FiPS® - Final Phase Simulator

Combined simulation of dynamic and thermal fluid-structure interaction

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Abstract
This document contains information about the thermal coupling, as it is integrated in Airbus DS' analysis tool FiPS®. This tool provides the unique capability of simulating interconnected systems under technical aspects, in particular dynamic and thermal fluid-structure interactions. The tool's development was co-founded by the German Space Agency (DLR) in frame of the launcher technology maturation program PREPARE. FiPS® is introduced by a description of its basic functional principle, the components it consists of and of its modes of operation. This is followed by an overview of how the of thermal models are created for their application in FiPS® and the way of visualizing thermal simulation results.

1. Introduction

Simulation of in-flight spacecraft behaviour and its corresponding control is challenging. Both orbit and attitude control must work precisely in order to reach destination and to avoid losses. Environmental and vehicle-internal effects influence orbit and attitude of a spacecraft. Among all the requirements for an accurate orbit the most important one is that the spacecraft points towards the correct, i.e. the flight direction.

What appears obvious can transform into an arbitrarily complex problem on trying to consider the system "spacecraft" as realistic as possible. Realistic is, that the spacecraft has propulsion tanks filled with free to move propellants. Realistic is, that a moving propellant mass influences the motion of the whole spacecraft. Realistic is also, that heat is conducted into the tanks, e.g. by solar exposure, engine activity or simply by the electrical system of the spacecraft. As a consequence, cryogenic propellant gets in contact with warm tank walls. Due to evaporation, tank pressure changes. That in turn influences the thruster efficiency of the cold gas attitude control system. These points are only a few examples for many processes occurring within the system "spacecraft". But these points are the relevant driving forces for the development of the thermal coupling included in FiPS®. [1][2]

FiPS® is a software tool for resolving and visualizing dynamic and thermal interactions between a spacecraft and its propulsion tanks' contents. On the basis of the principle "actio est reactio", vehicle's motion is coupled to that one of the propellants [3]. Setting a closed loop control model on top of this interaction, FiPS® serves amongst others as testing environment for control algorithms. The heat transfer processes allow the improved estimation of mission's propellant mass budget and also the enhancement of the design of existing hot gas thruster models as well as the design of cold gas thruster models.

In the following, the components of FiPS® are briefly described. Moreover, this paper gives an insight on how the thermal coupling, as it is currently implemented in FiPS®, works from a functional point of view.

2. The building blocks - implemented tools

2.1 Main components

MATLAB® and Simulink®: The Matrix Laboratory, or short MATLAB®, is a numerical computing environment for the solution of mathematical problems, in particular the manipulation and solution of matrices, and the graphical display of these solutions. Simulink® is an extension of MATLAB® and allows the modeling and simulation of e.g. physical and technical systems. In conjunction with FiPS®, Simulink® is used to simulate and to visualize the control process, which is implemented in a spacecraft's control system, as well as the rigid body dynamics and the propulsion system. [4]

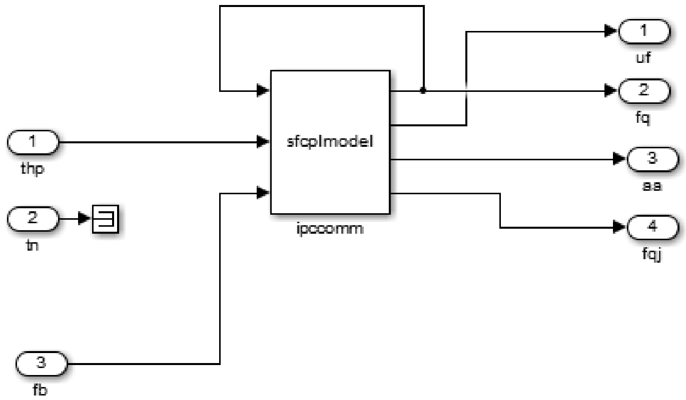

Figure 1: Simulink block example

FLOW-3D®: FLOW-3D® is a CFD code, which is used at Airbus DS for the determination of fluid motion and fluid thermal behavior within spacecraft tanks. Based upon the volume of fluid and the finite volume methods, FLOW-3D® solves basically the Navier-Stokes, the mass continuity and the fluid energy equations for three-dimensional computational cells (compare Figure 2). [5]

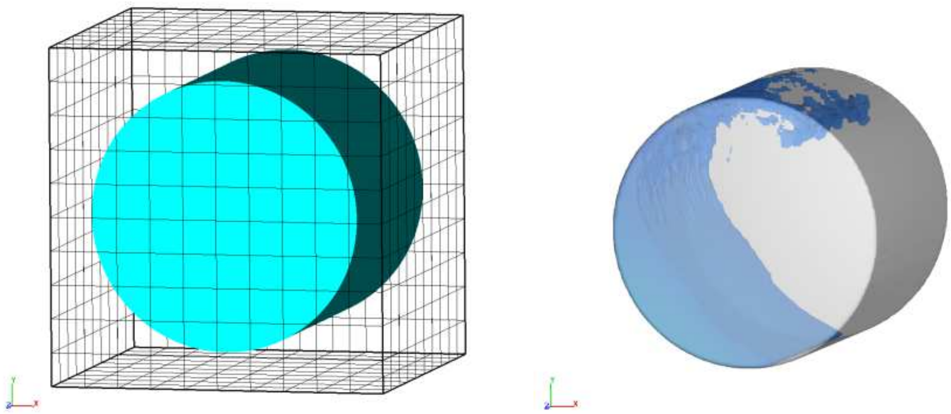

Figure 2: Complementary model of a cylindrical tank within a mesh block (left) and sloshing liquid within the same cylindrical tank (right) in FLOW-3D®

ESATAN-TMS®: The thermal analysis tool ESATAN-TMS® is applied at Airbus DS for the determination of heat distribution on the surface and within the interior of spacecrafts. Thermal analysis is performed for conductive and radiative heat transfer processes within solid structures e.g. to determine the heat input due to solar exposure. Convective heat transfer processes within fluids are simulated in order to estimate e.g. the consequences of evacuation of air-filled cavities during the spacecraft's launch. In order to establish a model in ESATAN-TMS®, components of the spacecraft are idealized in form of nodes (see Figure 3) with assigned characteristics to the component they represent respectively. Solutions are obtained by solving heat equations for finite differences. [6]

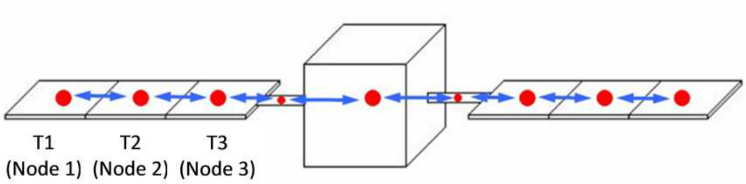

Figure 3: Node model of a satellite in ESATAN-TMS®

2.2 Post-processing and visualization

In order to display simulation results, the component's respective visualization features can be used in first place. For example, in MATLAB® implemented plotting functions can be used to show simulation results of e.g. the forces' and torques' variation of time.

Secondly, there is a procedure integrated in FiPS®, which sums up and displays all simulation results. Display methods for thermal analyses only and for combined dynamic and thermal analyses are available.

The key to put the pieces together is currently the "Virtual Reality Modeling Language" (VRML). MATLAB® has already implemented a VRML feature to visualize its results. In case of FLOW-3D®, the FLOW-3D® output has to be processed into a .wrl-file, which is the file extension of VRML. At first, the liquid surface is transformed into STL (Surface Tessellation Language) format with a FLOW-3D® post-processing feature. This way .stl-files are obtained for any desired simulation time step. In a second step, a conversion tool converts these .stl-files into a .wrl-file. Finally, vehicle's VRML information is merged with MATLAB®'s dynamic and FLOW-3D®'s propellant VRML information. After that, simulation results can be shown in form of pictures or also as an animation for the whole spacecraft. The example below shows an Ariane 5 ME upper stage with implied payload, LH2 and LOX tank.

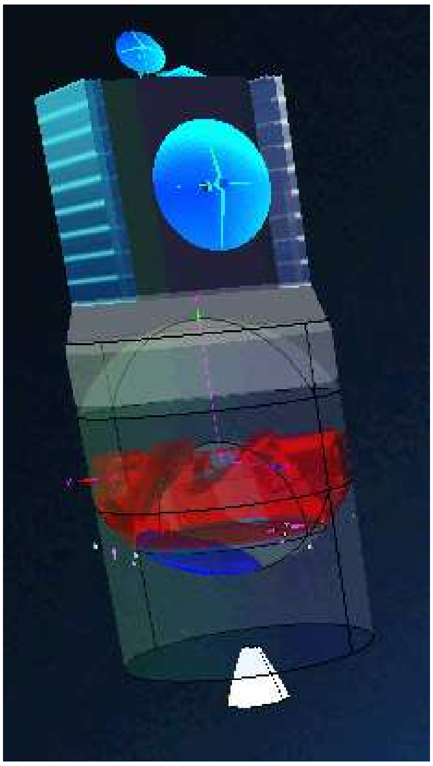

Figure 4: Plot of a FiPS® analysis result of an Ariane 5 ME upper stage with an implied payload

3. The basis - functional principle of FiPS®

3.1 Modes of operation

FiPS® consists of a Microsoft Visual Basic graphical user interface (GUI), a Microsoft EXCEL data base, a main code written in C/C++, a rigid body FORTRAN code and the before mentioned commercial tools MATLAB®/Simulink®, FLOW-3D® and ESATAN-TMS®.

The GUI enables the user a convenient application of FiPS®. Together with the EXCEL data base, the GUI facilitates the management of simulation inputs. All required input is then passed on to the main code. Its task is to start, observe and terminate MATLAB®/ Simulink®, FLOW-3D® and ESATAN-TMS®, further referred to as processes. Hence, the main code is the core of inter-process communication. It provides a shared memory area, by means of which the processes exchange data. A schematic representation of the main components of FiPS® and their interactions is shown in Figure 5.

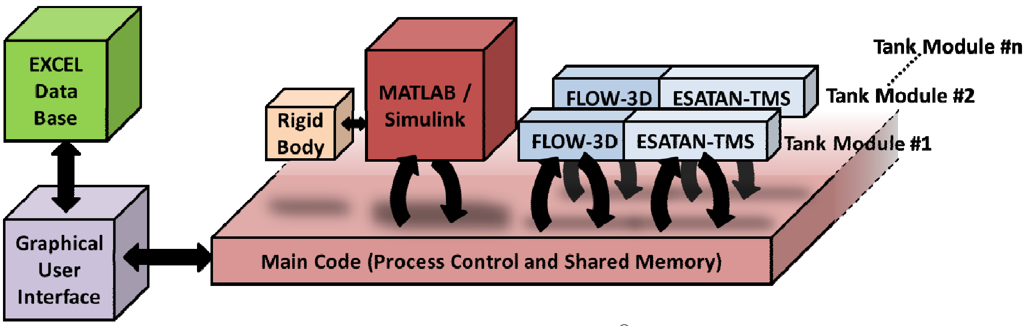

Figure 5: Block diagram of FiPS® components

It is possible to simulate any user-defined amount of tanks. A basic configuration is to consider a spacecraft's fuel and oxidizer tanks only. An expanded and more realistic model is to include also pressurization and payload tanks into the simulated system.

Each tank is regarded within FiPS® as a module, the basis of which is a CFD model created by means of FLOW-3D®. Depending on the preferred operation mode, the tank module may also contain a corresponding ESATAN-TMS® process. There are two modes of operation: dynamic only or dynamic and thermal in combination.

When a pure dynamic analysis with FiPS® is required, then each tank module consists solely of one FLOW-3D® process. The coupling type in use is the dynamic coupling, which represents the data exchange only between MATLAB®/Simulink® and FLOW-3D® via the main code. This is described more in detail in section 3.2.

A thermal analysis is conducted by means of the thermal coupling in combination with the dynamic coupling. Here each tank module consists of one FLOW-3D® and one corresponding ESATAN-TMS® process. Data exchange takes place only between these two, again via the main code. The description of the thermal coupling can be found in section 3.3. When a combination of both coupling types is chosen, all three components, MATLAB®/ Simulink®, FLOW-3D® and ESATAN-TMS® are in use.

3.2 Dynamic coupling

Imagine a well-loaded road tanker that suddenly has to break when approaching a traffic light, which turned unexpectedly to red. It is quite a struggle for the driver to stop the truck. Even after the driver managed the truck to stop, the sloshing liquid load inside of the tank will keep the whole vehicle wobbling for quite a while after the stop. The course of actions taking place between the truck and its tank contents is comparable to that one of a spacecraft. Whenever the spacecraft changes its state of motion, the tank contents will react to it, even though inertially. The difference of the spacecraft to the road tanker is that there is no road a break would be effective on. There is nothing the spacecraft could hold on to. The only means of a spacecraft to handle liquid motion as a consequence of maneuvers is by treating them as disturbance forces and torques on the whole system of the spacecraft. It allows the controller to react respectively by activating or deactivating the thrusters. This way it is ensured that the vehicle stays within the preferred attitude frame and on the provided track.

In order to simulate dynamic interactions between a spacecraft and its propellants, an interface between Simulink® and FLOW-3D® was developed. In Simulink®, the whole system "spacecraft" is modeled in form of a closed loop control. Simulink® addresses the rigid body code, which solves the equations of motion taking into account also the disturbance forces and torques resulting from liquid motion. These are provided by FLOW-3D®. In return, FLOW-3D® receives as a result from the solution of the equations of motion linear and angular accelerations. On top of this exchange of quantities there is a closed-loop attitude control. It compares the command variables to the measured values and adjusts vehicle movement by thruster activation respectively, if necessary. The explained relations are displayed in Figure 6.

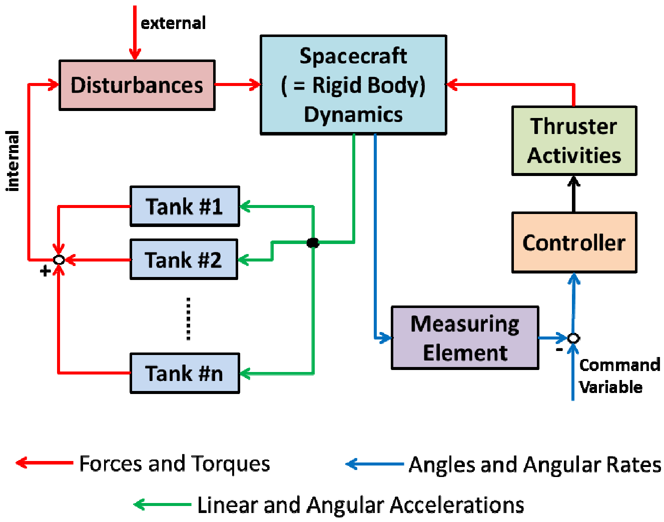

Figure 6: Control structure of FiPS®

3.3 Thermal coupling

The resolution of thermal interactions between propellants and surrounding tank structure is realized by means of a data exchange between FLOW-3D® and ESATAN-TMS®. The capability of simulating thermal interactions within the tank system enables to determine the corresponding pressure development within the tank due to evaporation processes. If the pressure is known, this information can be used at first for the design and then for the simulation of a cold gas propulsion system. It supplies realistic behavior of the upper stage due to a more accurate reaction of the attitude control. The cold gas propulsion system with all its pipes, branches, valves etc. can be modeled in Simulink®. Knowing the pressure conditions within the pipeline, the available thrust level at each thruster can be derived.

The state-of-the-art before the development of the thermal coupling was that models of a cold gas propulsion system were based upon a simplified polynomial mathematical model. They considered a pressure decrease in the pipeline system during thruster activation phases and a pressure increase during phases when the thrusters are not in use. In this case, pressure evolution is only specified by on- and off-times of the thrusters. This does not represent the real physical conditions.

In FiPS® tank voids and the therein moving propellants are modeled by means of FLOW-3D®. The tank walls are modeled by means of ESATAN-TMS®. This approach was chosen, as ESATAN-TMS® is much faster than FLOW-3D® in calculating heat conduction in tank walls using a comparable mesh grid resolution. If heat processes are resolved realistically, evaporation rates can be determined likewise accurately. As a consequence, the evolution of pressure can be obtained, which is the source of input for a cold gas thruster model.

The interaction between both tools is based upon an exchange of heat flux and temperature information (see Figure 7) [7]. In order to be able to exchange data, the models used for both tools need to be compatible. As for the interface, it was decided that the ESATAN-TMS® model is generated by means of FLOW-3D®. Chapter 4 gives a more detailed description of the way, how thermal models are built.

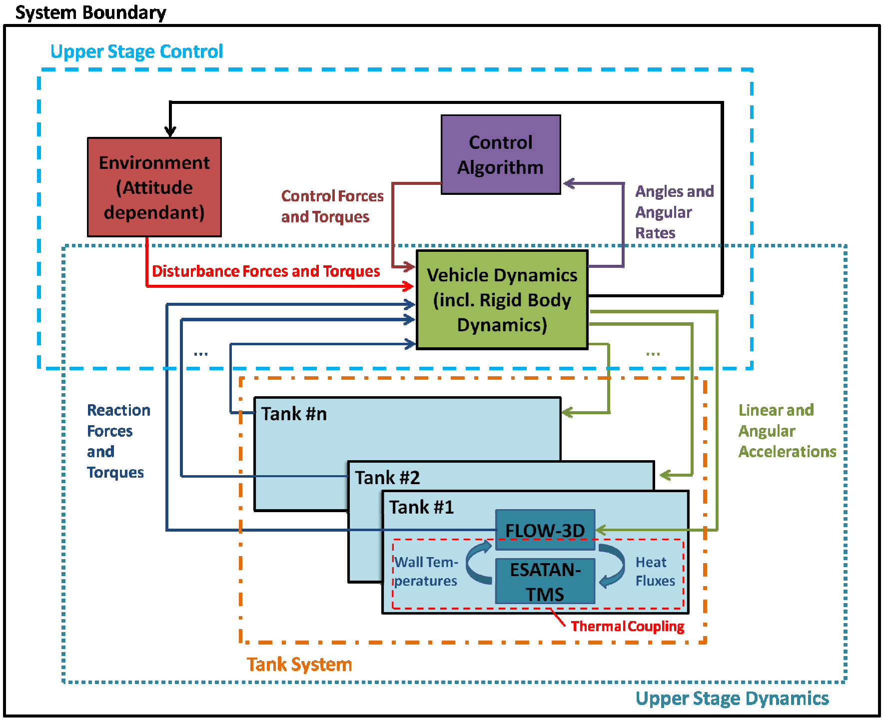

Figure 7: Basic functional principle of FiPS® with the integrated thermal coupling

4. Thermal modeling for the application with FiPS®

A straight and plain way to generate compatible models is to use one of the tools in order to create the input data for the model of the other tool. The easiest way to do this is by means of an one-to-one approach. In the case of FiPS®, a tank is modeled first in FLOW-3D®. This step is in any case necessary, as the dynamic coupling part of FiPS® needs a CFD tank model for simulation. But then, in a consecutive step, the thermal (ESATAN-TMS) model is created by means of this CFD model in a way, that one FLOW-3D® cell is one ESTAN-TMS® node. How this is done is illustrated in Figure 8.

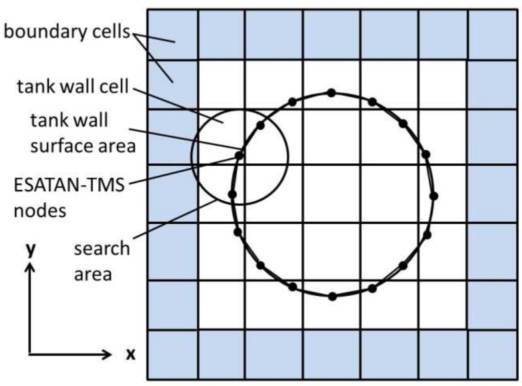

Figure 8: EMG method “find neighbors by distance”

Figure 8 shows the currently used method of finding neighbouring nodes by distance. The search distance depends on the mesh cell size times a magnifying factor, whereas magnifying factors between 1.4 and 2.0 are reasonable. By this range it is ensured to cover big distances between two nodes which are adjacent by definition. But at the same time no nodes are grouped together, which are in their distance beyond closer neighbour nodes.

During the node generation process, not only the nodes' locations are determined, also the node characteristics are assigned. To these belong:

- surface area of the tank wall element,
- thickness,
- volume,
- heat capacity
- and mass

of each tank wall element represented by a node. Further, for each node pair the characteristics of the conductor is determined, which are in main distance and cross sectional area between the nodes.

Figure 9 shows the result of a thermal model generated by means of the CFD tool FLOW-3D® for an Ariane 5 ESC-A LOX tank. This process is called "ESATAN-TMS model generation" (EMG).

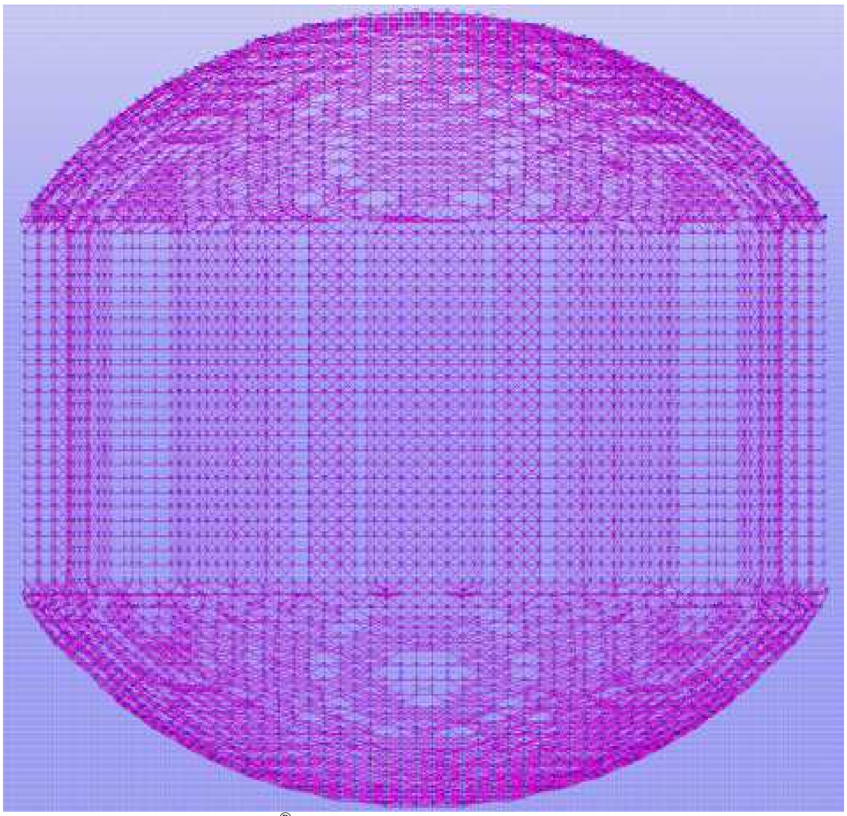

Figure 9: Visualization of an ESATAN-TMS® node model of a Ariane 5 ESC-A LOX tank produced by FLOW-3D®

In theory, by EMG any geometry can be translated from FLOW-3D® to ESATAN-TMS®. Supposable is for example the use of the EMG method to create ESATAN-TMS® models for the application in the frame of thermal analysis with ESATAN-TMS® only in an automated manner. So far, the EMG is used for simulations with FiPS® only.

5. Visualization of thermal results

The function of visualizing FiPS® simulation results was implemented first in the year 2006. Figure 10 shows a screenshot of the animation for an A5ME upper stage. This example shows the upper stage implied by outlining its contours and thus giving insight into the stages' tanks. Each propellant is displayed monochromatic. In the given case the LH2 propellant is colored red and the LOX propellant blue. The distribution of the propellants within the tank depends on the effects of the flown maneuvers. In the shown case a spin maneuver has been flown, so that the propellant cumulates in form of a ring at the outer tank walls.

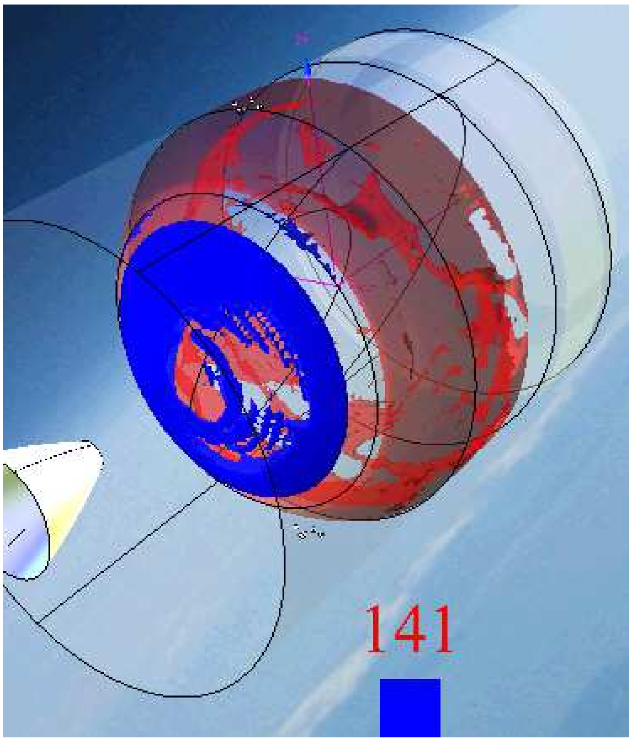

Figure 10: Animation screenshot showing uni-colored propellants within the tanks of an A5ME upper stage

Due to the new feature of the thermal coupling, the need arouse to display additionally the thermal results of a FiPS® simulation run. As the thermal coupling represents the interaction of heat exchange between liquid propulsion and tank wall, it is required to show both propellant and tank wall temperatures.

The animation method used for FiPS® is based upon the virtual reality modeling language (VRML). The CFD tool FLOW-3D® produces for each history time step a file in the surface tessellation language (STL) format of a desired object, i.e. the propellant or the tank wall surface. The facets of these surfaces can then be colored with respect to their temperature.

For the visualization of the thermal results two different view types have been developed. The first approach is shown in Figure 11. The picture shows an Ariane 5 ESC-A upper stage without payloads. In this illustration the LH2 propellant is colored, while the LOX propellant is held in grey. As both propellants have completely different temperature ranges (LOX around 90K and LH2 around 20K), it is not reasonable to show both propellants colored according to their temperature in one picture at the same time.

The second approach comprises the illustration of the tank wall temperature. In order to illustrate the temperature development in the best way, the tank was cut in two and swung open, as exemplarily shown in Figure 12 for the LOX tank of the Ariane 5 ESC-A upper stage. Again, the propellant is held in grey and partially transparent in order to focus on the tank wall. It was decided to show the propellant in this form, as it is essential for understanding the change of the tank wall temperature as a consequence of propellant motion.

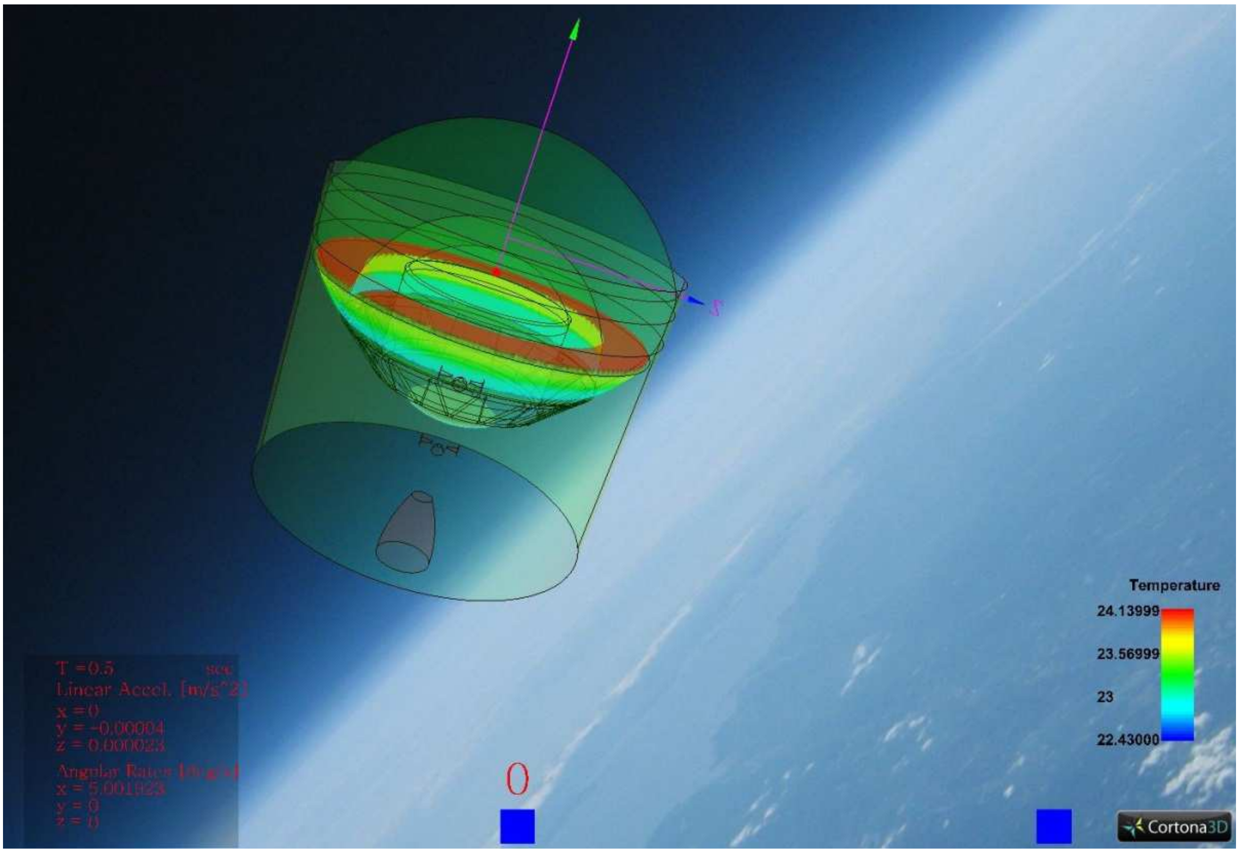

Figure 11: Temperature stratification of the propellant in an Ariane 5 ESC-A upper stage LH2 tank

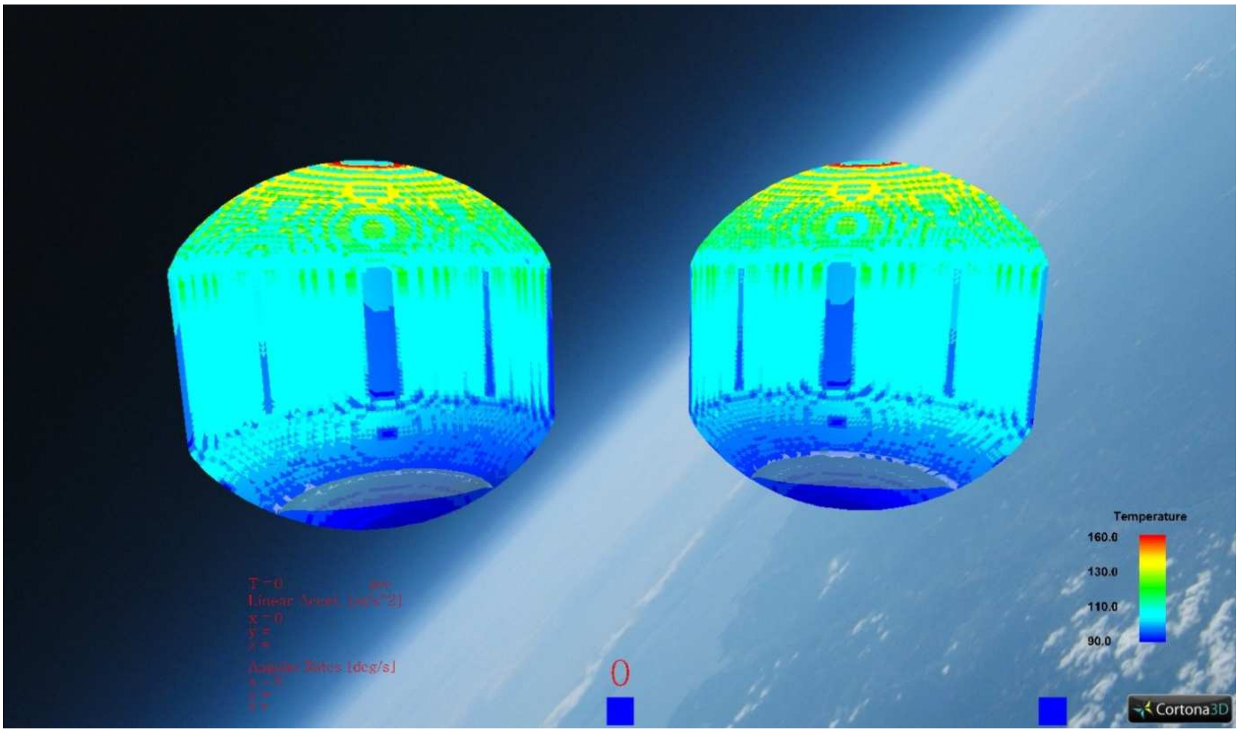

Figure 12: Temperature distribution at the tank wall surface in an Ariane 5 ESC-A upper stage LOX tank

6. Conclusion

The recently in FiPS® implemented thermal coupling enables the analysis of the pressure development inside the propellant tanks as a consequence of vehicle and hence propellant motion. This is crucial for the extension of the simulated system in particular by the propellant lines and thrusters. So far, the modeled thermal system is limited to the vehicle's propellant tanks. As a next step, it is aspired to expand it to a simplified model of the whole vehicle. By this, effects like solar exposure, thruster activities and on-board electronics, that conduct heat from the vehicle structure into the tanks, are supposed to be covered in FiPS® simulations as well. FiPS® plays an important role in the reduction of development costs and is hence amongst others involved in the Ariane 6 program.

Abbreviations

A5ME	Ariane 5 Midlife Evolution
CFD	Computationl fluid dynamics
EMG	ESATAN-TMS model generation
ESC-A	Étage Supérieur Cryotechnique Type A
FiPS®	Final Phase Simulator
LH2	Liquid hydrogen
LOX	Liquid oxygen
STL	Surface tesselation language
VRML	Virtual reality modeling language

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