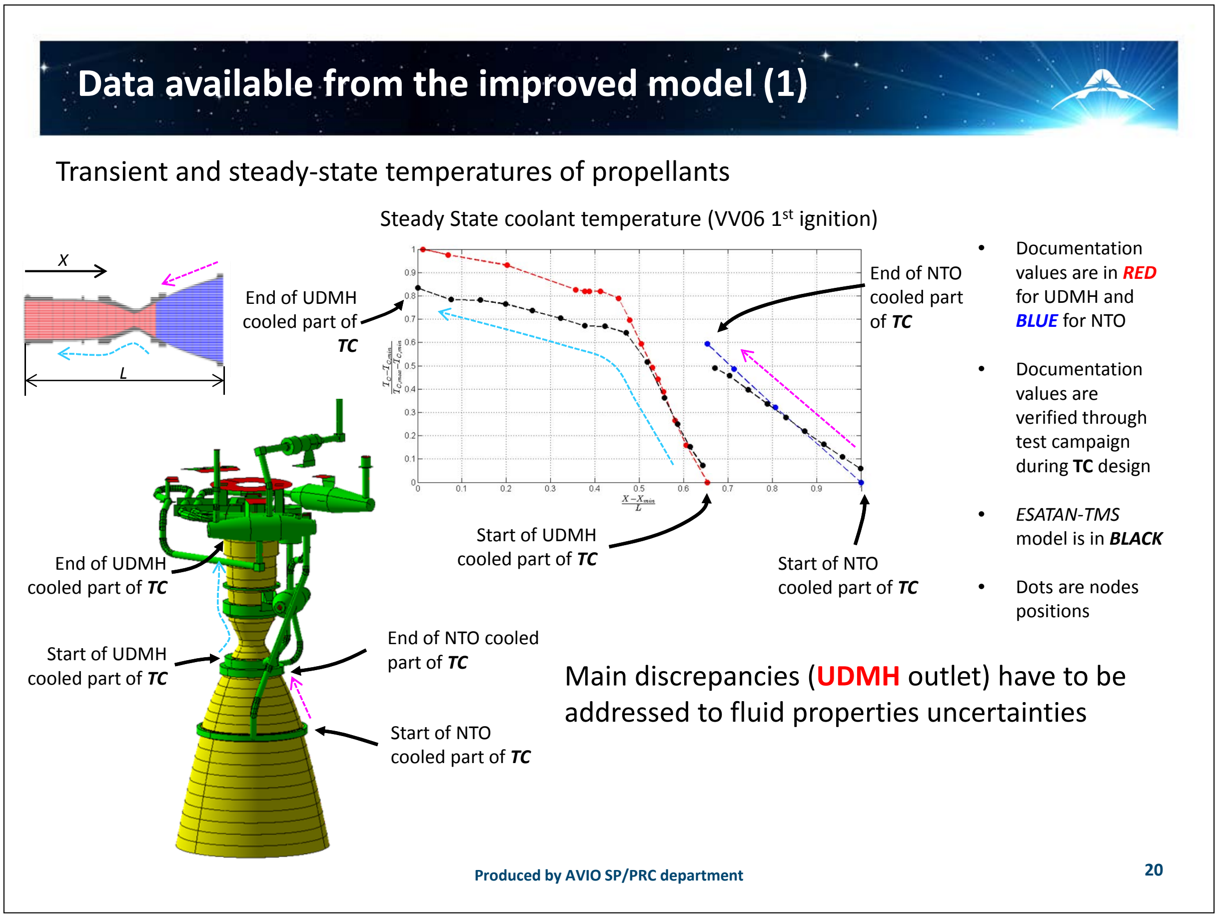
19


Data available from the improved model (1)
Transient and steady-state temperatures of propellants
Steady State coolant temperature (VV06 1st ignition)
X
L
End of UDMH cooled part of TC
End of NTO cooled part of TC
Start of UDMH cooled part of TC
Start of NTO cooled part of TC
End of UDMH cooled part of TC
Start of UDMH cooled part of TC
End of NTO cooled part of TC
Start of NTO cooled part of TC
Documentation values are in RED for UDMH and BLUE for NTO
Documentation values are verified through test campaign during TC design
ESATAN-TMS model is in BLACK
Dots are nodes positions
Main discrepancies (UDMH outlet) have to be addressed to fluid properties uncertainties
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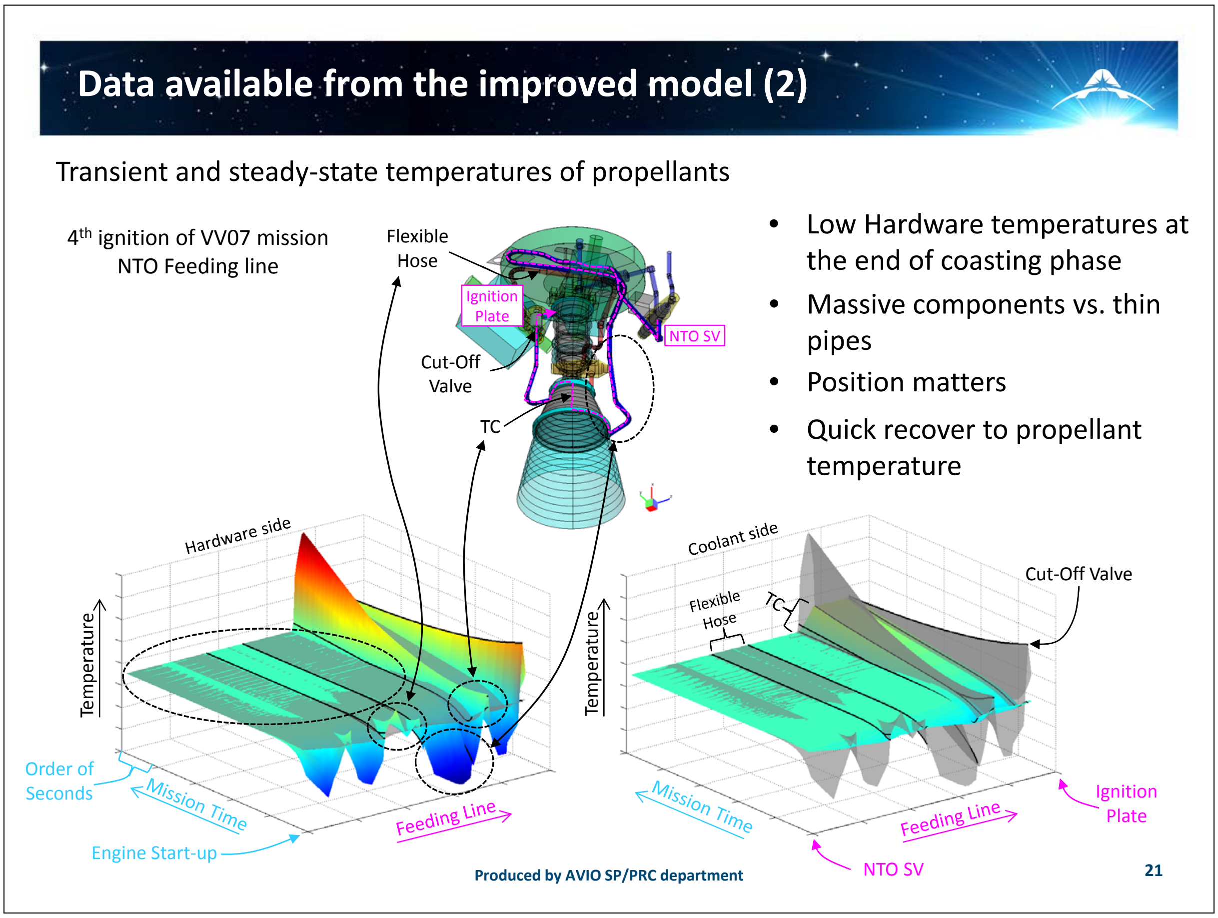
Data available from the improved model (2)
Transient and steady-state temperatures of propellants
4th ignition of VV07 mission
NTO Feeding line
Flexible Hose
Ignition Plate
NTO SV
Cut-Off Valve
TC
Low Hardware temperatures at the end of coasting phase
Massive components vs. thin pipes
Position matters
Quick recover to propellant temperature
Hardware side
Temperature
Order of Seconds
Mission Time
Engine Start-up
Feeding Line
Coolant side
Flexible Hose
TC
Cut-Off Valve
Temperature
Mission Time
Feeding Line
Ignition Plate
NTO SV
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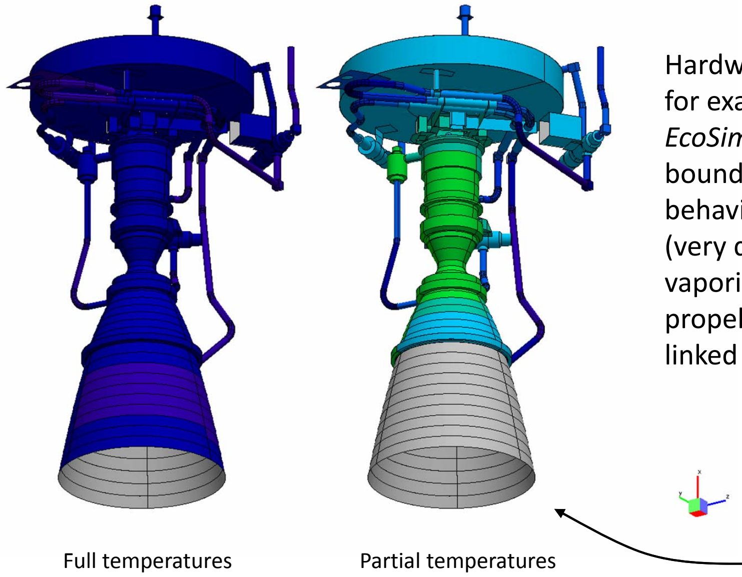
21

Data available from the improved model (3)

Hardware temperature maps

2nd ignition of VV05 mission



Hardware temperatures are used for example in a dedicated *EcoSimPRO* model as thermal boundary condition to simulate NTO behavior across engine start-up (very quick transient with partial vaporization of propellant) to asses propellant temperature at ignition, linked with *HF* instabilities

Full temperatures range

Partial temperatures range

Each frame is 10s simulation time for and overall duration of 200s

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22

Resume

- The VEGA launch vehicle Thermal Model has been improved for what concern the **LPS**, introducing propellant feeding lines.
- Detailed geometry of piping, gimbaling, supports and valves have been included.
- Thermal properties for each new component have been defined and relevant nodes linked to the rest of the **LV TMM**.
- New discretization of **TC** has been introduced to better reproduce temperature gradients in the walls and correctly interact with cooling fluids.
- *ESATAN-TMS* FHTS capabilities have been investigated and a brief overview of main characteristics presented.
- *ESATAN-TMS* fluid libraries have been created for used propellants.
- Application of fluidic network has been implemented to simulate nominal operative condition of VEGA **LPS**.

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23

Conclusions

- Hydraulic and Heat Exchange parameters have been compared with reference data and documentation (experimental data), resulting in a good correlation between model and expected values.
- The improved model has been verified with respect to previous VEGA flights VV04, VV05 and VV06 sensor measurements, again resulting in a very good correlation both for transient and stationary phenomena.
- Thanks to the Improved **TMM**, new reliable data are now available during VEGA **LV** launch preparation phases.

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24

Thanks

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25