Appendix F

Development of numerical tools for design and verification of ablative thermal protection systems

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Abstract

In recent years there has been a great collaborative work between Thales Alenia Space Italia and the Energetic Department of Politecnico of Turin devoted to the study of ablative heat shields. Two different numerical tools for the analysis of the behaviour of charring ablative materials have been developed within the frame of a co-founded internal research program.

The first of these tools, called Ablatherm, is a Matlab®-based code that can be used during the initial design phase: it implements a simple model (that uses a very reduced set of material properties), it has a short case settings time and execution time and it is very flexible (it can be used both through a script file or a Graphical User Interface). This tool was tested using analytical benchmarks and real test cases and is now used by TAS-I for heat shield design.

The second tool, still under development, uses the state of the art both for the model and for the tool implementation, in order to perform rapid, full 3D simulations. This tool, developed on OpenFoam platform, implementing a more complex model and requiring higher test case setup time and a huge amount of material data that must be provided for a full run, is mainly intended for final verification of the full system configuration. For an intermediate design phase, it is also possible to use this second tool with a reduced set of parameters.

DEVELOPMENT OF NUMERICAL TOOLS FOR DESIGN AND VERIFICATION OF ABLATIVE THERMAL PROTECTION SYSTEMS

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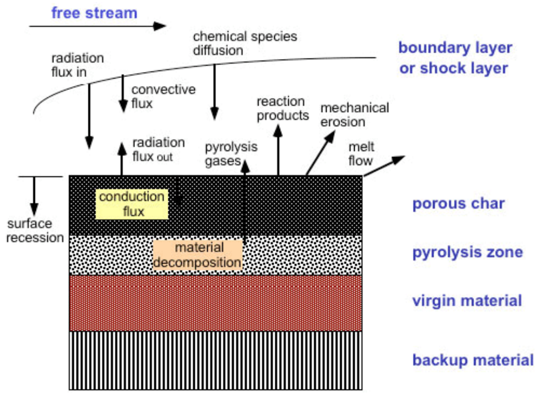
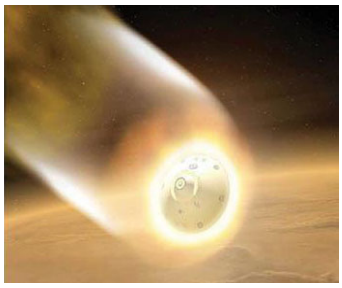
Ablative heat shields

- Not reusable.
- Light weight.
- Adaptable to mission constraints.
- Heat insulation properties enhanced through material degradation.
- Suitable for entry vehicle and SRCs.





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Characteristic of the used models

1D MODEL "*ABLATHERM*"

- Local 1D assumption.
- Simple model.
- Reduced set of parameters.
- Multi layer capability.
- Extremely low set up time and execution time.
- Ideal during initial design phase.

3D MODEL

- Full 3D Cartesian solver.
- State of the art model.
- High number of parameters (possible use of a reduced set).
- Multiple material within the domain
- Is not too much user friendly.
- Relatively long set up and run time.
- To be used for final, full body simulation.

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1D Model – Analytical model

- One equation model (energy conservation)+BC:

$$\begin{cases} \left(\rho c_p(\rho,T)\right)\dfrac{\partial T}{\partial t} + -\dfrac{\partial}{\partial x}\left(\lambda(\rho,T)\dfrac{\partial T}{\partial x}\right) + H(T)\dfrac{\partial \rho}{\partial t} = 0 \\ T(t=0) = T_0(x) \\ \lambda\dfrac{\partial T}{\partial x}(x=0,t) = q_c(t) \\ \lambda\dfrac{\partial T}{\partial x}(x=s(t),t) = q_w(t) \end{cases}$$

- Charring material (Arrhenius equation).
- Internal heat flux $q_c(t)$: adiabatic, convective and/or radiative heat flux.
- Surface heat flux boundary condition:

$$\underbrace{q_w}_{\text{Net wall heat flux}} = \underbrace{\left(\underbrace{\psi}_{\text{Blowing}}\; q_{conv_0} + q_{rad_0}\right)}_{\text{External flux}} - \underbrace{q_{rad}}_{\text{Surface radiative heat flux}} - \underbrace{Q_{rece}\,\rho_{carb}\,\Delta s}_{\text{Recession heat}}$$

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1D Model – Necessary data

- Material properties:
  - Virgin and charred densities.
  - Arrhenius coefficients.
  - Pyrolysis reaction and surface recession enthalpy.
  - Temperature dependence of specific heat, thermal conductivity, surface emissivity, both for virgin and charred material.

- Heat flux data (as function of surface temperature, cold wall evaluation, net values).

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1D Model - Implementation

- Finite Element Method (FEM) discretisation.
- Non linear Newton-Raphson method for fast and accurate non linearity resolution (surface radiation).
- Automatic grid generation, with linear plus logarithmic spacing; for multi layer cases, the number of elements per layer calculated through mean conductivity.
- Blowing evaluation at run time.
- Initial steady state temperature distribution evaluation.
- Implemented using Matlab© environment .
- Usable as command line function or through a Graphical User Interface (GUI).

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1D Model - Validation vs. CMA

- Performed by means of comparison with commercial 1D software (CMA):
  - Test cases → sizing of a silicon based ablator on different areas of the external surface of a re-entry vehicle.
  - Available thermal-ablative properties have been implemented in both codes.
  - Thermal simulation extended in the 1D simplified code to the reproduction of the convective and radiative heat exchange inside the vehicle.
  - The pyrolysis heat behaviour as function of material temperature has been introduced in AblaTherm.
- W.r.t. CMA, AblaTherm does not account for:
  - Surface transport of chemical energy.
  - Convective transfer by pyrolysis gases: $\rho c_P \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + \frac{\partial \lambda}{\partial x}\frac{\partial T}{\partial x} - H\left(-\frac{\partial \rho}{\partial t}\right) + \frac{\dot{m}_g}{A}\frac{\partial h_g}{\partial x}$
- Difference in sizing results lower than <10%.

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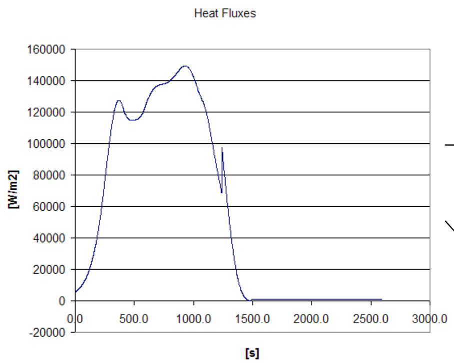
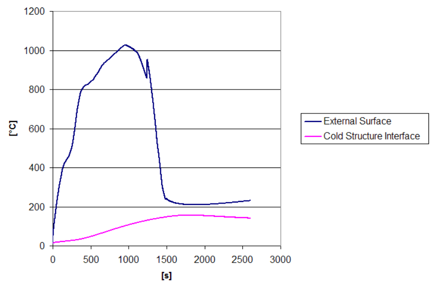
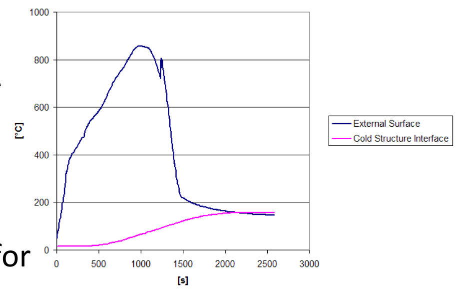
1D Model - Validation vs. CMA





CMA simulation

- Case on vehicle re-entry.
- Different modelling of surface thermo-chemistry.
- Sizing results (i.e. shield thickness) differ for less than 10%.



AblaTherm simulation

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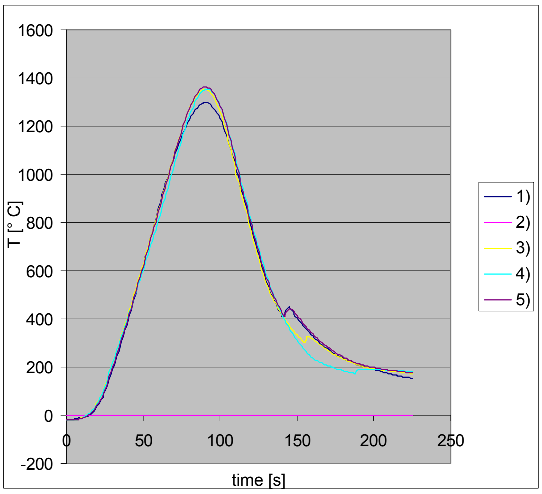
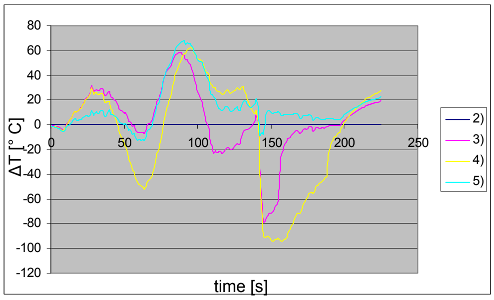
1D Model - Validation vs. SAMCEF Amaryllis

Comparison with simulation results of a Mars entry vehicle frontshield:

SHIELD SURFACE





1) Amaryllis simulation results
2) Empty
3) AblaTherm results, with prescribed heat fluxes correction
4) AblaTherm, with ABLAT heat fluxes correction
5) AblaTherm, with foam conductivity as function of atmospheric pressure

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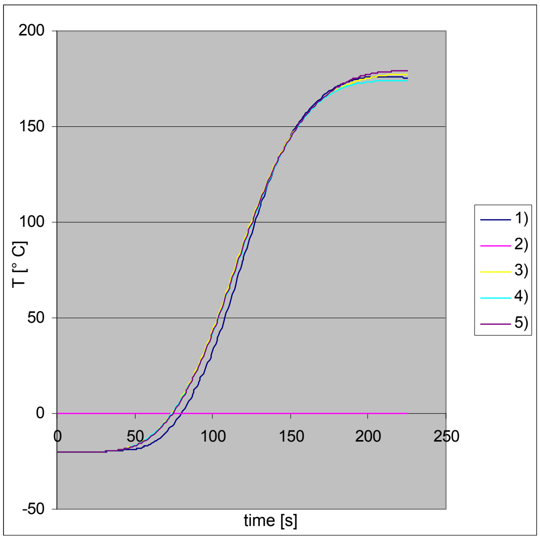
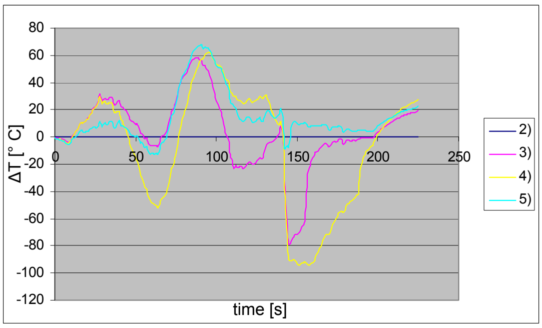
1D Model - Validation vs. SAMCEF Amaryllis

Comparison with simulation results of a Mars entry vehicle frontshield:
ABLATIVE/COLD STRUCTURE INTERFACE





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4) AblaTherm, with ABLAT heat fluxes correction
5) AblaTherm, with foam conductivity as function of atmospheric pressure

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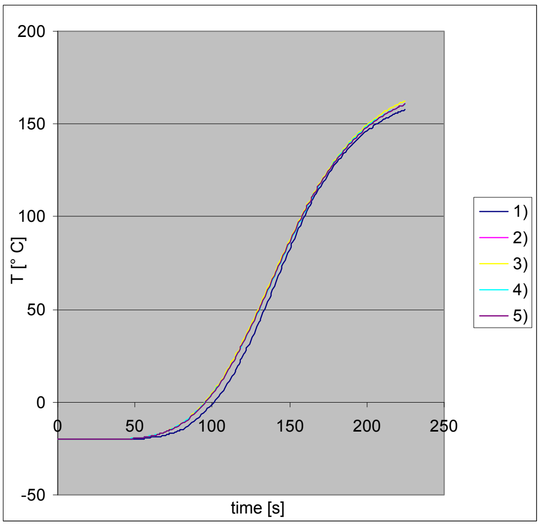
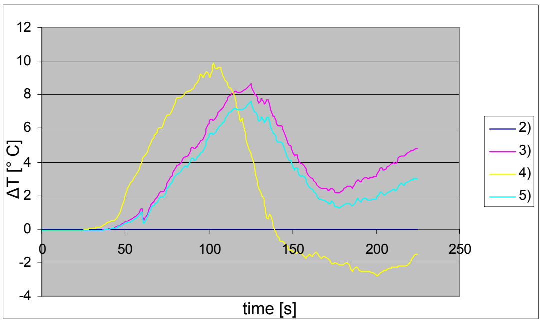
1D Model - Validation vs. SAMCEF Amaryllis

Comparison with simulation results of a Mars entry vehicle frontshield:
COLD STRUCTURE/INTERNAL FOAM INTERFACE





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5) AblaTherm, with foam conductivity as function of atmospheric pressure

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3D Model – Analitical model

- 3 equation model (energy, solid mass and gas mass conservation equations) + closure equations (Ideal gas law, Darcy law) + BC (Amar, A. J. "Modeling of One-Dimensional Ablation with Porous Flow Using Finite Control Volume Procedure", *North Carolina State University,* **2006**).

$$\begin{cases} \dfrac{d}{dt}\displaystyle\int_V \rho e dV + \oint_{\partial V} \phi \rho_g h_g \vec{v}_g \cdot \vec{n} dS - \oint_{\partial V} k \nabla T \cdot \vec{n} dS - \oint_{\partial V} \rho h \vec{v}_{mesh} \cdot \vec{n} dS = 0 \\ \dfrac{d}{dt}\displaystyle\int_V \rho_i dV - \oint_{\partial V} \rho \vec{v}_{mesh} \cdot \vec{n} dS = \int_V \dot{m}_i dV \qquad \text{for } i = 1,..,n \\ \dfrac{d}{dt}\displaystyle\int_V \phi \rho_g dV + \oint_{\partial V} \phi \rho_g \vec{v}_g \cdot \vec{n} dS - \oint_{\partial V} \phi \rho_g \vec{v}_{mesh} \cdot \vec{n} dS = \int_V \dot{m}_g dV \\ \vec{v}_g = -\dfrac{K}{\phi \mu} \nabla p \\ p = \rho_g \dfrac{\Re T}{M_g} \end{cases}$$

- Pyrolysis gas in local thermal equilibrium.
- Pyrolysis energy absorption through mixture internal energy evaluation.
- Charring material (Arrhenius equation).
- Surface BC under development.

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3D Model – Necessary data

- Material and gas properties:
  - Virgin and charred sub-densities and Arrhenius coefficients for each decomposition reaction, material composition coefficients.
  - Solid: temperature dependence of specific heat, thermal conductivity, surface emissivity, both for virgin and charred material. Extent of reactions dependence of porosity and gas permeability.
  - Gas: temperature dependence of specific heat, gas molecular mass and viscosity.
  - Formation enthalpy and reference temperature for virgin, char and gas.
- BC: different standard conditions, some specific under development.

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3D Model - Implementation

- Finite Volume Method (FVM) discretization.
- Implemented using the open source OpenFOAM suite. Advantages:
  - parallel run in both shared and distributed memory machines (MPI protocol, on workstation or clusters).
  - Based on open source platform (Linux) and open source suite.
- Use unstructured grid (complex geometric shapes, different cell shapes).
- Grid importation capabilities.
- Simplified model wich can run neglecting the gas effects (non gas data needed)

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3D Model test case

- Geometry and grid: 10x10 cm, 100x400 cells.
- Boundary conditions:
  - North side: time variable, uniform external heat flux :

$$q(t)=\left((t<100)\cdot 11e6\cdot\left(\sin \pi t/_{100}\right)^2+(t\geq 100)1000\right)\left[W/_{m^2}\right]$$

with surface reradiation; time variable uniform pressure:

$$p(t)=\frac{2e5}{200}\cdot t\ [Pa]$$

  - South and East side: adiabatic and impermeable.
  - West side: impermeable, time variable uniform temperature:

$$T(t)=2500\cdot\left(\sin\left(\frac{\pi t}{1000}\right)\right)^2+300\,[K]$$

- Material data: PICA15 - NASA TM 110440 (1997).

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3D Model Results – 1

- Performances: solution time on a 8-core workstation → 1400 s.
- Following movie description:
  - Background color: material density (red → max, blue → min).
  - Colored lines: isotemperature lines, colored with temperature scale; lines at [(300:20:400) (600:200:3800)] K.
  - Vectors: oriented using pyrolysis gas velocity and colored using pyrolysis gas velocity magnitude.

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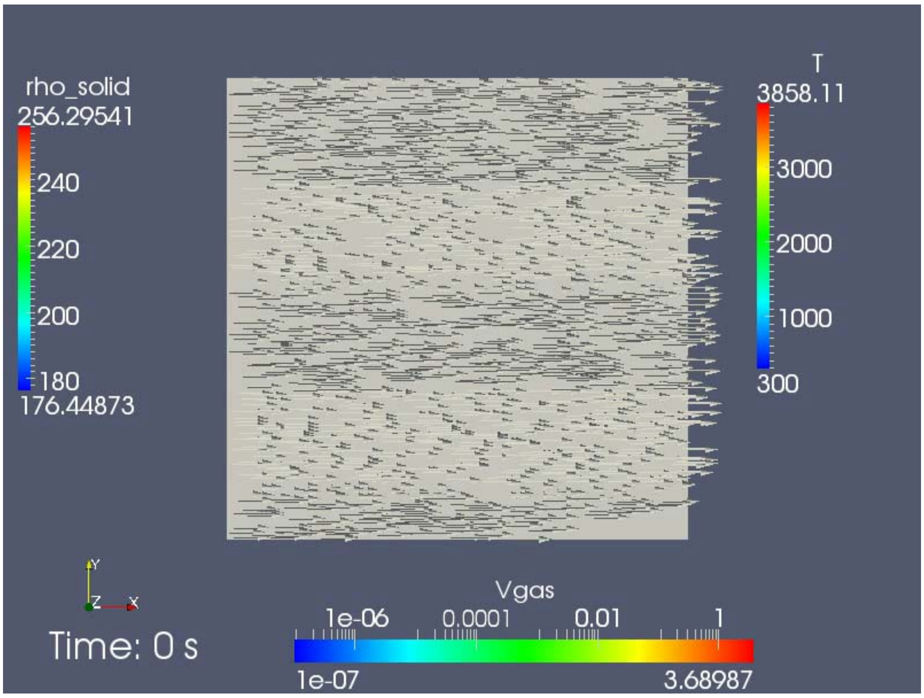

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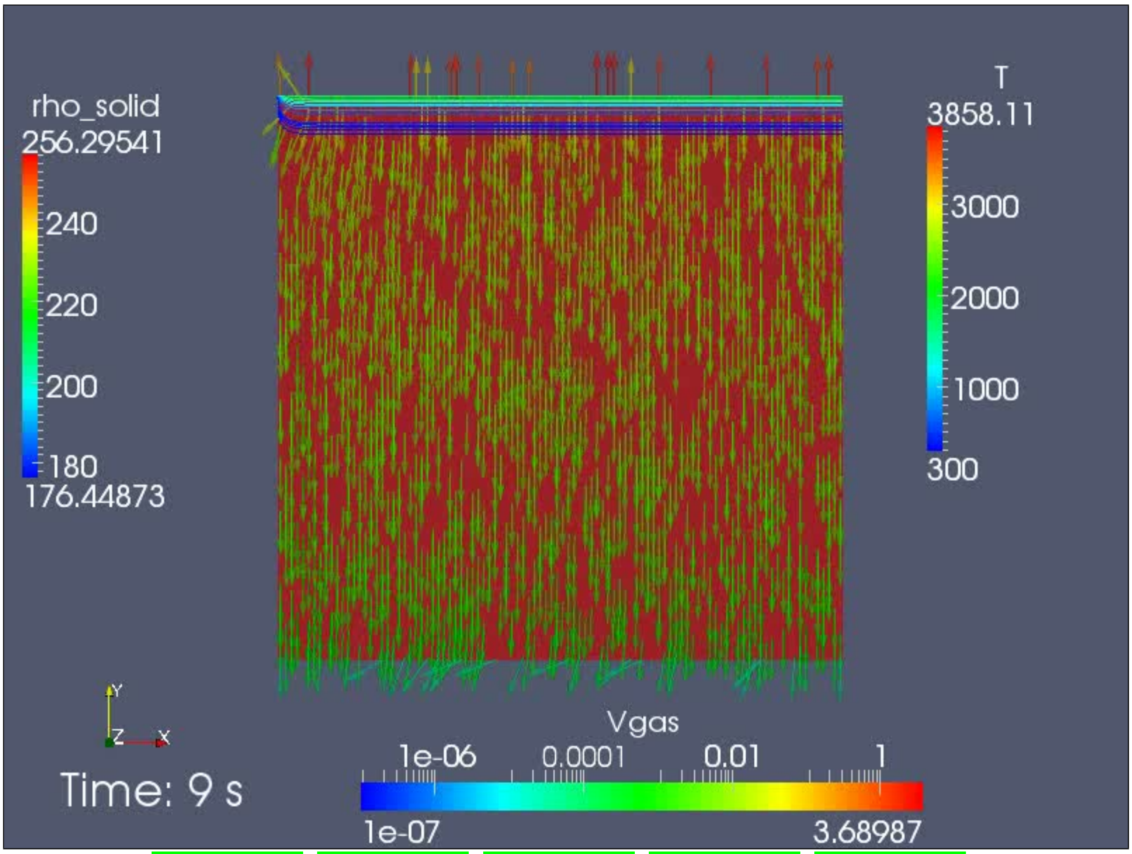

Slow | Normal | Fast | Play/Pause | Stop

3D Model Validation vs. AblaTherm

- The solutions obtained using the two codes are compared. To perform the comparison, the following steps were performed:
  - Ablatherm run was performed neglecting surface recession and applying the same profile for the heat flux (without the blowing correction).
  - 3D code run: temperature solution extracted on the East side of the domain (negligible 2D effects).

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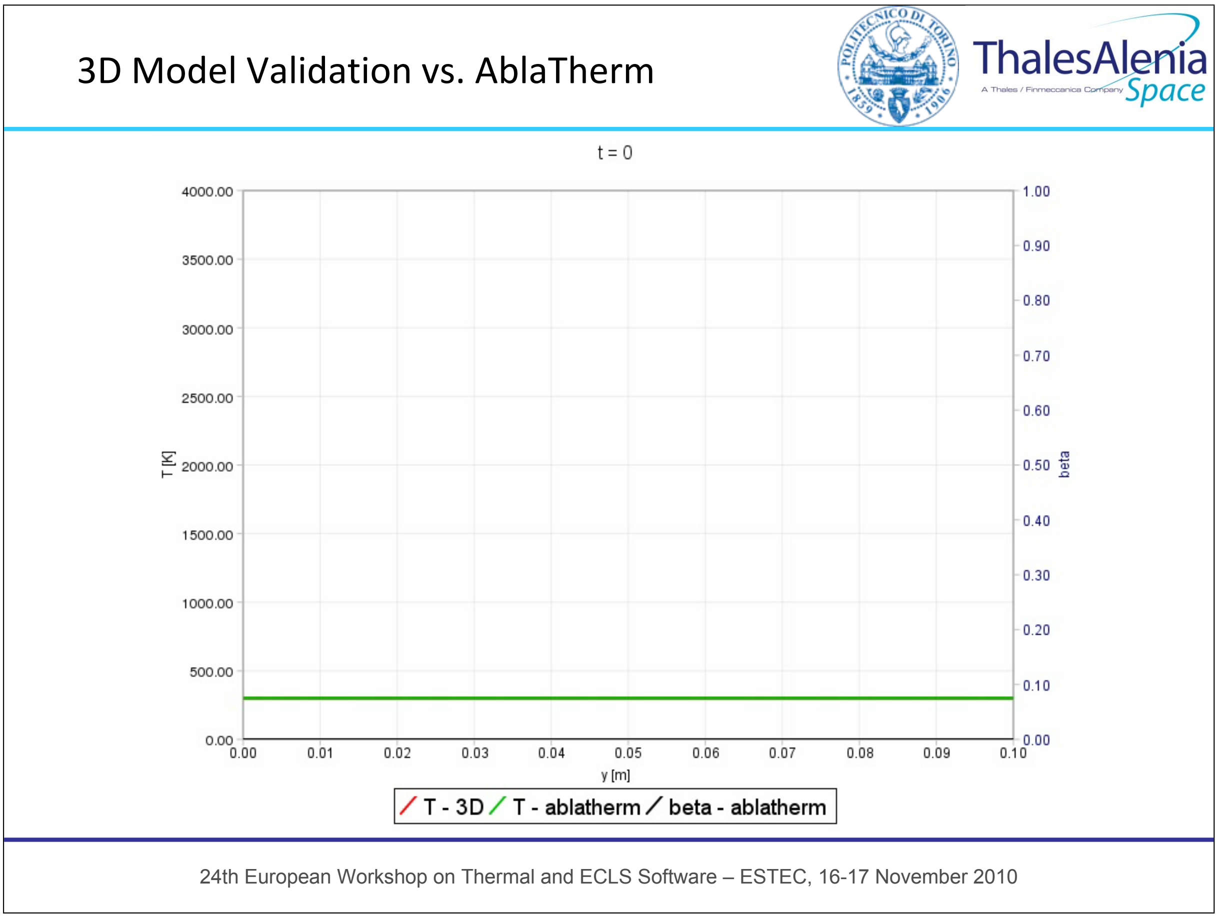
3D Model Validation vs. AblaTherm
t = 0
T [K]
beta
y [m]
T - 3D
T - ablatherm
beta - ablatherm
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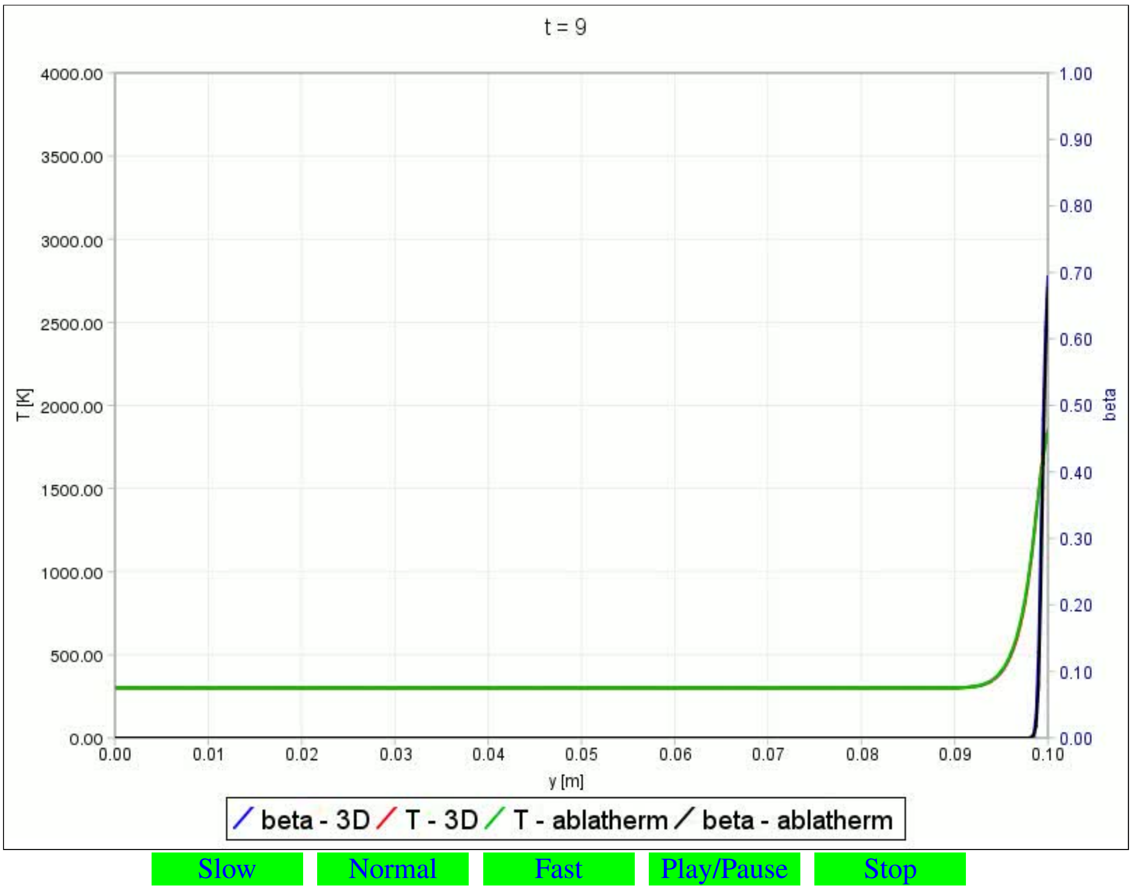
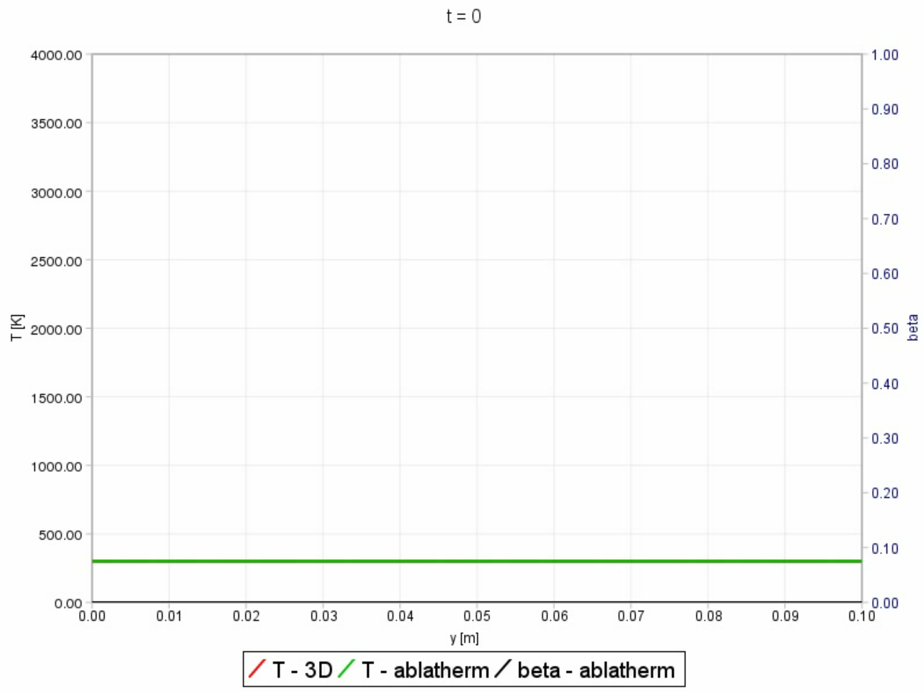

t = 9
T [K]
beta
y [m]
beta - 3D
T - 3D
T - ablatherm
beta - ablatherm
Slow
Normal
Fast
Play/Pause
Stop

3D Model Validation vs. AblaTherm

ThalesAlenia Space



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Future works

ThalesAlenia Space

- Finalization of the 3D code:
  - surface recession models implementation.
  - Different surface heat flux Boundary Conditions implementation.
- Studies for integration with ESATAN.

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ANY QUESTIONS?

THANKS FOR YOUR ATTENTION.

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