Simulation of Ariane 5 SCA System with euces Tool

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ABSTRACT

The euces project was initiated to be prepared for the future role of EADS as stage system prime for stage and launcher developments. Launcher stages for NGLV need to meet ambitious mission and operational demands. The paper will present a brief overview of the currently existing COMPONENT libraries and its possibilities as well as an application example which will be a simplified functional model of the ARIANE 5 ES SCA-VUS system w.r.t. physical model formulation of its incorporated components, its schematic, data initialisation and simulation results obtained. The simulation results will be compared to flight data of a dedicated flight.

INTRODUCTION

euces S/W development is an EADS Astrium *internal initiative* specifically dedicated to the development of launcher system and stage analysis software for the simulation of functional behaviour of launcher stages during its ground and flight phases. It incorporates the time-dependent simulation of the complete propulsion system including all its interacting components. In more detail, it comprises the evaluation of pressurant and propellant consumption, mass flows in the piping system, pressure regulation, feed-line chill-down in case of cryogenic propellants, engine characteristic parameters, ignitions and shut-down of engine and the sequence evaluation for the main propulsion or attitude control system. The categories involved are heat and mass transfer, thermodynamics, hydraulics, pneumatics, phase change of propellants, combustion, control and thermal aspects, as well as specific component design for tanks, valves, regulators, turbo machinery and rocket engines as a central role.

For the relevant hardware component formulation the existing hardware design of ARIANE 5 ES upper stages was taken into consideration, i.e. all hardware components have to be mathematically modelled adequately having an impact on the system simulation results.

euces will be based on EcosimPro kernel which was initially an ESA funded S/W tool developed by EAI for dynamic modelling and simulation for networks incorporating fluid flow (gaseous and liquid, heat and mass transfer, chemical reactions, controls, etc.) providing a user-friendly simulation environment for modelling simple and complex physical processes. It provides an object-oriented approach towards creating reusable component libraries and expresses the system behaviour in terms of differential-algebraic equations and discrete events. The COMPONENTs will be linked via PORTs together to a complete system. PORTs are needed to exchange interconnection information between COMPONENTs such as pressure, temperature or mass flow rate.

1. COMPONENT LIBRARY DEVELOPMENT

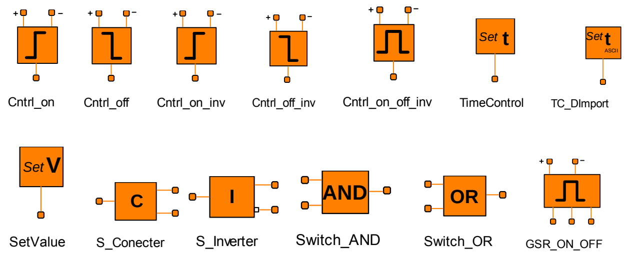
The objective of the euces project is the development of object-oriented S/W using EcosimPro kernel for functional physical model formulations and simulation of space propulsion H/W components and systems. The project tasks are linked to:

- tanks of known geometric configuration under 1g liquid level position
- pneumatic pipe system elements
- hydraulic pipe system elements
- engine system elements
- agglomeration in libraries
- generation of simulation models of dedicated sub-systems
- generation of simulation models of dedicated propulsion systems
- comparison to ground/flight measurements

The actual component LIBRARIES in "workspace" euces and their main content are briefly presented for the different libraries.

AUXILIARY:

- global constants, complementary CONTROL (EAI) components, port definitions, complementary mathematical functions



Mathematical functions have been implemented for solving quadratic and cubic equations, for linear curve and plane interpolation, for calculation of grid cover matrices for static and moving grids.

SOLID_PROPERTIES:

- Titanium, Carbon, AL2219, H920A, Dacron filled with He, Dacron filled with N_2, Cryosof, AL7020, stainless steel

The solid properties considered are density ρ, heat conductivity λ, specific heat capacity c partly in dependence of temperature T.

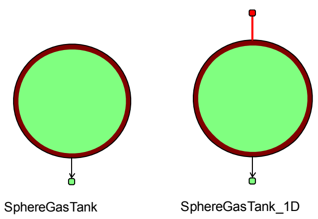
FLUID_PROPERTIES:

- Air, H_2, He, MMH, N_2H_4, N_2, N_2O_4, O_2, H_2O, R123, HFE7000

The fluid properties considered are for *ideal* gas and liquid phase density ρ, saturation pressure p_s, saturation temperature T_s, specific isobaric/isochoric heat capacity c_p/c_v, specific enthalpy h, specific internal energy u, isothermal compressibility κ, volume expansivity β, isochoric tension coefficient γ, heat conductivity λ, dynamic viscosity η, surface tension σ. In case of He also a real gas factor Z is considered as well as a pressure dependence for the specific enthalpy h.

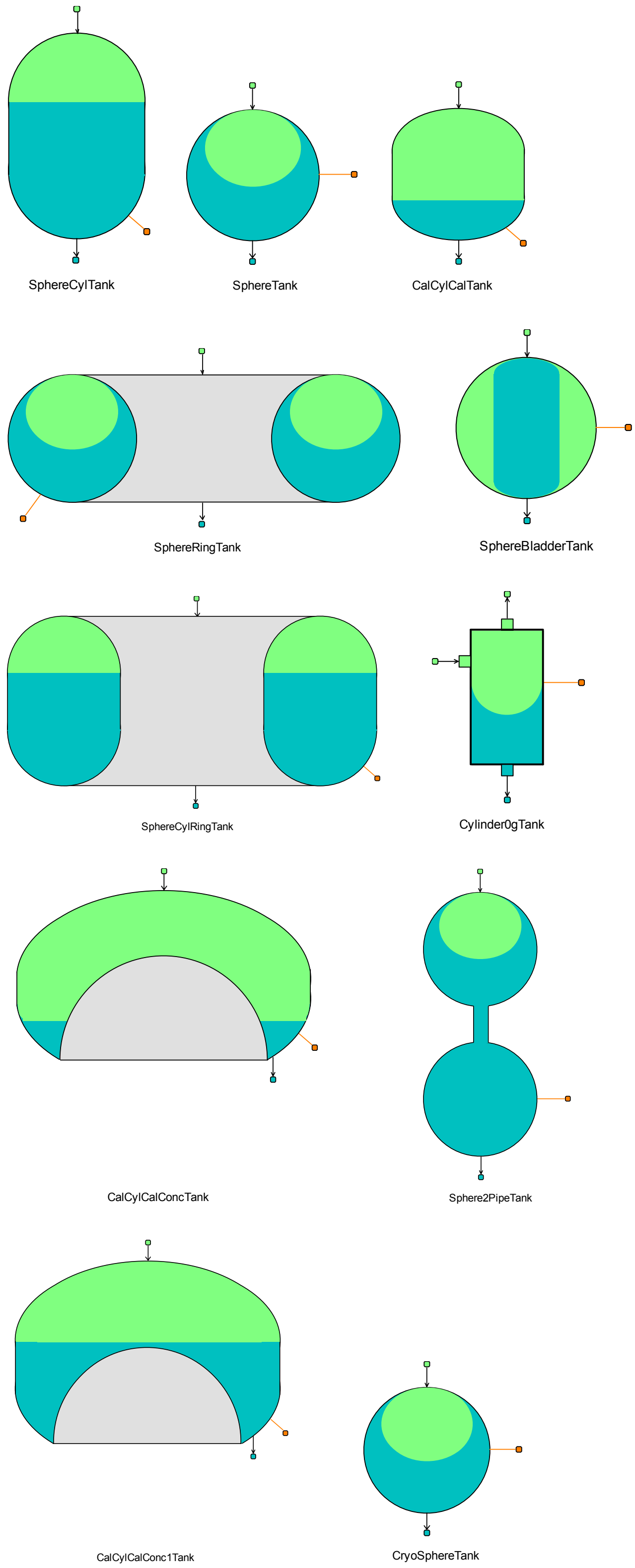
GAS_TANKS:

- gas part: 1 or 2 gasses, 0 or 1D discretized
- spherical tank wall: heat conduction 1D radially discretized
- internal heat transfer functions



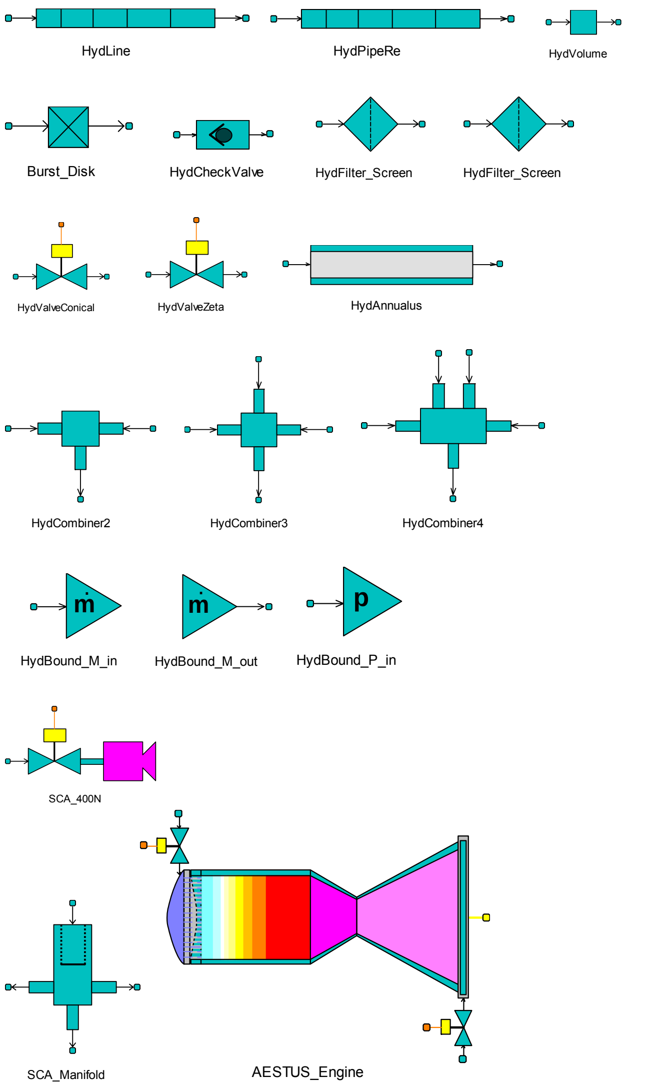
PROP_TANKS:

- ullage part: 2 gasses, 1 gas in PORT
- liquid part: pure liquid or 2-phase
- moving liquid level with surface calculation
- internal heat and mass transfer functions
- different tank shapes
- tank wall 0D heat conduction separated for gas/liquid part
- time-dependent external heat load or temperature separated for ullage and liquid part



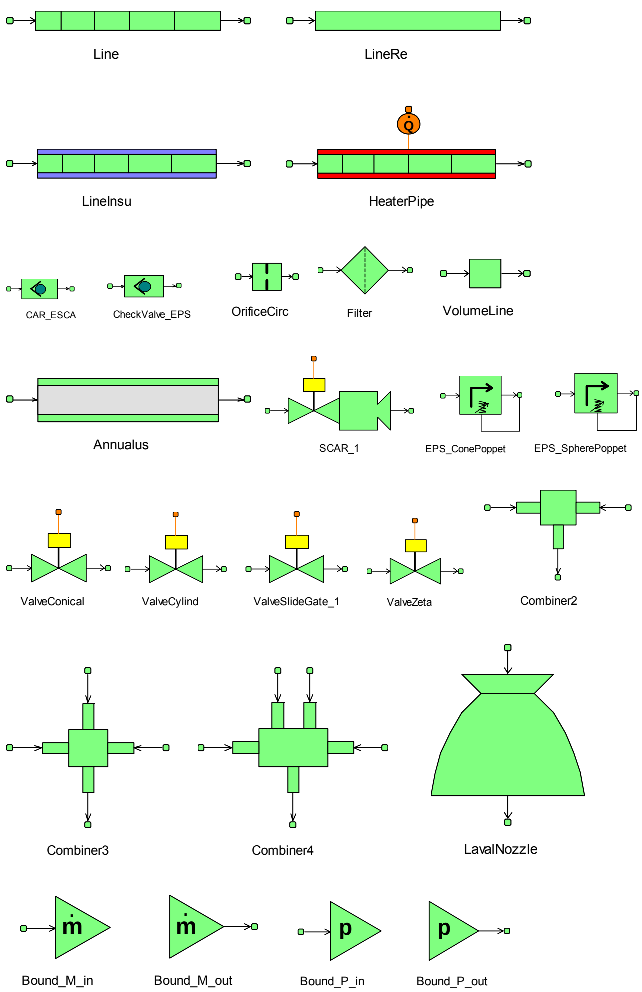
HYDRAULIK

- liquid components, only forward flow
- pipes (RC) and volumes (C) include fluid volume with thermodynamic properties and consideration of wall and flow calculation
- divider/combiner (RC) include fluid volume with thermodynamic properties and flow calculation
- valves, orifice, bust disc, filter (R) consider flow calculation
- hot gas thrusters (R) consider flow calculation, performance is modelled incl. test adjustments
- check valve consider force balance at poppet and flow calculation in dependence of poppet position



PNEUMATIK

- gas components, only forward flow
- pipes (RC) and volumes (C) include gas volume with thermodynamic properties and consideration of wall and loss calculation
- divider/combiner (RC) include gas volume with thermodynamic properties and flow calculation
- valves, orifice, filter (R) consider flow calculation
- check valves, regulators (R) consider force balance at poppet and flow calculation in dependence of poppet position
- cold gas thruster (R) consider flow calculation, performance is modelled via nozzle equation



2. APPLICATION ON ARIANE 5 SCA VUS

2.1 SCA-VUS MODEL - SCA-VUS reaction control system, shown in fig. 2-1, is based on a storable mono-propellant Hydrazine propulsion system, which is composed of 2 sets of 3 bladder tanks pre-pressurized by Nitrogen at initially 26 bar and is operated as blow-down system. It is located inside the VEB around its internal circumference. The propellant flows through a PVs block and is then divided into 2 thruster clusters, each equipped with 4 thrusters symmetrically arranged. These are fast catalytic N_2H_4 decomposition thrusters including a fast switching valve for short thrust pulse bits. The operational chamber pressure can vary between 13 bar and 4 bar at a maximum thrust of ~400 N. The SCA propulsive model is a simplified representation of the used and installed system H/W.

It has been reduced to the main functional components to characterize and adjust the behaviour and the performance of the reaction control system for the ATV flight mission. The system is composed of the following *main* components:

- 6 titanium propellant/pressurant bladder tanks
- 3 pyro-valves (PVs)
- 8 thrusters incl. valves
- N_2H_4 and N_2 fill and drain valves and associated pressure transducers
- tubing

The SCA-VUS tubing system is arranged as follows:

- tanks arranged in 2 clusters of 3
- distribution lines: from tanks to management lines also called isolation node
- supply lines: from management lines to thrusters
- thrusters distributed in 2 brackets of 4 thrusters symmetrically disposed
- dissymmetrical configuration of SCA-VUS

The isolation node between the distribution and the supply lines is made up of 3 PV: one branch with 2 PV in series, used for the main flow and aside, a bypass including a PV and flow restrictors to avoid water hammer on opening of the PV.
Fig. 2-1 displays the schematic of the SCA-VUS propulsion system to simulate the behaviour of the missions. The tanks are modelled as spherical bladder tank with a standpipe.

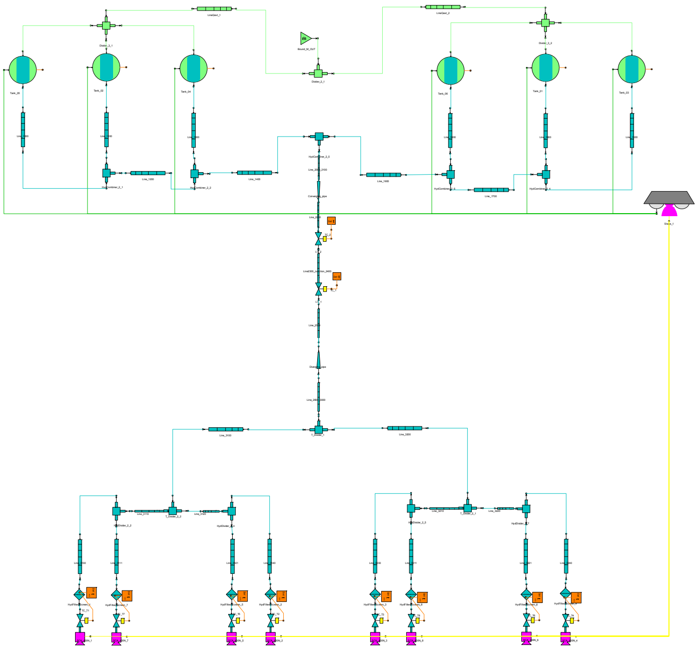


Fig. 2-1: euces schematic of SCA-VUS model

The bladder inside the tank in nominal configuration is assumed to be filled with 35.86 kg of hydrazine N_2H_4 in nominal flight configuration. In terms of spatial geometry, the fact that the SCA-VUS system is circular has not been taken into account. It was therefore expected that the pressure loss may be underestimated compared to reality.
As far as the feed system is concerned, usual formula on loss coefficients from text books were used for cylindrical straight pipes, elbows, expansion, contraction, junctions and valves; the involved loss coefficients ξ to be implemented into each COMPONENT.

For each mission simulation, the relevant thruster activation profiles are implemented into the component TimeControl_Import allowing an ASCII file to refer to. The operational phase for reaction control by SCA starts after separation of the 2 EAP. The exemplary flight taken into account for the comparison of SCA model simulation results to flight transducer measurements is ATV JV. It is used as a 1st example for the euces COMPONENT model capability in EcosimPro kernel for such an application.

2.2 COMPONENTS - The physical formulation of the EPS components used in schematic will be briefly described hereafter for selected COMPONENTs.

<u>Propellant Tank</u> - The physical formulation of the *ullage gas* is based on the mass and energy conservation for a gas.

The rate of change of gas mass m' inside the tank is given by:

$$m' = \dot{m}_o \tag{2.1}$$

The rate of change of gas density ρ' is given by:

$$m' = \rho V' + \rho' V \tag{2.2}$$

The rate of change of gas pressure p' can be obtained from the derivative of the state equation:

$$\rho' = \frac{\partial \rho}{\partial T} T' + \frac{\partial \rho}{\partial p} p' \tag{2.3}$$

The rate of change of gas specific enthalpy h' inside the tank is given by:

$$m\,h' + m'h - p'V = \dot{H}_o - \dot{Q}_{ph} + \dot{Q}_{w,u} \tag{2.4}$$

$$\dot{Q}_{w,u} = \alpha_{w,u}\, S_{w,u}\, (T_{w,u} - T) \tag{2.5}$$

where $\dot{Q}_{w,u}$ is the heat flux between tank wall and gas and $\dot{Q}_{ph}$ is the heat flux between liquid phase interface and ullage. The rate of change of gas temperature T' is given by:

$$h' = \frac{\partial h}{\partial T} T' + \frac{\partial h}{\partial p} p' \tag{2.6}$$

with:

$$\frac{\partial h}{\partial T} = c_p = 3.5\, R_{N_2} \quad 2.7$$

and

$$\frac{\partial h}{\partial p} = 0 \quad 2.8$$

The heat transfer coefficient $\alpha_{w,u}$ is dependent on the flow conditions within ullage, i.e. natural convection. For free convection, the following Nusselt number is used for Ra number > 10^3:

$$Nu_{free} = 0.098 \cdot (Gr \cdot \Pr)^{0.345} \quad 2.9$$

As characteristic length l for the ullage or liquid part of a propellant tank, the respective volume V is used by:

$$l = \left(\frac{6V}{\pi}\right)^{\frac{1}{3}} \quad 2.10$$

The physical formulation of the *liquid pool* is based on the mass and energy conservation.

The rate of change of *liquid* mass m' inside the propellant tank is given by:

$$m_l' = -\dot{m}_{pro} \quad 2.11$$

The rate of change of liquid density ρ_l' can be obtained from:

$$m_l' = \rho_l V_l' + \rho_l' V_l \quad 2.12$$

The rate of change of pressure p' is obtained from the derivative of the ullage pressure:

$$\rho_l' = \frac{\partial \rho_l}{\partial T_l} T_l' \quad 2.13$$

The rate of change of liquid specific enthalpy h_l' inside the tank is given by:

$$m_l h_l' + m_l' h_l - p' V_l = -\dot{H}_{pro} + \dot{Q}_{ph} + \dot{Q}_{w,l} \quad 2.14$$

$$\dot{Q}_{w,l} = \alpha_{w,l}\, S_{w,l}\,(T_{w,l} - T_l) \quad 2.15$$

where $\dot{Q}_{w,l}$ is the heat flux between tank wall and liquid. The heat transfer coefficient $\alpha_{w,l}$ is dependent on the flow conditions within the liquid, whereby only natural convection is considered acc. to equ. 2.34. The rate of change of liquid temperature T_l' is given by:

$$h_l' = c_{p,l}\, T_l' \quad 2.16$$

with:

$$c_{p,N_2H_4} = 3075.1 \left[\frac{J}{kg\,K}\right] \quad 2.17$$

The conservation of energy is set for both tank compartments - ullage (u) / liquid (l) - separately. On each tank wall part a time-dependent heat load $\dot{Q}_s$ can be applied.

$$\rho_s\, c_s\, T_s'\, V_s = \dot{Q}_s - \dot{Q}_w \quad 2.18$$

The determination of the *filling level* is dependent on the propellant filling rate and the tank geometric shape. In this case the tank is composed of a calotte ring shape with a central cylinder being topped by calottes.

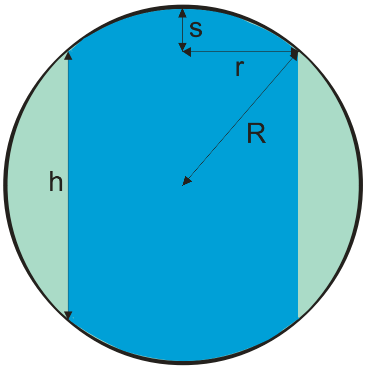


Fig. 2-2: geometry of spherical bladder tank

The pressure dependent stretching rate of the propellant tank is considered via the variation of the radius R_p of the tank. The modified volume V_p is defined as:

$$V_p = V_t\left(1 + \chi\,(p - p_a)\right) \quad 2.19$$

The volume of the sphere can be obtained by:

$$V_{sp} = \frac{4\pi}{3} R^3 \quad 2.20$$

and the volume of the cylinder can be obtained by:

$$V_{cyl} = \pi\, r^2\, h \quad 2.21$$

The relation between the cylinder radius and height with the sphere radius can be obtained by using *Pythagoras´ theorem*:

$$h = 2\sqrt{R^2 - r^2} \quad 2.22$$

From which the cylinder volume follows in terms of R and r:

$$V_{cyl} = 2\pi\, r^2 \sqrt{R^2 - r^2} \quad 2.23$$

The 2 spherical calottes can be obtained by:

$$V_{cal} = \frac{\pi s}{6}\left(3r^2 + s^2\right) \quad 2.24$$

The height of the calotte is:

$$s = R - \frac{h}{2} = R - \sqrt{R^2 - r^2} \quad 2.25$$

The bladder volume can be expressed as $V_b = V_{cyl} + 2 \cdot V_{cal}$:

$$V_b = \frac{4}{3}\pi\left(R^3 - \left(R^2 - r^2\right)\cdot\sqrt{R^2 - r^2}\right) \quad 2.26$$

For a given bladder volume, it follows for the cylinder radius r:

$$r = \sqrt{R^2 - \left(R^3 - \frac{3}{4\pi}\cdot V_b\right)^{\frac{2}{3}}} \quad 2.27$$

The gas volume is:

$$V_g = V_{sp} - V_b = \frac{4}{3}\pi\left(R^2 - r^2\right)\cdot\sqrt{R^2 - r^2} \quad 2.28$$

The gas-bladder surface is:

$$S_{gb} = 4\pi r \cdot \sqrt{R^2 - r^2} \quad 2.29$$

The bladder-wall surface is:

$$S_{gw} = 4\pi R \cdot \left(R - \sqrt{R^2 - r^2}\right) \quad 2.30$$

The gas-wall surface is:

$$S_{gw} = 4\pi R \cdot \left(R - \sqrt{R^2 - r^2}\right) \quad 2.31$$

The wall-ambient surface is:

$$S_{wa} = 4\pi R^2 \quad 2.32$$

Liquid Line, Divider, Combiner - The physical formulation for *liquid* part of these COMPONENTs is identical to the one presented for the Liquid Tank, besides the different PORT numbers which have to be considered in the mass and energy balance, respectively. The conservation of momentum accounts additionally for the hydrostatic height. For the Line, a heat transfer correlation by Nu number is used, accounting for laminar and turbulent flow conditions inside the tube:

for Re < 2300:

$$Nu = \sqrt[3]{3.66^3 + 1.61^3 \operatorname{Re}\Pr\frac{d}{l}} \quad 2.33$$

for Re > 2300:

$$Nu = 0.0214 \operatorname{Re}^{0.8}\Pr^{0.4}\left(1 + \left(\frac{d}{l}\right)^{\frac{2}{3}}\right)\left(\frac{\Pr}{\Pr_w}\right)^{0.11} \quad 2.34$$

The conservation of momentum is expressed in steady state formulation for the in- and outflow rate as follows:

$$p_i - p = \frac{\varsigma}{2}\frac{\dot{m}_i^2}{2\rho A^2} \quad 2.35a$$

$$p - p_o = \frac{\varsigma}{2}\frac{\dot{m}_o^2}{2\rho A^2} \quad 2.36b$$

The coupling to a wall is not considered for the Divider and Combiner. The physical formulation of the Line is already published in detail, see [1].

SCA Thruster - The physical formulation of the *thruster* COMPONENT is basically derived from thruster measurements to express relevant correlations for the start-up/shutdown and steady state conditions. The main indication for thruster performance is the thrust profile for variable ON/OFF pulse lengths.

For Pulse Operation:
max. chamber temperature,

$$T_{c,\max} = g_1\, p_{valv}^{g_2} \quad 2.36$$

max. chamber pressure,

$$p_{c,\max} = b_1\, p_{valv}^{b_2} + b_3 \quad 2.37$$

thrust coefficient,

$$C_{FCD} = a_1 + a_2\, p_{c,\max}^{a_3} \quad 2.38$$

sonic outflow factor,

$$\gamma = \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}}\sqrt{\frac{2\kappa}{\kappa+1}} \quad 2.39$$

theoretical thrust coefficient,

$$C_{FCD,th} = \eta\cdot\sqrt{\frac{2\kappa}{\kappa-1}}\cdot\gamma \quad 2.40$$

ON pulse temperature ratio,

$$T_R = \frac{T_{c,of} - 273.15}{T_{c,\max} - 273.15} \quad 2.41$$

pressure time constant,

$$\tau_{RP} = e_1 + T_R^{e_2} \quad 2.42$$

temperature time factor,

$$\tau_T = c_1 + c_2 \; p_{valv}^{c_3} \qquad 2.43$$

flow conductance,

$$K = h_1 + \left(p_{valv} - p_c\right)^{h_2} \qquad 2.44$$

OFF pulse pressure time constant,

$$\tau_{DP} = f_1 + p_{c,of}^{f_2} \qquad 2.45$$

thrust,

$$F = A_{th} \; C_{FCD} \; p_c \qquad 2.46$$

mass flow rate,

$$\dot{m} = x \; K \; \sqrt{p_{valv} - p_c} \qquad 2.47$$

with x varying between $0 \le x \le 1$ as valve position.

specific impulse,

$$I_{sp} = \frac{F}{g_o \dot{m}} \qquad 2.48$$

For the simulation of the chamber pressure p_c and chamber temperature T_c the transient formulation was chosen in dependence of valve position and its derivative:

a) $\dot{x} > 0$ or $x > 0.99$

$$\dot{p}_c = \frac{1}{\tau_{RP}} \left(p_{c,\max} - p_c\right) \qquad 2.49$$

$$\dot{T}_c = \frac{1}{\tau_T} \left(T_{c,\max} - T_c\right) \qquad 2.50$$

b) $\dot{x} < 0$ or $x < 0.01$

$$\dot{p}_c = -\frac{1}{\tau_{DP}} \, p_c \ln\left(f_3\right) \qquad 2.51$$

$$\dot{T}_c = \frac{1}{\tau_{dt}} \left(T_{c,hold} - T_c\right) \qquad 2.52$$

c) others

$$\dot{p}_c = 0 \qquad 2.53$$

$$\dot{T}_c = 0 \qquad 2.54$$

The valve switching is performed from close to open or vice versa also in transient formulation:

$$\dot{x} = \frac{1}{\tau_{valv}} \left(\left(0/1\right) x_o - x\right) \qquad 2.55$$

2.3 RESULTS AND COMPARISON FOR SCA MODEL

- The flight phase simulations that have been performed are based on the actual thruster activation mission profile that was executed during flight V181.

During previous analysis phases, a SCA-VUS flight functional performance prediction has been performed with the minimum, average, and maximum mission profiles.

The following main steps have been performed in the frame of this earlier analysis:

- evaluation of the CAP Model for SCA (A5 GS)
- post-performing of a former Level 1 computation from TLS with CAP model
- establishment and validation of SCA (A5 GS) Ecosim Model
- upgrade of model to SCA-VUS (A5 ES) configuration
- validation of the model by redoing predictions of SCA-VUS performance according to the DF & CAP model
- further cross-checking by other tools, simulations and tests

The euces model for SCA-VUS has now been used to simulate the functional behaviour of the SCA system and to calculate the corresponding mass consumption, pressure evolution, and thrust levels during flight V181.

The following input data was used to perform the SCA V181 simulation with euces model:

- actual thruster activation mission profile
- actual stage acceleration measurement data
- actual loaded hydrazine mass
- actual pressure level in tanks observed at lift-off

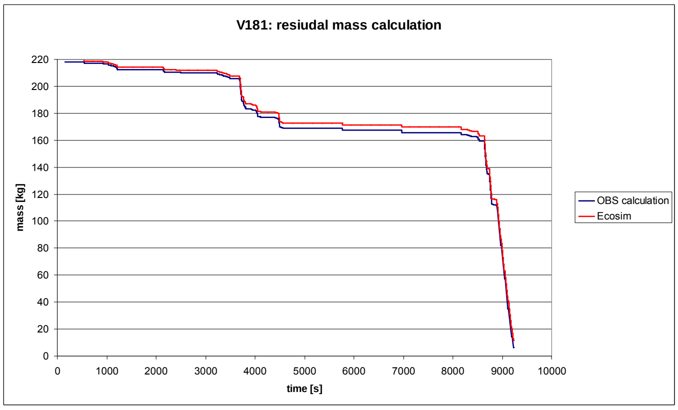


Fig. 2-3: euces residual propellant mass compared to OBS results

Fig. 2-3 shows the residual propellant mass as calculated by the euces model in comparison to the OBS calculation. The maximum offset between the two models is about 4 kg after ATV separation and before the second EPS re-ignition. This corresponds to a relative deviation of 2.4%.

Tab. 2-1 shows the delta evolution of the mass consumption throughout the mission between the euces model and the OBS model which gives a slightly higher propellant consumption than the euces model simulation and is therefore conservative in this regard. Also note that regarding propellant consumption, the simulation is conservative compared to the formerly used CAP/DF model.

time, s	Δm, kg	relative discrepancy, %
0	0.00	0.00
1000	0.36	0.16
2000	0.05	0.02
3000	0.14	0.07
4000	2.12	1.14
5000	2.28	1.32
6000	3.88	2.27
7000	2.30	1.36
8000	2.30	1.36
9000	2.79	3.56

Tab.2-1: delta mass consumption evolution

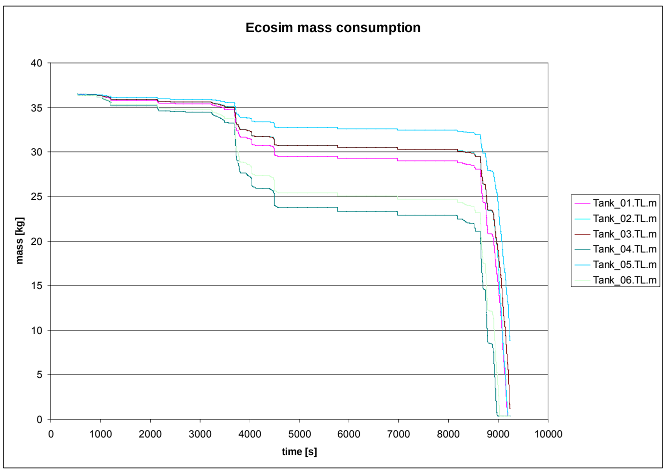


Fig. 2-4: euces propellant mass consumption per tank

Figure 2-4 shows the mass consumption calculated by euces model for each individual tank.

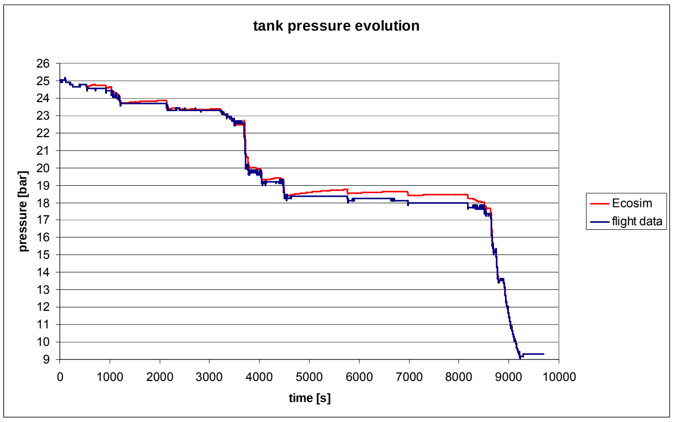


Fig. 2-5: euces tank pressure evolution compared to flight measurement

Figure 2-5 shows the averaged tank pressure evolution as calculated by euces in comparison to the actual flight measurement data.
The euces model over-predicts slightly the remaining tank pressure during the ballistic phases. The resulting pressure decreases during SCA activations are predicted precisely, anyhow. The maximum offset between the simulated pressure data and the flight measurement data is 0.5 bars, corresponding to a relative deviation of 2.5% during the long ballistic phases between ATV separation and the second EPS re-ignition.

It means that during the long ballistic phase, the heat entering the tank (leading to a pressure increase) is overestimated. This behaviour could be improved by taking the VEB correlation results for V181 and apply them as environment on the SCA tank surface instead of using a fixed temperature on all tanks (taken from one measurement).

time, s	Δp, bar	relative discrepancy, %
0	0.00	0.00
1000	0.20	0.82
2000	0.10	0.42
3000	0.10	0.43
4000	0.23	1.16
5000	0.24	1.31
6000	0.33	1.81
7000	0.43	2.39
8000	0.48	2.67
9000	0.02	0.17

Tab. 2-2: delta pressure evolution

CONCLUSION

The ARIANE 5 SCA propulsion model shows as a propulsion system example again the power and possibilities of the EcosimPro object-oriented S/W approach and the physical modeling approach of euces libraries. A well adjusted set of model parameters for the SCA could also be achieved w.r.t. the flight measurement data delivered. The euces model simulates accurately both the propellant mass consumption as well as the tank pressure evolution with mission time.

In comparison, the OBS and the euces model simulation give similar results regarding mass consumption. Comparison of pressure evolution provides good agreement with the sensor measurements except slight deviations for long coasting phases, where the euces model over-predicts the pressure evolution. Corrections may be linked to better thermal loads during this phase. The relative discrepancy between pressure flight sensor data and the model simulation remains under 3% throughout the mission.

Compared to the V162 (L516) Level 1 analysis done with the former SCA-CAP software, the euces model shows comparable error margins. For instance, the maximum difference in mass consumption between the SCA-CAP model and the OBS calculation for flight V162 was 1.73% (2 kg, initial mass 115.5 kg). In comparison, the maximum difference in mass consumption between the euces model and the OBS calculation for flight V181 is 1.77% (3.88 kg, initial mass 219.2kg).

Regarding pressure, the maximum difference between the SCA-CAP model and the pressure sensor data on flight V162 was 0.16 bar. In comparison, the maximum difference between the euces model and the pressure sensor data on flight V181 is 0.23 bar before the long ballistic phase and 0.48 bar during the long ballistic phase

ACKNOWLEDGEMENT

The euces Project Part II was funded by BMBF (federal ministry of education and science) with account no. 50RL0620 and is performed at EADS Astrium GmbH, Bremen.

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NOMENCLATURE

Latin letters

A	cross section	m²
c_D	discharge coefficient	
c_p	specific heat capacity at const. pressure	J/kg/K
C	thrust coefficient	
d	diameter	m
F	thrust	N
g	gravity acceleration	m/s²
Gr	Grasshoff number	
h	height	m
h	specific enthalpy	J/kg
H	height	m
I_{sp}	specific impulse	s
l	characteristic length	m
K	flow conductance	$kg/s/bar^{0.5}$
L	length	m
m	mass	kg
$\dot{m}$	mass flow rate	kg/s
$\tilde{M}$	molar mass	$kmol/m^3$
Nu	Nusselt number	
p	pressure	Pa
Pr	Prandtl number	
r	radius	m

$\dot{Q}$	heat flux	W
R	radius	m
R	specific gas constant	J/kg/K
Ra	Rayleigh number	
Re	Reynolds number	
s	calotte height	m
S	surface	m^2
t	time	s
T	absolute temperature	K
V	volume	m^3
w	flow velocity	m/s
Z	compressibility factor	
$' = \partial / \partial t$	time derivative of property	1/s

Greek letters

α	heat transfer coefficient	$W/m^2/K$
β	isothermal compressibility	1/K
η	dynamic viscosity	Pa s
κ	adiabatic exponent	
λ	heat conductivity	W/m/K
ς	loss coefficient	
ρ	density	kg/m^3
ξ	mass fraction	
π	ratio of circumference to diameter of circle	

Indices

a	external
b	bladder
c	combustion chamber
cal	calotte
cyl	cylinder
DP	pressure decay
e	east
$free$	natural convection
fu	fuel
FCD	thrust · discharge coefficient
g	gas
hsp	half sphere
i	inlet
l	liquid
max	maximum
o	outlet
of	at OFF command
p	pressure corrected
ph	phase I/F
pro	propellant
P	pressure
R	ratio
s	solid
sp	sphere
t	tank
th	theoretical
tot	total
T	temperature
u	ullage
w	wall

DEFINITIONS, ACRONYMS, ABBREVIATIONS

A5	**A**riane **5** Launcher
BMBF	**B**undes**m**inistierium für **B**ildung und **F**orschung
C	**C**apacitance
CAP	**C**omputer **A**ided **P**ropulsion
EAI	**E**mpresarios **A**grupados **I**nternational, Madrid
EADS	**E**uropean **A**eronautic and **D**efense **S**ystems
EL	**E**cosimPro **L**anguage
ESA	**E**uropean **S**pace **A**gency
euces	european cryogenic engineering software
H/W	**H**ard**w**are
I/F	**I**nter**f**ace
L528	Ariane 5 **L**auncher **528**
NGLN	**N**ew **G**eneration **L**aunch **V**ehicles
OBC	**O**n **B**oard **C**omputer
OBS	**O**n **B**oard **S**oftware
P/L	**P**ay**l**oad
PV	**P**yro **V**alve
R	**R**esistance
RC	**R**esistance **C**apacitance
SCA	**S**ystème de **C**ontrôle d'**A**ttitude
SSO	**S**un **S**ynchronous **O**rbit
S/W	**S**oft**w**are
VEB	**V**ehicle **E**quipment **B**ay

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