ORION MPCV INTEGRATED OVERALL THERMAL MATHEMATICAL MODEL DEVELOPMENT

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ABSTRACT

The development workflow of thermal and thermal-fluidic Integrated Overall Thermal Mathematical Model (IOTMM) of the Orion Multi-Purpose Crew Vehicle (MPCV) ESM (European Service Module) is presented. Orion MPCV is an affordable solution for multiple mission capability, and as such shall be designed to withstand a large variety of environments going from International Space Station (ISS) to Low Lunar Orbits.

The model simulates the behavior of the ESM Active and Passive Thermal Control Systems (ATCS & PTCS). The high integration of the ATCS and PTCS as well as the adoption of breakthrough concept components represented a challenging modeling activity. This resulted into the most complex model so far developed in Thermal Desktop environment by TAS-I.

The IOTMM development relied also on several multiphysics software tools - such as ANSYS Workbench, COMSOL Multiphysics, and NX Space System Thermal - to reach the suitable degree of accuracy into the modeling of radiators, coldplates, and brackets.

The results obtained through the analysis campaign are a key point for the ATCS and PTCS design assessment in the frame of the MPCV ESM Preliminary Design Review (PDR) achievements. Thanks to the adopted modeling techniques an highly parameterized IOTMM was built, minimizing user-level operations. This made possible to cope with the fast changing design typical of dense schedule development phases. Moreover, the large set of missions the Orion MPCV ESM shall be able to deal with required fast yet precise design trimming, for which the IOTMM flexibility represented an enabling feature.

Further improvements from the thermal-fluidic modeling standpoint are foreseen, for they are currently included as external non-graphical SINDA/FLUINT submodels. Nevertheless the presented activity is an important heritage step forward into the adoption of a fully graphical approach to the development of complex IOTMMs.

INTRODUCTION

Orion MPCV is an affordable solution for multiple mission capability, and as such shall be designed to serve as manned exploration vehicle and emergency vehicle in a large variety of environments going from International Space Station (ISS) to LLO (Low Lunar Orbits). More in depth, the spacecraft will serve as the primary crew vehicle for missions beyond LEO and will act as a backup system for the International Space Station (ISS) cargo and crew delivery.

Under an agreement between NASA and ESA MPCV will be powered and supported by the European Service Module (ESM). In the frame of the B2 design phase Thales Alenia Space Italy (TAS-I) is supporting EADS Astrium LMX in the development of the ESM.

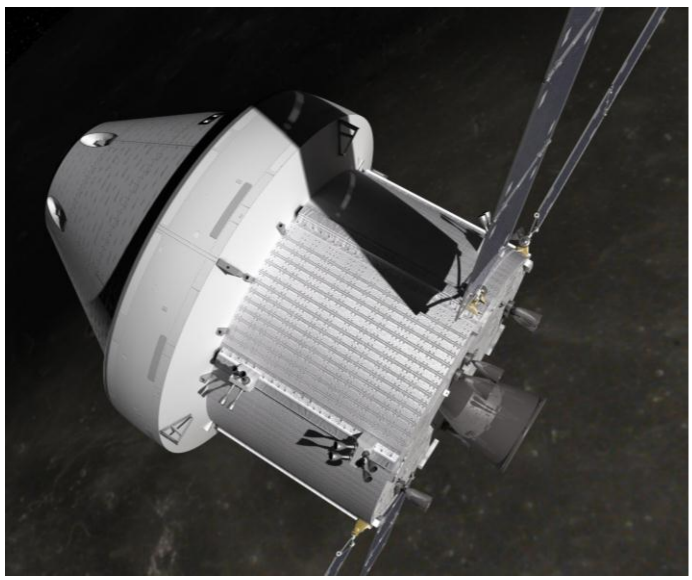

Figure 1. The MPCV ESM with the Orion Crew Vehicle attached on top (courtesy NASA).

In particular, TAS-I is in charge of the ESM Active and Passive Thermal Control Systems (ATCS & PTCS) design. To achieve the design goals and thus fulfill the mission requirements, an Overall Thermal Mathematical Model (IOTMM) was built.

The model simulates the behavior of the ESM Active and Passive Thermal Control Systems (ATCS & PTCS). The high integration of the ATCS and PTCS as well as the adoption of breakthrough concept components represented a challenging modeling activity. This resulted into the most complex model so far developed in Thermal Desktop environment by TAS-I.

The IOTMM development relied also on several multiphysics software tools to reach the suitable degree of accuracy into the modeling of radiators, coldplates, and brackets.

INTEGRATED MODELING OF THE ESM

The ESM IOTMM is the outcome of the integration of several models results into a main frame built in Thermal Desktop environment. Each software involved into such a modeling workflow was chosen bearing in mind its performances, physics capabilities, and operational constraints. This led to define a specific modeling field for each tool, as shown in Figure 2.

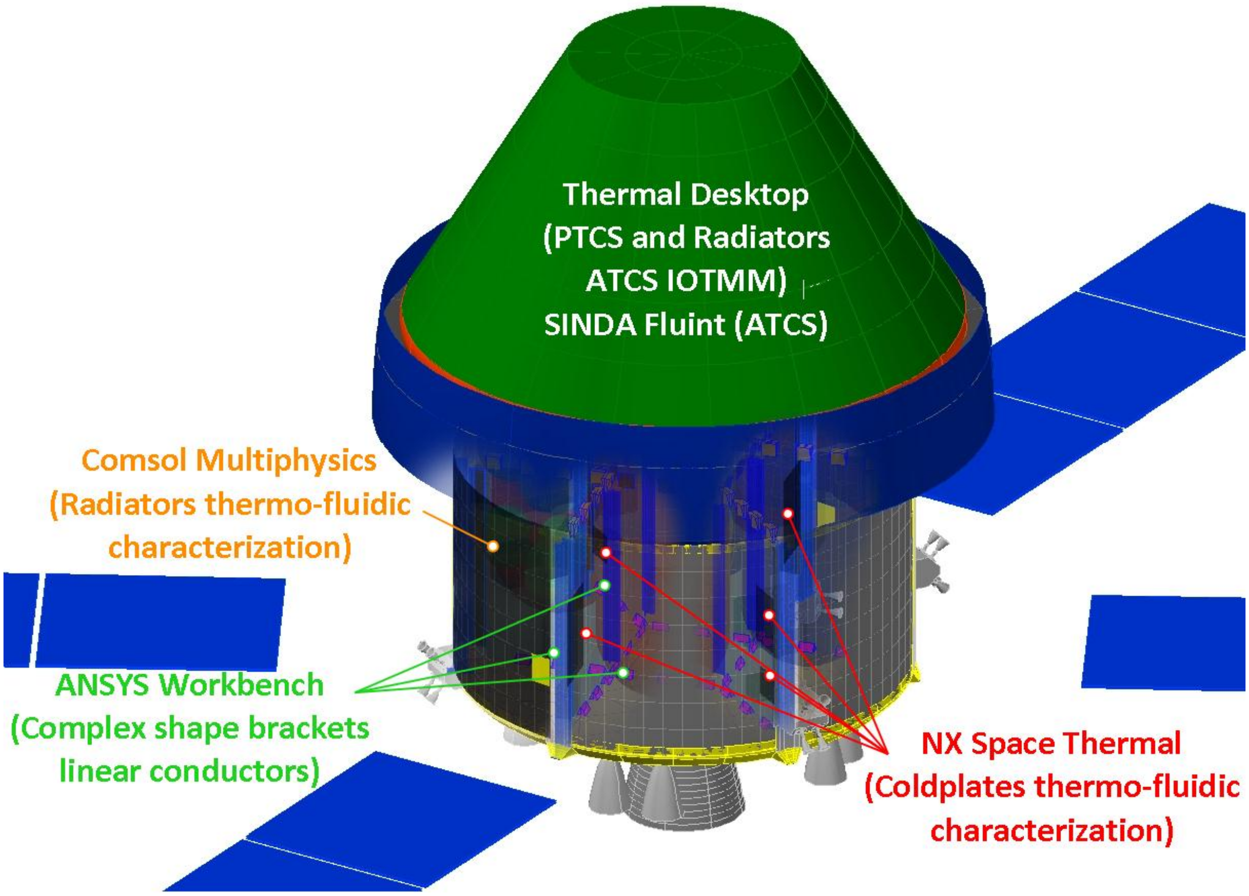

Figure 2. Modeling tools field of application. The image depicts the IOTMM.

Several reasons contributed to the selection of the software tools. The main reasons are linked to peculiar tools capabilities, which made the specific software package suitable for the relevant field of application. Nonetheless, the in house presence of experienced users as well as of the needed software licenses played a key role. An overview of the key features which led to the selection of each tool is reported in Table 1.

It has to be noted that the challenging development schedule of MPCV ESM once more highlighted the necessity of minimized user intervention for non-productive yet time consuming activities (such as units system translation and model delivery format). The latter also being driven by requirements asked by the customer, not only of the present project, for the used components are developed focusing on a re-usability concept.

Table 1. Modeling tools key features

Software tool	Modeling field	Key features
Thermal Desktop	IOTMM (PTCS and Radiators ATCS)	• fast model building • solver speed • automated translation to/from imperial units system • customer required format
SINDA FLUINT	ATCS	• solver speed • automated translation to/from imperial units system • customer required format • does not require additional GUI license
Comsol Multiphysics	Radiators T/F characterization	• fast model building • robust CAD interface • mixed 1D/3D CFD capabilities
ANSYS Workbench	Brackets linear conductors	• fast model building • robust CAD interface • also used by structural department (license sharing)
NX Space System Thermal	Coldplates T/F characterization	• fast model building • robust CAD interface • ESATAN format exporting capability (ESA constraint for further projects scenarios)
Dassault Systèmes Isight	Coldplates T/F characterization	• robust and effective interfacing with NX Space Thermal

A more in depth review of the activities carried on for each modeling aspect is reported hereafter.

<u>Coldplate model</u>

Each coldplate (C/P) item was modeled at IOTMM level by defining an equivalent overall heat transfer coefficient (HTC), calculated with the following formula:

$$HTC = \frac{Q/A}{\overline{T}_{SKIN} - \overline{T}_{FLUID}}$$

HTC was physically represented by the conductor between the coolant and C/P skin (at which the avionics is interfaced), as depicted in Figure 3.

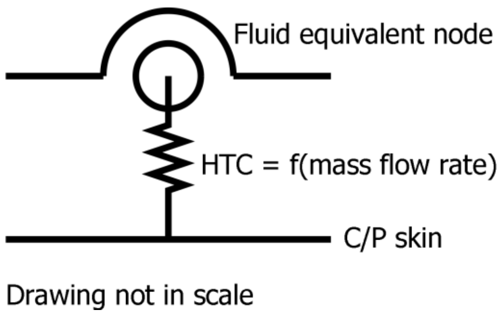

Figure 3. HTC concept.

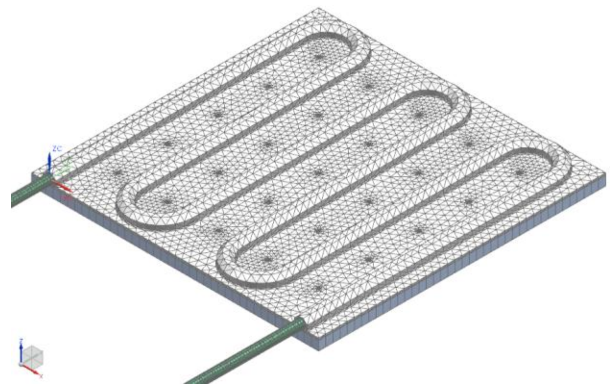

Figure 4. Cold Plate NX/TMG TMM.

Needed data for the HTC computation was the outcome of detailed TMM (cooling fluid average temperature and temperature distribution over the C/P skin, the avionics base plate interface).

The detailed model was developed in NX Space System Thermal 7.5.3 (MAYA TMG solver). A TMM overview is given in Figure 4.

The C/P behavior was simulated by means of a correlated model where the reference test conditions were implemented. By exploiting test data the following key conditions were modeled:

- external environment (the higher is the test boundary uniformity, the easier is the implementation into TMM, resulting in less correlation errors);
- conductive interface between C/P and heat load application doubler;
- heaters configuration: nine equivalent loading surfaces simulated the heater devices.

The main correlation parameters were:

- C/P matrix thermal conductivity: initial value estimated considering the datasheet values and the related uncertainties;
- convective heat transfer between coolant and pipes wetted area: initial value estimated with Gnielinski formula (turbulent regime), maximum and minimum values calculated with standard uncertainties (25%);
- additional interfaces contacts.

A DS iSight optimization was instructed to run several solver instances by dynamically change the aforementioned parameters defined into the solver input file (INPF, Figure 5).

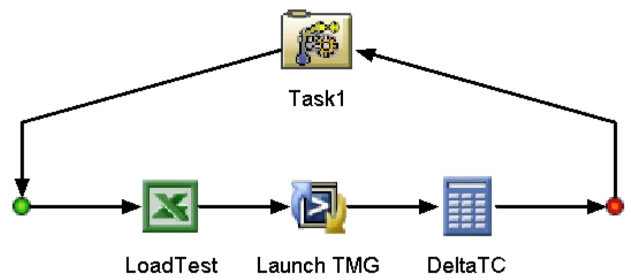

Figure 5. Integrated optimization loop for correlation (iSight).

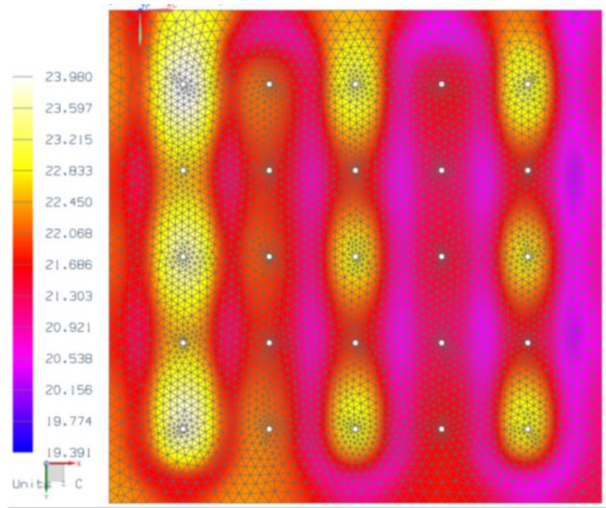

Figure 6. Cold plate interface skin temperature contour example.

The optimization objective was to reduce:

- the local control point temperature error (i.e. the temperature read by the thermocouple versus the equivalent TMM control point temperature);
- the average temperature error;
- the standard deviation.

After an initial survey of the parameters limits (to confirm the stability and reliability of the correlation), the optimization led to a temperature error lower than 0.5 °C (0.9 °F) for the 90% of the considered 24 control points (10% of the errors are lower than 1 °C (1.8 °F)).

From this correlation, the NX TMM was set up to match the operative mass flow conditions: assuming the power load to be homogeneous, the C/P heat transfer (or rather, the C/P equivalent conductor per unit area) is only mass flow dependent (if modification in thermal conductivity through the matrix is negligible), therefore is independent from both the load level and the inlet fluid temperature. The average C/P skin temperature was eventually obtained by the computed thermal map (Figure 6).

<u>Radiator panel local model</u>

The Radiator Panel local thermal model was developed in COMSOL Multiphysics 4.3a.

The Radiator Panel model was based on a high fidelity 3D Finite Element (FEM) mesh (Figure 7). For fluid section, the additional module Pipeflow was used. The Pipeflow module was used for simulations of fluid flow and heat transfer in pipe and channel networks so that flow was 1D modeled. This choice was quite effective on nodes numbering limitation, thus excluding the software CFD capabilities.

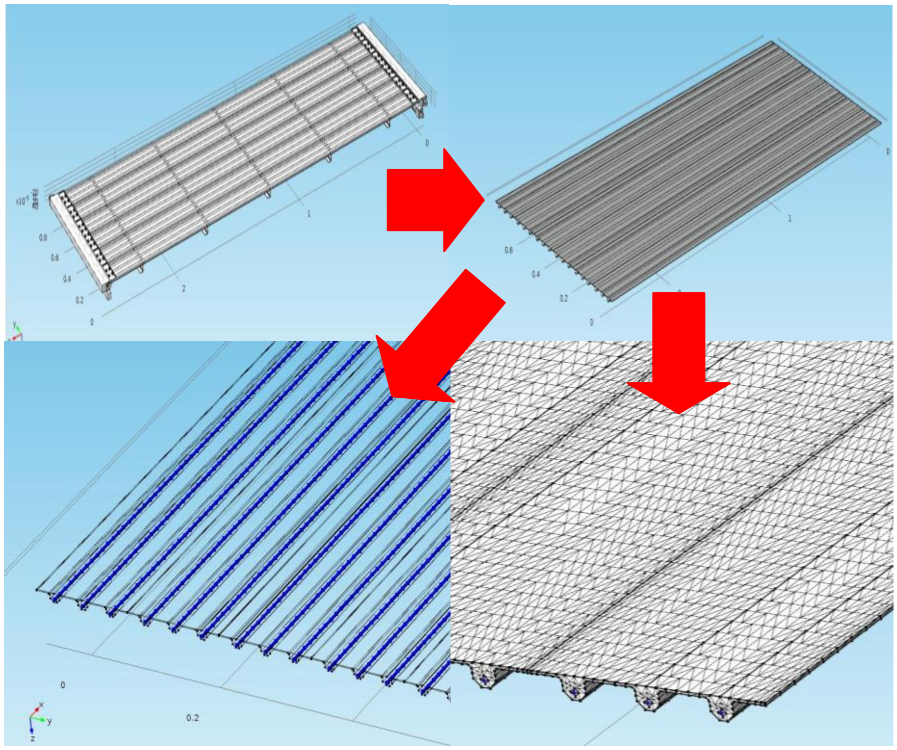

Figure 7. Mesh generation workflow.

The COMSOL TMM was developed by following several phases, in particular:

- CAD model import and adaption from CATIA V5 model (inlet/outlet connectors and manifolds were neglected; additional edges added to accommodate 1D fluid channel elements);
- an initial triangular mesh was generated on the panel front surface and then extruded along the longitudinal direction. The resulting prism elements were then converted to tetrahedral elements by adding diagonal edges;
- physical properties of the model were accurately defined to simulate the real thermal fluidic behavior (key parameters: material properties, thermal couplings, boundary conditions such as thermal insulation, boundary temperatures, surface to ambient radiation, inlet mass flow rate).

The simulation setup objective was to reflect the thermal vacuum test operative condition and thus to correlate the model versus the test campaign outcomes.

The main efforts were devoted to the definition of the boundary conditions and the thermal coupling between fluid and panel.

A surface-to-ambient radiation coupling was set up on the panel active surface to model the heat flux rejected to the environment. An Isolation boundary condition was applied on all other panel surfaces to simulate the Multi Layer Insulation (MLI). The fluid domain was simulated using a 1D model to limit the nodes number: temperature and flow rate boundary conditions were applied at the channel inlets, while pressure and outflow boundary conditions were applied at the channel outlets.

The turbulent convective heat transfer between the fluid and the internal wall of the channels was computed on the basis of Gnielinski correlation, which makes possible to calculate the Nusselt number for a fully developed turbulent and transition flow (Re > 3000):

$$Nu_{turb} = \frac{(f_D/8)\cdot(\mathrm{Re}-1000)\cdot \mathrm{Pr}}{1+12.7\sqrt{f_D/8}\cdot\left(\mathrm{Pr}^{2/3}-1\right)} \rightarrow H = Nu \cdot \frac{k_{fluid}}{d_{channel}}$$

Where:

- Re and Pr are the Reynolds and Prandtl numbers of the channel flow;
- f_d is an empirical friction coefficient;
- $d_{channel}$ is the channel diameter;
- k_{fluid} is the fluid thermal conductivity;

The Nusselt number leads to the equivalent thermal conductivity calculation (*H*).

The model was validated by comparing the results obtained with the outcomes of a thermal vacuum test campaign. Several steady-state simulations were performed in different environmental conditions, and the analytical results were evaluated in terms of panel surface temperatures and Heat Rejection Capability (HTC, defined as power irradiated per unit area).

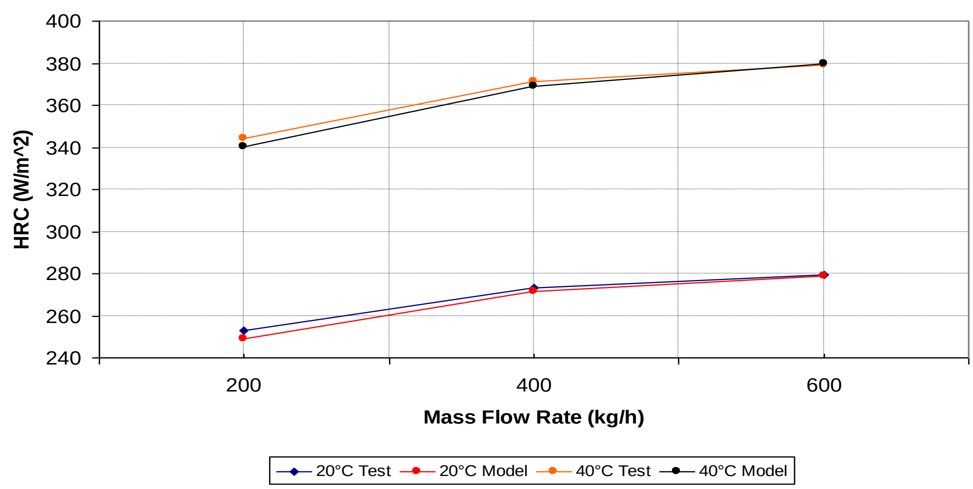

Figure 8. Model versus test results comparison for different inlet fluid temperatures.

The model proved to be very accurate:

- the value of the HRC predicted by the model was in good agreement with test data (Figure 8).
- the temperature mismatch for the radiator panel surface was lower than 1.5 K for more than 70% of the control points.

ATCS SINDA FLUINT model

MPCV ESM thermal hydraulic mathematical model was raw coded in SINDA/FLUINT v5.5 language. The purpose of this model was to fully reproduce the service module ATCS, except for the radiators part built in Thermal Desktop.

The ESM active thermal control system was defined by two redundant loops constituted by the following components:

- pump: modeled as a mass flow rate set (the actual pump is to be defined);
- coldplates: heat sinks for the avionics;
- IFHX: heat exchanger among ESM and crew module loops;
- radiators: are the unique rejection sink for the ESM, configured with three branches of two curved radiators each (six radiators in total);
- three way valve: devoted to the fluid coolant (HFE) temperature control for C/P and IFHX inlets.

A schematic of the ATCS is depicted in Figure 9.

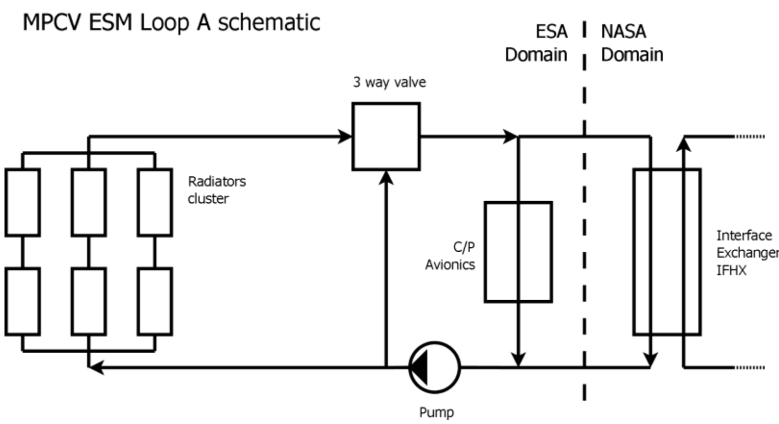

Figure 9. MPCV ESM ATCS Sinda-FLUINT THMM.

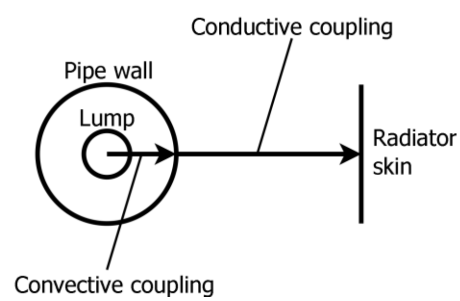

Figure 10. Radiators pipe to skin conductances chain.

The modeled components (pump excluded) were defined as follows:

- coldplates: obtained by the detailed model developed with NX/TMG and characterized by an equivalent overall heat transfer coefficient;
- three way valve: constituted by two control valves driven by a variable loss coefficient. The loss factor of the first branch is the reciprocal of the second one. Therefore the control simulates the behavior of a valve able to distribute the mass flow through two different branches;
- Radiators: the model was based on a COMSOL correlated detailed model. A simplified SINDA/FLUINT model was developed to simulate the radiators behavior for the system analysis. The radiators simplified model local schematic is represented in Figure 10.

The parameters concurring to the radiators behavior definition were:

- convective heat transfer between pipe internal surface and the coolant: defined with a combination of classical laminar (constant Nusselt number), transition (Hausen) and turbulent (Gnielinski) correlation (Prandtl, Reynolds number dependent), and updated at every time step;
- conductive coupling between pipe and radiator skin: dependent on the geometrical configuration of the radiator and the conductivity of the matrix material. The referred conductance was calculated by developing a local radiator model involving a single radiator pipe (figure 7).

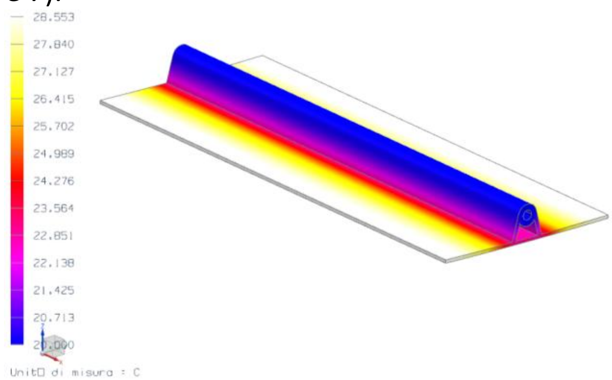

Figure 11. Local radiator pipe model.

By submitting a load over the radiator skin and by considering the internal surface of the radiator tube as boundary, the temperature difference between tube internal surface and radiator skin (average) was obtained and thus an equivalent linear coupling was calculated.

The SINDA/FLUINT simplified model was validated by comparison with respect to the COMSOL correlated model. As reported by Table 2 (sink temperature case -80 °C (-46 °F), coolant inlet temperature case 20 °C (68 °F)) COMSOL correlated THMM versus SINDA/FLUINT THMM errors are always lower than 10% (heat rejection error was always lower than 2%).

Table 2. SINDA/FLUINT vs COMSOL THMM differences.

Mass flow rate (per pipe)	18.2 kg/h (40 lbm/h)	24.2 kg/h (54 lbm/h)
Coolant outlet temperature error	-3.5%	-1.5%
Skin average temperature error	+4.4%	-8.1%
Radiative heat rejection error	-1.6 %	+0.8%

For this purpose, the SINDA/FLUINT optimization routines were, using the following correlation parameters:

- the radiator panel IR emissivity;
- the radiator material thermal conductivity (skin to pipe linear conductance);
- the radiator convective heat transfer coefficient.

To improve the passive and active thermal control synergy, the radiators thermal hydraulic model was developed within the Thermal Desktop modeling environment through the FloCad tool.

The last main component, the IFHX, was provided by NASA to solve coupled ESM/CM heat exchange and rejection issues. The key parameter to be optimized was the mass flow passing through the interface heat exchanger branch, which shall be as higher as possible to extract the maximum power from the CM.

Complex brackets modeling

For the vehicle is characterized by complex CNC machined brackets which are both difficult to be modeled with suitable accuracy and important links of the inner to outer environments thermal coupling chain, a local analysis approach was applied.

To reduce the time usually devoted to the model building through geometrical primitives when dealing with common lumped parameters software suites, an FE tool was used: ANSYS Workbench R14.0.

The modeling activity was not strictly limited to the linear conductor calculation. In fact a rough geometrical representation of the biggest brackets was built to take into account the radiative contribution of the relevant components.

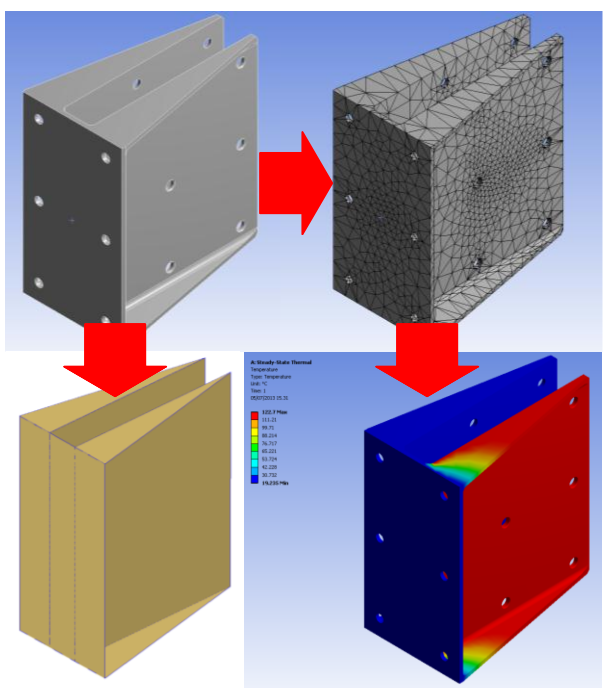

Figure 12. ANSYS modeling workflow for a rather simple bracket

The analysis activity consisted into a tidy yet effective approach (Figure 12) constituted by the following steps:

- CAD model import and simplification from CATIA V5 model;
- set up of fictitious temperature boundaries on contact surfaces;
- steady state run to assess temperature drop among the interfaces;
- building of the geometrical model in Thermal Desktop;

Into a system characterized by stringent design requirements, a proper couplings calculation is the key to reduce modeling uncertainties. The threshold-like response of ATCS systems like the one used in MPCV (i.e. ATCS allocated mass increases suddenly beyond the radiators heat rejection capability saturation) made a key point out of the minimization of modeling approximation. The latter was quite high in the past, when the complex shape brackets were roughly reduced barely using 2D/3D primitives resembling the real component with a high degree of conservatism.

Integrated Overall Thermal Mathematical Model

All the aforementioned contribution generated input data or code to be included into the IOTMM. The latter was completely developed by means of Thermal Desktop v5.5 software.

So far TAS-I developed models for US market were mainly built coding SINDA input from scratch and merging the TMM model with the relevant Thermal Desktop GMM outcome. Thus the GUI approach was used barely for the heating rates and radiative coupling generation.

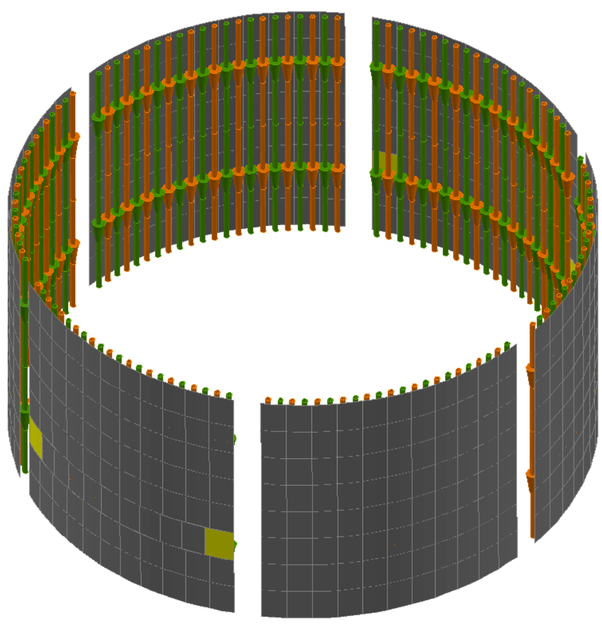

Figure 13. ATCS radiators channels.

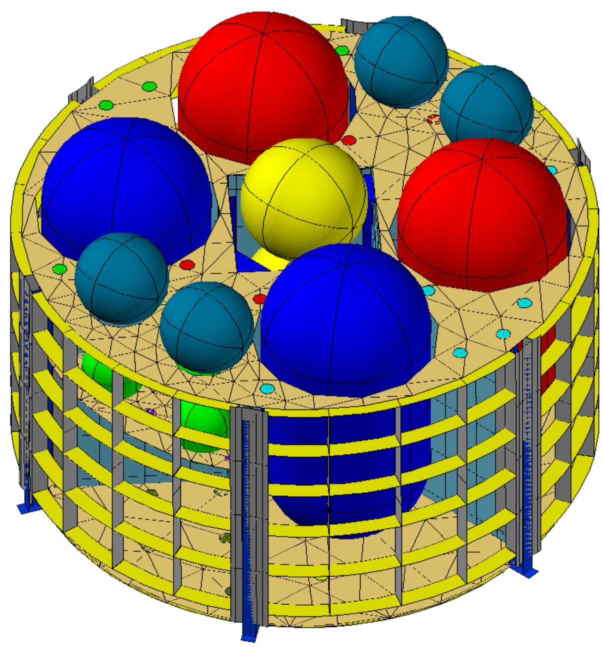

Figure 14. Internal room (structure, tanks).

With the MPCV ESM model the company wanted to change the approach by building the main core of the model through the GUI functions. The latter basically met two requirements: the customer required format and the modeling speed, mandatory to develop such a complex model in short time. The technical needs which pushed towards the GUI adoption were also driven by the extended capabilities given by this approach. In particular:

- the complex CNC machined bulkheads through which the storage tanks pass would have been hard to be modeled without the Thermal Desktop FE Mesher tool (Figure 14). On the other hand there was no other option for the tool is not able to handle boolean operations;
- an extended use of the contactors feature, which relies upon ray tracing/point algorithm to assess the conductors among the surfaces, automatically coupled the items, with sensitive “side effects”:
    - great flexibility, i.e. when changes are occurring at configuration level the couplings are automatically updated;
    - makes easier the node-to-node matching between the channels and the radiators surfaces (Figure 13);
    - a binding choice when dealing with couplings involving FE modeled items;
    - pave the way for further heaters placement optimization (colored spots in Figure 14);
- the model translation to imperial units system is a one-click operation (except for the custom routines inserted at Network Element Logic level);
- the reducing of the model is simplified by parameterization through symbols;
- exporting capabilities towards other software platforms (i.e. temperature maps for thermal elastic analysis) are easily managed.

The above mentioned capabilities were extensively exploited to effectively integrate the local/subsystem models contributions.

CONCLUSIONS

The development workflow of thermal and thermal-fluidic Integrated Overall Thermal Mathematical Model of the Orion MPCV-ESM was presented. The activity was challenging from several standpoints and thus demanded a multi-disciplinar, multi-tool approach to cope with the strict accuracy requirements of a well optimized design. This led TAS-I thermal team to approach the problem by refining its usual multi-tool modeling technique, for almost all the available software tools have been used. A part from successfully meeting the key goal about the required accuracy, the exercise represented an important step forward into the adoption of a fully graphical approach to the development of complex IOTMMs.

In particular, the lessons learnt greatly improved both the modeling heritage and the used software. In fact the latter took advantage of the extensive use of advanced features, which sometimes revealed their limits (i.e. boolean operations capabilities) and were refined (i.e. optimized GUI behavior, and more submitted suggestions to be implemented) or corrected (i.e.

conversion factors fixing, mesh union handling, etc.) thanks to the software developers support and to the user built custom logics.

The presented analysis outcomes are about the contributions given to the IOTMM by the local/subsystems modeling tools, for the ATCS/PTCS integrated system analysis is currently ongoing. Nevertheless, the latter is achieving the expected goals in terms of accuracy and model robustness.

Moreover the model is in its final refinement, and changes are undergoing to match the latest configuration updates, once more confirming the flexibility of both the modeling tools and modeling approach. On the other hand a further integration step is foreseen, aimed to the fluidic loop rebuilding in Thermal Desktop FloCAD environment, as already done for the radiators channeling. Furthermore, an heater positioning optimization is going to be performed thanks to the placing of heaters on arithmetic surfaces contactor-coupled with the structure.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

ATCS	Active Thermal Control System
C/P	Cold Plate
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CM	Crew Module
CNC	Computer Numerical Control
ESA	European Space Agency
ESM	European Service Module
FEM	Finite Element Method
HTC	(overall) Heat Transfer Coefficient
IFHX	InterFace Heat Exchanger
IOTMM	Integrated Overall Thermal Mathematical Model
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LMX	Les Mureaux
MPCV	Multi-Purpose Crew Vehicle
NASA	National Aeronautics and Space Administration
T/F	Thermal Fluidic

TAS-I Thales Alenia Space - Italy

THMM Thermal-Hydraulic Mathematical Model

TMM Thermal Mathematical Model

PDR Preliminary Design Review

PTCS Passive Thermal Control System