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**An ESA State-of-the-Art Simulation Tool for Space Applications**

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**ABSTRACT**

During the last 16 years Empresarios Agrupados Internacional has been involved in the ESA multidisciplinary simulation tool project for space applications. From the very beginning the goal has been to produce state-of-the-art software for modelling complex and heterogeneous systems. The areas of application have been many: propulsion, electrical systems, fluids, environmental control, biological systems, etc. In 2000, EcosimPro became a commercial product, demonstrating that this effort is valid for application in fields other than space.

In 2006, a new, enhanced version 4.0 was launched with numerous improvements, such as better tools for the creation of mathematical models, connection to common tools such as Excel<sup>®</sup> and Matlab<sup>®</sup>, customer deck generation for end users, etc. A new generation of libraries and applications has also been produced for modelling multidisciplinary systems (fluids, hydraulics, thermal, electrical, control, etc). In yet another advance, connection to ESA standard SMP2 is foreseen in the coming months.

In recent years numerous applications have been developed in the field of space engineering, including a sample in the fields of Active Thermal Control Systems (ATCS) and the Environmental Control and Life Support Systems (ECLSS).

**ECOSIMPRO: A SIMULATION TOOL FOR SPACE APPLICATIONS**

**Introduction**

EcosimPro is a project developed by EA Internacional (Madrid) under contract with ESA. The project commenced in the early '90s with the aim of creating simulation software to model Environmental Control and Life Support Systems (ECLSS) for the European modules (COLUMBUS) of the International Space Station (ISS) and for Hermes. The original objective was not to construct a generic simulation tool, but a specific tool for the ECLSS. With time, it became evident that the software we had developed could be used to model any physical system (mainly in 0-D) which could be represented by algebraic and differential equations. For that reason, it was decided to create a generic tool.

Versions 1.0 (1992) and 2.0 (1996) were specific to ECLSS. In 1996, the decision was made to construct a new, completely generic version based on accumulated experience, which led to the launch in 2000 of version 3.0. Version 4.0 has now been issued with a completely new graphical interface.

To guarantee continuity of the tool, EA Internacional and ESA have signed an agreement under which ESA is the trustee of the source code for each new version, and in the event that EA fails to continue developing the simulation software, ESA now has the authority to do so. Furthermore, EcosimPro is a free tool for use by any member of ESA staff.

## EcosimPro Capabilities

The main capabilities of EcosimPro are:

- A simple object-oriented modelling language to represent simulation components. It allows functions to be called from external libraries in FORTRAN, C and C++
- A set of algorithms for symbolically handling equations responsible for classifying, arranging and minimizing the number of variables to be calculated. It also has wizards to close the mathematical models when there are more variables than equations, algebraic loops, etc
- Powerful algorithms to resolve algebraic-differential equation systems, enabling the modeller to forget about one of the more complex tasks in the area of simulation
- Non-causal modelling; the modeller introduces equations in any format and afterwards EcosimPro symbolically transforms them
- EcosimPro can be used to represent any problem which can be represented by Ordinary Differential Equations (ODE) and Differential Algebraic Equations (DAE), such as fluids, propulsion, control, heat transmission, electrical circuits, etc
- A user-friendly development environment with multiple windows for editing code, graphically viewing a model, running a model with variable plotters, etc
- The capability of postprocessing results
- Automatic generation of a C++ class with the final model ready for use by any user
- Automatic generation of a dynamic library which enables simulations to be executed from EXCEL©
- A deck generating tool for producing a final application external to EcosimPro, ready for use by users who are not specialised

## User Levels

A first-time user of EcosimPro must be aware that there are different user levels. These range from Level 1, which requires extensive knowledge both of the discipline to be modelled and of EcosimPro, to Level 4 which requires no prior knowledge whatsoever of EcosimPro. Below we address these levels in more detail

### Level 1 Users

Users at this level develop component libraries. They require extensive knowledge of the mathematics of the physical phenomenon to be modelled and wide knowledge of EcosimPro's modelling language. They need to understand the problem of modelling ODEs and DAEs. Level 1 users deal with the handling of discontinuities, the creation of algebraic loops, connection ports, component breakdown using inheritance, the creation of component icons, etc. Level 1 users are normally few and far between.

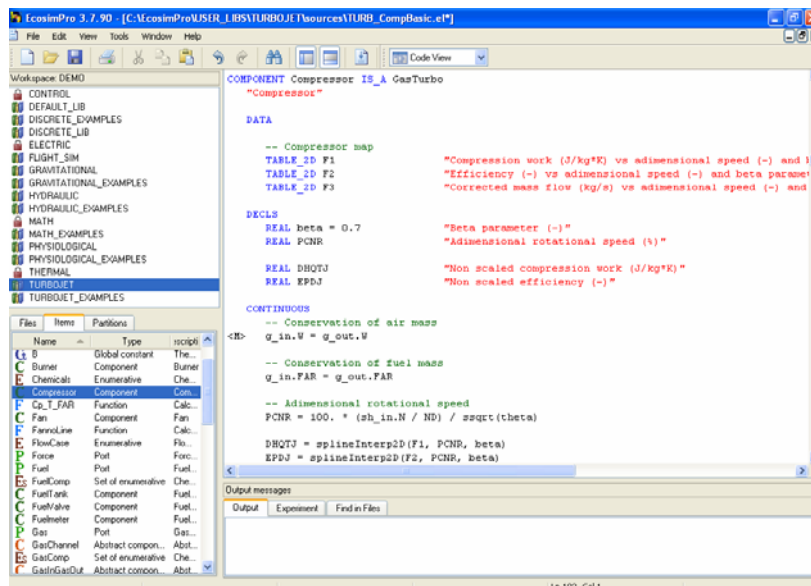


Fig. 1, EcosimPro snapshot of the code view (level 1)

On the left of the display in the above figure we can see the open libraries and some of their objects. On the right is the modelling code of a gas turbine physical component.

### Level 2 Users

These use the libraries developed by Level 1 users. They need no knowledge of the modelling language since they use a graphical tool which enables them to drag-and-drop components on the canvas and then connect them to make more sophisticated components. Although the work is more intuitive, it does require knowledge of the mathematical implications of connecting components because their objective ends when they create a final mathematical model which is as robust as possible.

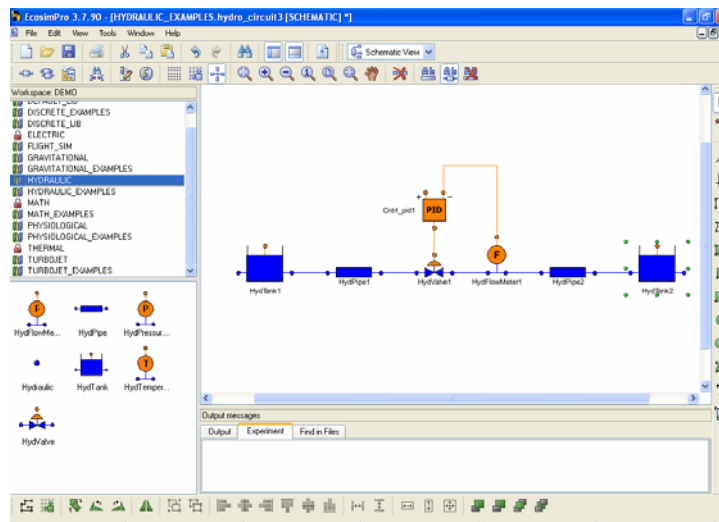


Fig. 2, EcosimPro snapshot of the schematic view (level 2)

In this case the library objects are displayed as icons. The view in the above figure is a hydraulic model with components from the HYDRAULIC library. This model will be converted into a new component which can in turn be used as a basic component in other models.

### Level 3 Users

These users do not create new components. What they do is run different simulations on models developed by Level 2 users. They are conversant with an easy-to-use experiment language with which they program steady state calculation, transient calculations, parametric calculations, etc. The graphical interface enables them to plot any simulation variable.

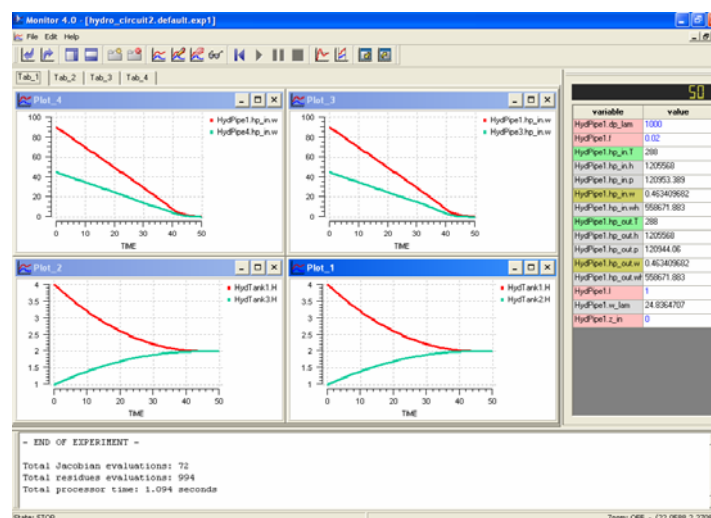


Fig. 3, EcosimPro snapshot of the Monitor (level 3)

At this level they can view the evolution of any variables by means of plotters and they can access them to see their numerical value or to change a datum.

#### Level 4 Users

The users do not need to know how to handle EcosimPro and they do not even need to have it installed. They use models generated by EcosimPro, but with certain limitations.

There are several types of Level 4 users:

- Users of a deck automatically generated from EcosimPro which creates a stand-alone application with a simple GUI which enables certain experiments to be executed changing a limited set of data. For example, the following figure illustrates the display of a deck generated for an EcosimPro model:

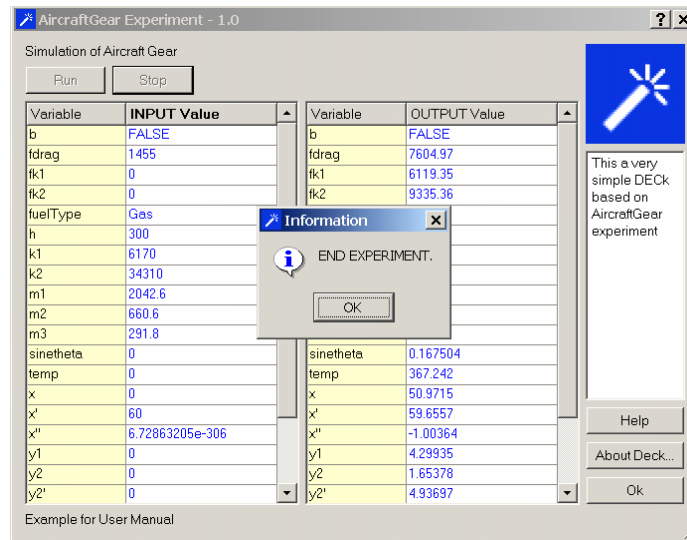


Fig. 4, Customer deck example snapshot of an EcosimPro model

- Users who wish to use models from Excel<sup>®</sup>; in this case, EcosimPro provides an add-in which is inserted in the Excel<sup>®</sup> toolbar, enabling connection with any model generated with the tool; for example:

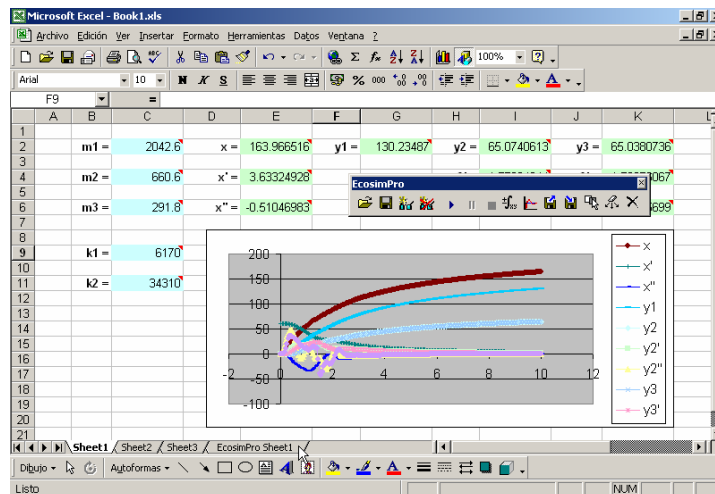


Fig. 5, Excel simulation snapshot of an EcosimPro model

- Users who re-use C++ to connect the generated model with their own simulation environment. In his case it is the user who programs the experiment to be created in C++, using any of the functions provided in EcosimPro's C++ API

- Users that need SMP2 standard to be connected. In this case the Level 3 users would export a model with the SMP2 standard wrapper that it will allow to reuse immediately in a space environment. This capability will be developed in the coming months

### **Current Status**

Currently (Oct-2006) the operating version is 3.4 and it is expected that tests on beta version 4 will be completed in the coming weeks. The features of the new release can be summarized as follows:

- A completely new graphical interface. The multiplatform Qt 4.0 framework has been used which will enable versions to be created for Linux and Unix in the near future. Displays are clearly established in the new GUI, based on the type of user concerned
- New steady state solvers which enable far more precise convergence information to be produced
- A tool to automatically produce customer decks of an experiment and enable non-users of EcosimPro to use the models
- Use of XML for storing all internal information
- Possibility to use external classes in C++ in an intuitive fashion

Future projects are in the works that will equip EcosimPro with new capabilities, such as:

- Generation of models using ESA's SMP2 Standard to interconnect simulation models. The development team has closely followed the evolution of this new standard and some prototypes have already been built
- Creation of optimisation and design capabilities to be able to analyse models which presently have to be exported to other environments so that these studies can be performed
- Compilation of the new version in Linux so as to have a multi-platform final version
- Distributed simulation using a CORBA-based or Web services-based environment

## **APPLICATIONS IN THE FIELD OF SPACE ENGINEERING**

### **ATCS: Refrigerator Freezer Rack (RFR)**

The Crew Refrigerator/Freezer Racks (RFR) are being developed and built at Astrium Friedrichshafen under ESA contract. The RFR will provide conditioned storage volume for astronaut food during transport in the MPLM and on board the ISS. To support the design of the RFR, a thermal model has been established at Astrium in the early project phase using the ESATAN code.

For demonstrating the capabilities of EcosimPro, the same model is built up with EcosimPro. The results are validated by comparing them to those from the ESATAN simulation [1, 2].

The phenomena represented by the model are:

- Heat transfer between the CV (cold volume), and between the CV and the environment
- Thermal capacity of insulation walls, external layer, drawers, cargo, and air
- Volume air flow from the balance between the pressure rise in the fan and the pressure drops
- Heat transfer from the cabin air by convection
- Detailed behaviour of the HX with the Peltier units
- Defrosting heating cycle
- Fluid flow through the wick and capillary channels in a simplified way
- Behaviour of the Peltier heat exchanger from performance curves

It can be structured in the following subsystems:

1. Rack subsystem
2. Cold volume subsystem
3. Cooling subsystem
4. Electrical subsystem
5. Defrosting subsystem

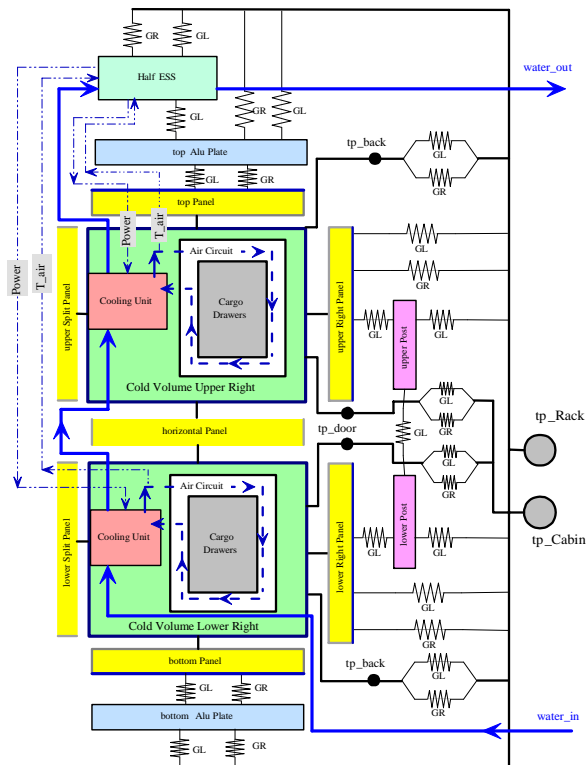


Fig. 6, Topology of the RFR component “HalfRackRight”

### *Differences between the EcosimPro and the ESATAN Thermal Models*

In the ESATAN model two identical submodels are joined together by one main model. In the EcosimPro model, only one-half is modelled, with the Electrical Subsystem also assumed to be separated into two identical halves. The EcosimPro model has been better structured by having separate submodels which are, in principle, freestanding and are connected via interface ports to the full system model. This well-honed structuring results in a good overview of the model. The submodels can also be easily used freestanding and verified separately before they are put together into the whole system.

Model implies a non-linear equation system. A FORTRAN solving routine using a Newton-Raphson method needed to be programmed for the ESATAN model whereas EcosimPro solves the equation system using its internal solvers. This made the programming work much easier and the convergence of the model could also be better achieved due the EcosimPro specific tracing to failure resolution.

Thermal connectors between the Cold Volumes and the Rack are built up in much more detail in the ESATAN model than it in EcosimPro. This is because it is a more complex, extensive tool which requires greater effort with detailing when connecting thermal nodes.

For modelling air flow, EcosimPro software is more suitable. The heat transfer coefficients to the air channel walls and the heat exchanger are calculated by EcosimPro from the geometrical details, parameters and physical properties of the materials. ESATAN needs to be provided with separately determined coefficients.

The humidity input, freezing on the heat exchanger fins and melting during the defrost periods could also be modelled relatively easily with EcosimPro. The humidity is not regarded in the ESATAN model.

### *Comparison of the Calculation Results*

Three simulation cases are investigated. A steady state analysis for both hot case and cold case, a transient analysis of a passive period with increasing ambient temperature and the system recovery, and other transient analysis of a door opening and closing cycle during normal operation.

Steady state operation mode, hot case and cold case:

The calculation results are quite similar. The differences of the heat input into the Cold Volumes is due to the more detailed (but not necessarily more realistic) modelling of the conductive coupling to the rack established in the ESATAN model.

8 hour passive period with increase of ambient temperature from 30°C to 49°C and recovery:

During transfer of the MPLM from the shuttle to the ISS and back, the power supply is switched off for a maximum of 8 hours. Calculating this scenario results in a maximum cargo temperature of -21°C in ESATAN (starting from -22.2°C steady state) versus up to -18.5°C (starting from -22.9°C steady state) in EcosimPro. After switching power on again, with ambient temperatures going back within 1 hour, the cargo reaches a temperature of less than -22°C within 25 hours (ESATAN) and 40 hours (EcosimPro).

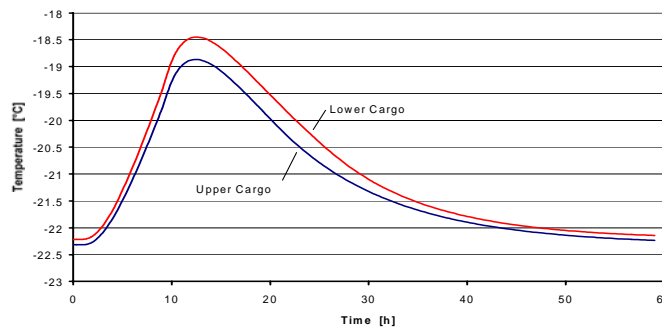


Fig. 7, Cargo temperature with passive phase of 8 hours (EcosimPro)

Door opening every 3 hours for up to 30 seconds at ambient temperature of 30°C:

Both models show similar behaviour, with cargo temperature increase to around -22°C.

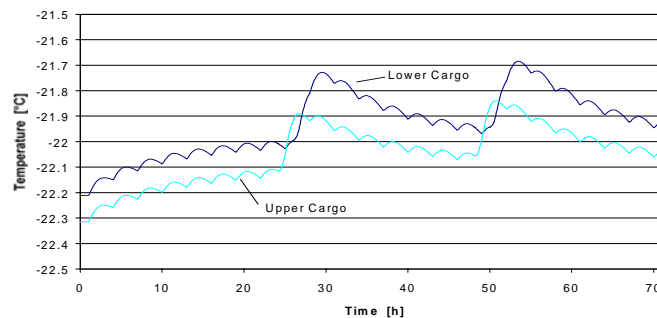


Fig. 8, Cargo temperature with door opening every 3 hours and defrost period after 24 hours (EcosimPro)

*Assessment of EcosimPro versus ESATAN*

The thermal modelling approach is based on the same laws of heat exchange and the results from ESATAN and EcosimPro are therefore quite similar. Differences arise due to different details when modelling the thermal conductors/radiators and for the modelling of air flow specific heat transfer coefficients, which in EcosimPro are done internally and directly adjusted according the corresponding variation of boundary conditions (e.g. due to variation of physical conditions with temperature), whereas in ESATAN an external calculation is necessary with corresponding data required as input.

Another advantage of EcosimPro is the possibility of directly plotting the calculation results. The resulting plot can then be further processed and transferred to the reporting document. EcosimPro also has a post-processing utility which

enables any variable or datum of a calculation to be plotted (the results being saved at each time step in a binary database file).

In general, the results are quite comparable and only deviate slightly due to different detailed modelling of the thermal connectors.

### ATCS: Loop Heat Pipes (LHP)

Loop heat pipes are two phase heat transport devices where the fluid circulation is achieved by capillary forces. Due to the complexity of the two-phase phenomena involved in LHPs, current models cannot simulate several performance characteristics. In the case of multiple evaporator or condenser LHPs, there are additional difficulties since it is necessary to take into account the dynamic interactions between the evaporators and condensers [3, 4].

This study focuses on the prediction of both steady-state and transient behaviour of the LHP and its validation with the experimental data.

LHP models can easily be used as a component of an integrated spacecraft thermal system. The mathematical model is also modular. In other words, each component has been modelled separately, which gives flexibility to the user. They can then be built by connecting the typical LHP components: evaporators, compensation chambers, transport lines, condensers or capillary flow regulators.

The main assumptions made in all the components are as follows:

- The working fluid is considered as homogeneous (ammonia, propylene...). That is, the fluid is a two-phase homogeneous mixture characterized by the vapour mass fraction (vapour quality)
- The calculated thermodynamic properties correspond to the two-phase mixture. The thermodynamic properties are calculated taking into account the amount of vapour and liquid in terms of vapour quality. However, in saturation conditions the thermodynamic properties are calculated separately for vapour and liquid phases
- The thermodynamic properties are obtained by interpolation using the tables built from NIST routines
- The LHP components exchange heat with the environment by convection and radiation
- The compressibility, transient and viscous effects are taken into account through the pressure drops calculated by following the fluid particles. The pressure drop calculations include empirical correlations for the pressure drop in a porous media

### Building the LHP Model

Three models were developed to verify the feasibility of the mathematical approach of the general components and to verify the correct behaviour of the capillarity flow regulator, a simple LHP, a multi-condenser LHP, and a multi-evaporator LHP.

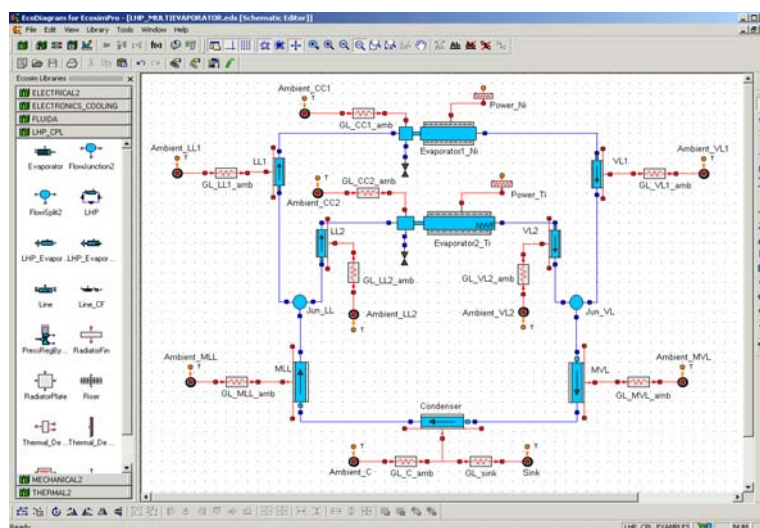


Fig. 9, Schematic of the EcosimPro multi-evaporator LHP design in EcosimPro



## Results and discussion

A steady-state analysis has been performed of the simple LHP to validate the working saturation temperatures as a function of the applied power, for ammonia, a sink temperature of 273K, and an ambient temperature of 294K.

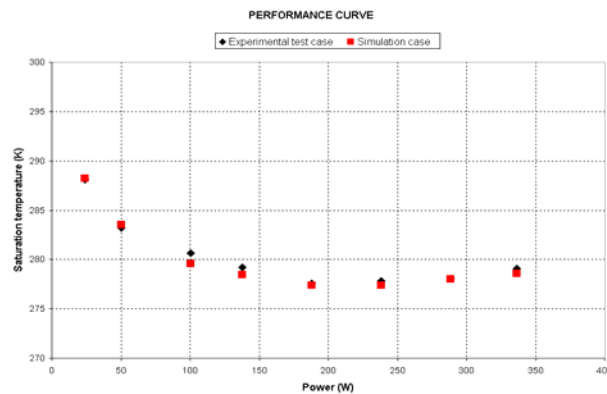


Fig. 10, Comparison of saturation temperatures between experimental and simulation results

Different transient analysis has been performed for the multi-condenser and the multi-evaporator LHP. For example, by setting one evaporator to a constant applied power and the other to a variable applied power, using ammonia as working fluid, a sink temperature of 283K, and an ambient temperature of 293K.

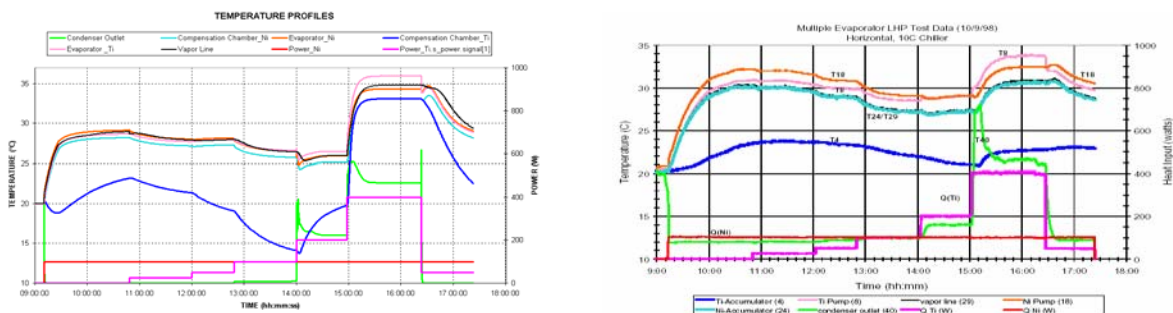


Fig. 11, Predicted and experimental profiles of the multi-evaporator LHP

The results obtained from the model are largely agree with the experimental results in both steady-state and transient cases. Some differences could be due to unknown experimental test parameters that have been assumed for transient simulation cases, such as the thermal isolation properties of some components.

## ECLSS: Air Revitalization System (ARES)

ARES Elegant Breadboard has been manufactured and has just been tested at EADS. An EcosimPro simulation model of the overall hardware system has been developed [5].

Its major functions in the Life Support System of the ISS would be to:

- Generate breathable oxygen from water
- Collect the produced CO<sub>2</sub> from the air cabin, and to control cabin CO<sub>2</sub>-level as required
- Convert CO<sub>2</sub> into water and methane
- Recover the produced water for use in the water management system

The ARES simulation model was developed to:

- Solve design problems of equipment and system operation mode
- Verify ARES system satisfied the expected functional requirements
- Design the preliminary control system
- Perform sensitivity studies (trade studied)

The Air Revitalization System consists of three assemblies:

- CCA, Carbon dioxide Collection Assembly
- CRA, Carbon dioxide Reduction Assembly
- OGA, Oxygen Generator Assembly

The ARES model was built to satisfy the following requirements:

- The model should be able to represent all the main operation modes of the system
- The model should be transient and be able to provide averaged consumptions and productions for one cycle
- The layout of the model should resemble the layout of the actual system
- The decomposition of the overall model into submodels should be similar to the decomposition of the actual ARES system into the different assemblies
- Each assembly submodel should be able to be tested and simulated individually
- The model should have a control system for each assembly (CCA, CRA, and OGA) and a control unit at the overall system level
- The simulation model should have all essential functions of ARES. The level of detail of the model should allow quantitative analyses of fluid parameters (mass flow, pressure, and composition), thermal parameters, and environmental parameters
- Each submodel has been built using components of the following EcosimPro libraries: ECLSS, Control and Thermal

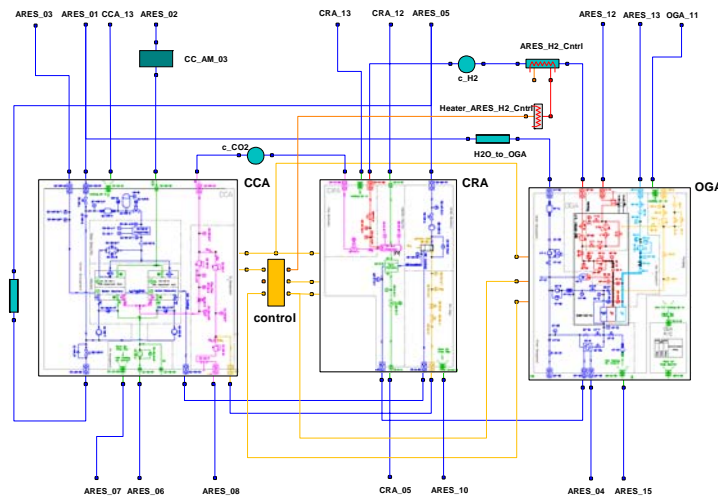


Fig. 12, Schematic of the EcosimPro ARES model

**ECLSS LIBRARY** – It involves multi-disciplinary simulation, such as, fluid flow, chemical reactions, electrochemical reactions, thermal transfer and biological processes. It provides a set of components to model the most typical equipment and process ECLSS systems: cabins, crew members, hatches, condensing heat exchangers, water separators, pipes and fittings, fans, pumps, reactors, etc. It includes thermodynamic functions to calculate the properties of the following two classes of working fluids:

- Coolants of pure substances, employing the same FORTRAN functions used by ESATAN/FHTS
- Perfect gas mixtures with or without water, where water can condense in solid or liquid phase

**THERMAL LIBRARY** – It contains components to build lumped parameter thermal models as diffusive thermal nodes, boundary thermal nodes, linear thermal conductors and radiative thermal conductors. It also provides specialized components to represent materials with temperature dependant properties, Peltier elements, multi-node walls and cylinders.

**CONTROL LIBRARY** – It contains components to build up block diagrams of control systems as transfer functions, discontinuous functions, discrete-time functions, mathematical functions, signal generators, multiplexors, demultiplexors and controllers.

## Main Simulation Results

To run the ARES model we have connected the model interfaces to appropriate boundary conditions and to a cabin model.

The cabin model is connected to a simple model of a thermal-humidity control system to keep cabin humidity and temperature near a prefixed value. Finally the cabin is also connected to a crew model. This crew model enables exchanges between live beings and their environment (O<sub>2</sub> consumption, CO<sub>2</sub> production...) to be represented. The number of crew members considered is seven.

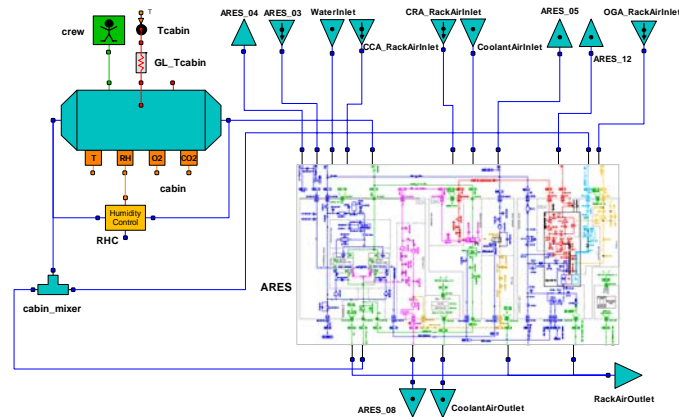


Fig. 13, Schematic of the EcosimPro ARES simulation test system model

ARES simulation model has been run for several day/night cycles. We have considered the orbit cycle duration to be 90 minutes and the day cycle has been considered to last 53 minutes.

The performance of the ARES model test, i.e. the ratio between consumed CPU time and total simulated time, has been around 17%. It keeps a good relationship between model complexity and simulation speed.

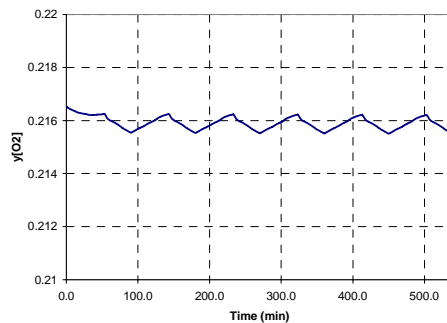


Fig. 14, Molar fraction of O<sub>2</sub> in the cabin. The crew consumption of O<sub>2</sub> is considered constant during all the cycles

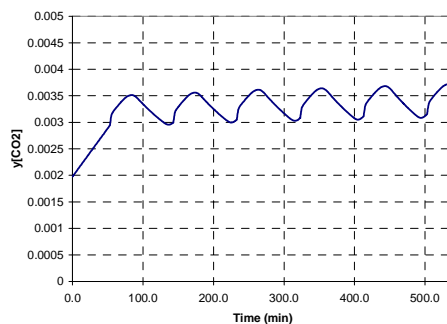


Fig. 15, Molar fraction of CO<sub>2</sub> in the cabin. It keeps below the maximum requirement value of 0.4% vol.

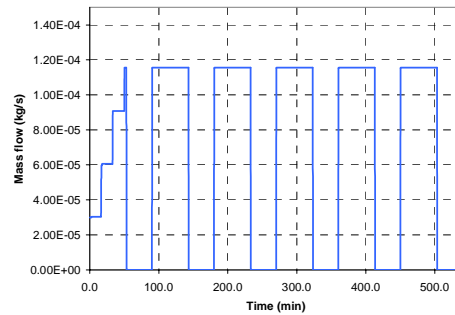


Fig. 16, Oxygen mass flow produced in OGA. OGA startup is carried out in stages

The simulation model is pending validation with experimental data from the test campaign of actual hardware. This will enable the response of the model to be improved. It is expected that this model will be useful for future improvements or redesign of the Air Revitalization System.

## CONCLUSIONS

EcosimPro is currently a first-rate option for developing simulation models for space applications, as this article has demonstrated. The stage of development currently attained enables the user to model very complex systems in the areas of control, thermal analysis, ECLSS, propulsion, just to name a few, and to export these models to a realistic environment simply and directly.

The generation of C++ code with the final model is further proof of the versatility of EcosimPro models, which can be reused in different distributed technologies such as CORBA, Web Services, SMP2, etc.

Since EcosimPro has been linked to ESA from the beginning, it has been possible to enhance it in line with ESA's requirements or those proposed by other contracting companies. A maintenance agreement is now in place between EA Internacional and ESA to allow making improvements to the tool every year. This special relationship means that EcosimPro can be enhanced in the ways ESA considers of most interest to its future developments.

Finally, a version of EcosimPro that generates models compatible with SMP2 will soon be released so that the models created with the tool can be interconnected with ESA's standard environment.

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