

Modelling environmental control and life support systems (ECLSS) and loop heat pipes with EcosimPro

Almudena Rueda¹ and Raúl Avezuela², Pedro Cobas³
Empresarios Agrupados Internacional, Madrid, Spain, 28015

and

Ramón Pérez-Vara⁴
IberEspacio, Madrid, Spain, 28010

EcosimPro is used by the European Space Agency (ESA) as the standard tool to support Environmental Control and Life Support Systems (ECLSS) analysis. EcosimPro is a generic, flexible and modular tool based on the concept of object-oriented programming. It is capable of solving a large set of Differential-Algebraic equations (DAEs). These features make EcosimPro a multidisciplinary tool and as such it can be used to model different application domains, including electrical circuits, hydraulic networks and thermal and chemical systems, to name just a few. The new enhanced EcosimPro, version 4.6, released in November 2009, features numerous improvements. Among these are an upgraded wizard for creating mathematical models, customer deck generation for end users, a new attribute editor to configure component data more easily, improved treatment of post-processing results, and new wizards for performing parametric studies and optimization analyses. This paper shows how EcosimPro and its new capabilities make it easier for the user to model complex systems such as ECLS systems or two-phase heat transport devices.

I. Introduction

Ecosimpro is a simulation tool that can be used to model any kind of dynamic system that can be represented by means of differential-algebraic equations (DAEs) and/or ordinary differential equations (ODEs), as well as discrete events. This tool is integrated within a visual environment that provides an intuitive framework to develop simulation work in a user-friendly and easy way.

EcosimPro is based on object-oriented programming so it allows existing components to be reused. It also includes a symbolic handler to apply non-causal modelling and the numerical solving methods it uses serve to solve complex differential-algebraic equation systems.

This simulation tool has been developed by Empresarios Agrupados Internacional (EA Internacional, Madrid) within the framework of a project that was started in the 1990s in collaboration with the European Space Agency (ESA). The purpose of this project was to develop a simulation software tool capable of modelling the Environmental Control and Life Support Systems (ECLSS) of the European modules (Columbus and Hermes) of the International Space Station (ISS).

¹ Project Engineer, Simulation Department, auf@ecosimpro.com.

² Project Engineer, Simulation Department, rao@empre.es.

³ Head of EcosimPro Development Team, Simulation Department, pce@ecosimpro.com.

⁴ Deputy General Manager, IberEspacio, rpv@iberespacio.es.

In time, after a constant development and use of EcosimPro, a commercial product was obtained (the first commercial version, EcosimPro 3.0, was released in the year 2000). This program was capable of modeling more than the primary system of the ECLSS but also many other types of process (mainly in 0D):

- Fluid systems
- Heat transfer
- Control systems
- Electrical systems
- Aeronautical or space propulsion
- Mass and energy balance
- Chemical reactions
- ...

EcosimPro is currently the official tool of the ESA for the modelling of environmental control and life support systems, and for the areas of satellite propulsion and power systems.

Various areas are modelled in these systems (fluid flow, heat transfer, electro-chemical, biological, etc), thus reflecting the convenience of EcosimPro for multidisciplinary process simulation, since it is a highly flexible tool that adapts easily to different types of system.

This information presented in this paper is based on EcoSimPro version 4.6 that was released in late 2009. It included numerous upgrades in the creation of models and their resolution, debugging and postprocessing. New capacities have also been added, including an attribute editor, a new wizard to select the order of the components and their connections, the generation of decks in various platforms and a wizard for parametric studies, among others.

This article provides a general description of the new capacities of EcosimPro and its application to libraries for the simulation of ECLSS and LHP (Loop Heat Pipes) systems.

II. New Features of EcosimPro 4.6

Before focusing on the new capacities included in this new version, below is a summary of their main characteristics:

- 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.
- Powerful algorithms to solve algebraic-differential equation systems, enabling the modeller to forget about one of the most complex tasks in the area of simulation
- Non-causal modelling: the modeller introduces equations in any format and afterwards EcosimPro symbolically transforms them
- A user-friendly development environment with multiple windows for editing code, graphically viewing a model, running a model with variable plotters, etc
- Automatic generation of a C++ class with the final model ready for use by any user

Below is a brief explanation of some of the new capabilities that allow greater control of the simulation process stages. They can be classified as follows:

A. New capabilities of the language:

- New functions to read tables (1D, 2D or 3D) in ASCII or XML format
- Use of classes in components, functions and experiments
- Possibility of introducing units in the variables by means of the word UNITS
- Possibility of working with relative paths
- Definition of variables as PRIVATE so they are not visible in experiments and cannot be reported, edited or viewed

B. Attribute editor:

New attribute editor to allow users to arrange the data of a component into one or more tabs.

C. Variable properties wizard:

There is a new wizard that can be accessed through the schematic diagram or a component partition and contains a set of properties for each of the model variables. These properties are the following:

- Alias
- Visible property
- Trace property

D. New wizard assistant:

There is a wizard that allows different types of calculations (steady state, transient and parametric) within a single experiment.

E. Deck generation:

EcosimPro includes a deck generation wizard which, based on a given experiment, helps the supplier to create a deck. A deck corresponding to an experiment consists in encapsulating the experiment. This allows the supplier (creator) to deliver his work to a customer (user) in a known way.

F. Debugging tools:

- Generation of a log file with more information on the evolution of the simulation
- New tool for evaluating the simulation performance
- Deactivation/activation of the resolution of the internal algebraic boxes in steady state or transient calculations (solveAlgebraicBoxes(TRUE or FALSE))
- Selection of the TRACE property for the required variables to display the evolution of their values in all the iterations of the steady state calculations
- Three different criteria for global convergence and two possibilities to calculate the model waste may be selected

G. Optimization Tool:

The purpose of the general optimization assistant is to help users to define and resolve optimization problems. Very different types of problems can be solved by using this technique: design studies, control optimization, parameter estimation, planning, etc.

III. ECLSS Library

A. Overview

EcosimPro is the European Space Agency (ESA) standard tool to support Environmental Control and Life Support Systems (ECLSS) analysis.

ECLSS modelling involves multi-disciplinary simulation, since ECLS operations consider a very wide range of different phenomena such as fluid flow, chemical reactions, electrochemical reactions, heat transfer and biological processes.

The ECLSS library is an EcosimPro professional library which provides a set of components to simulate the most typical process units, equipment and processes of the ECLS systems, such as cabins, crews, heat exchangers, pipes, pumps, reactors, electrolyzers, etc.

This library is mainly adapted to the thermo-hydraulic analysis of air cabin loops of conventional ECLSS, but special case fluid flow problems like venting lines or pressure regulators can also be analysed.

The library was designed with the limitation that low pressure losses are assumed in the components. Nevertheless, EcosimPro is a flexible tool and it is possible to overcome the current limitations by designing new components whose formulation considers a wider range of phenomena.

The ECLSS library enables you to simulate heat transfer, chemical reaction and mass/energy balance, and to analyse system pressure drop based on user-specified operating conditions.

Models built with the library components assume that mass flow and heat flow are one-dimensional. The intensive variables like pressure, temperature or compositions are assumed to have average values in the control volumes or nodes considered (lumped modelling). The majority of components are capable of evaluating reverse flow. Moreover, one or more types of fluids can be considered in the system, depending on the fluid loops in the ECLSS.

The library includes thermodynamic functions to calculate the properties of the following two types of working fluids:

- Perfect gas mixtures with or without water, where water can condense as a solid or liquid and whose pressure must be approximately atmospheric pressure or lower
- Real fluids like pure gases, water and pure liquid coolants

The intuitive EcosimPro graphical tool offers user-friendly drag-and-drop methodology and input data editors that help to build the flow sheet for the ECLSS model and specify the input data and parameters.

EcosimPro enables the user to easily develop new components or modify existing components in order to provide the ECLSS components with the required level of fidelity. This can be done graphically through a simple, user friendly interface, or through EcosimPro's object-orientated language which makes it possible to reuse existing codes.

The library has been designed so that the process control system can be included using the standard CONTROL library and so that the system's thermal control system (TCS) can be included using the standard THERMAL library. These two libraries are provided with EcosimPro.

The ECLSS library enables users to carry out trade studies and preliminary designs of ECLS systems and to determine the component, subsystem and system off-design performance. Furthermore, it enables users to perform long duration transient analyses with reasonable CPU time consumption.

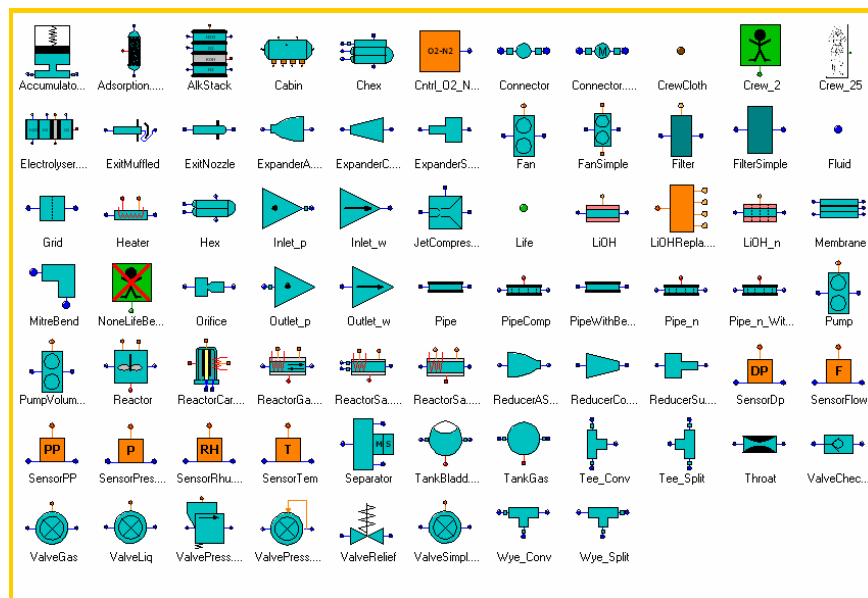


Figure 1. Palette of ECLSS Library.

B. Components

The library (Fig. 1) includes a wealth of ECLSS components and boundary condition components to build the system simulation model:

- Cabin: it represents a standard air volume or cabin. It takes into account the phenomena of deposition of the condensed liquid water and ice and the evaporation of the water film on the cabin wall. The cabin model is usually connected to submodels representing parts of the air management subsystem or to other cabins using hatches, and it can be connected to the thermal control system submodel and to the crew component
- Crew: it represents crew members. Some of the phenomena that have been taken into account in the formulation of this component type are metabolic activity, breathing, evaporative and sensible heat losses from skin, skin blood flow, predictions of thermal comfort and thermal sensation, among others
- Fittings: there are some friction components to take into account pressure losses in the system, such as expanders, reducers, grids, wyes, tees, orifices, mitre bend, etc
- Pipes: there are several models of pipes with different levels of complexity to take into account thermal delay, bends, or molecular flow in venting lines

- Valves: the library includes several valve models to represent check valves, pressure regulator valves, liquid and gas valves
- Boundary conditions: the library contains a set of components to specify the system boundary conditions, such as temperature, composition of the working fluid, pressure, mass flow, etc
- Sensors: the library includes a set of sensors which can be used to implement ECLSS control loops
- Other components: the library also contains models of equipment normally found in ECLS systems, such as pumps, fans, tanks, filters, and models of more specific ECLS equipment, such as chemical reactors, fuel cell stacks, electrolyzers, membranes, LiOH cartridges, etc.

C. Application Example

Currently the ECLSS library is being used for the modelling and simulation of the closed loop Air Revitalisation System (ARES). The ARES is the result of more than 20 years of applied and focused R&D work by EADS SPACE Transportation engineers in the area of closed loop processes in space habitats, financed by EADS-ST and co-funded by the European Space Agency (ESA) and the German Aerospace Center (DLR).

ARES is a subsystem of the environmental control and life support system and shall be designed for implementation within the Multi Purpose Laboratory Module (MLM) of the International Space Station (ISS). The ARES rack consists of the following assemblies:

- Carbon Dioxide Concentration Assembly (CCA)
- Carbon Dioxide Reduction Assembly (CRA)
- Oxygen Generation Assembly (OGA)
- Multifiltration Assembly
- ARES Controller and Power Assembly

And the major functions of ARES in the Life Support System of the MLM would be to:

- Generate breathable oxygen from water
- Collect the produced CO₂ from air cabin and to control cabin CO₂-level as required
- Convert CO₂ into water and methane
- Recover the produced water for use in the water management system.

The EcosimPro ARES model includes sub-models of the CCA, CRA, OGA and the control system and will be used to design the control strategy and to predict the performances of the system changing some system parameters.

Fig. 2 shows a former model of the assembly OGA⁶ in order to show the capability of EcosimPro to model multidisciplinary systems including thermal couplings, a control system and a thermo-fluid system.

In addition, a specific library in EcosimPro is being developed within the framework of ESA project called ALISSE (Advanced Life Support System Evaluator) for the modelling of CELSS (Closed Environmental Life Support Systems) where the following phenomena are taken into account:

- Gas-liquid equilibrium
- Acid-base equilibrium
- Finite rate of biological growth
- Finite rate chemistry

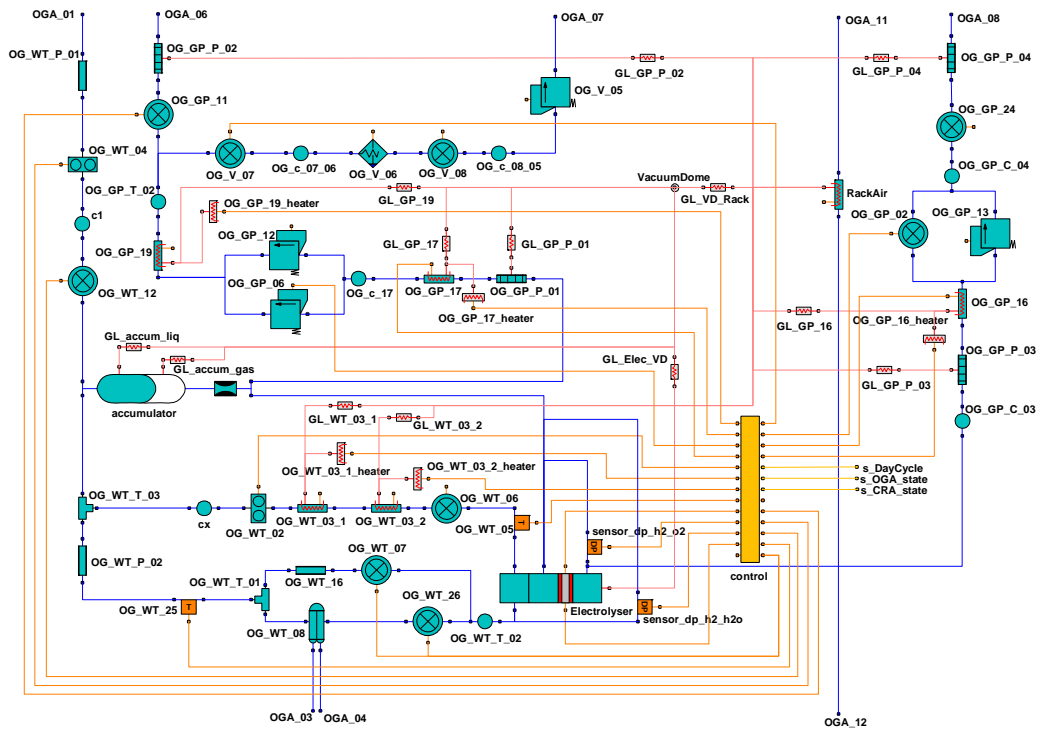


Figure 2. EcosimPro simulation model of OGA.

IV. LHP Library

A. Overview

Loop Heat Pipes (LHPs) are two-phase capillary pumped thermal transport devices for transporting heat with a small temperature drop. The main characteristics of these devices are: high power transport capability, operation against gravity, high temperature stability, fast and strong diode action, design flexibility, robustness and reliability. Due to these characteristics, LHPs are being proposed or effectively used for thermal control in several fields of application including avionics cooling for aircraft, solar facilities, electronics cooling and especially for spacecraft thermal control.

Fig. 3 shows a typical LHP, which consists of an evaporator (with a porous wick), a compensation chamber, a condenser and two transport lines (one for the vapor and the other for the liquid). The power is directly applied to the evaporator. Under this heat load, the saturated liquid in the wick evaporates and the capillary forces developed in the porous wick cause the movement of the vapor towards the vapor line. In the condenser, the vapor condenses as a result of the heat rejection. Then, the liquid flows through the liquid line to the compensation chamber and finally returns to the evaporator.

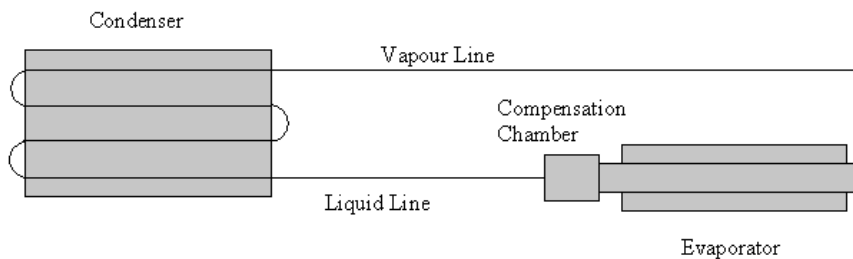


Figure 3. Typical LHP configuration.

IberEspacio has developed two EcosimPro libraries for the simulation of LHP systems and their thermal interfaces.

- TPCS library: TPCS stands for Two-Phase Control System. This library focuses on the transient simulation of LHPs and their thermal interfaces including the start-up phase using a minimum number of experimentally determined parameters. Fig 4 depicts the palette of components of this library
- LHP_SS library: This library focuses on the design and prediction of the steady-state performance characteristics of LHPs. Fig 5 shows the palette of components of this library

These libraries have been developed considering a modular approach, that is, each component has been modelled separately.

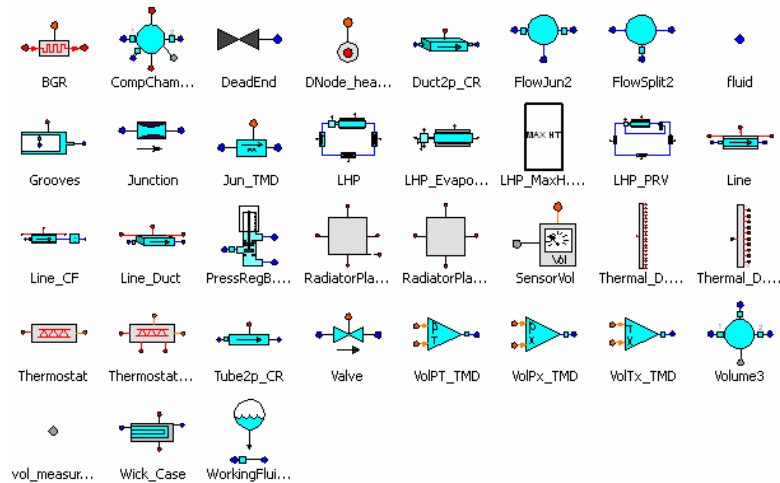


Figure 4. Palette of TPCS Library.

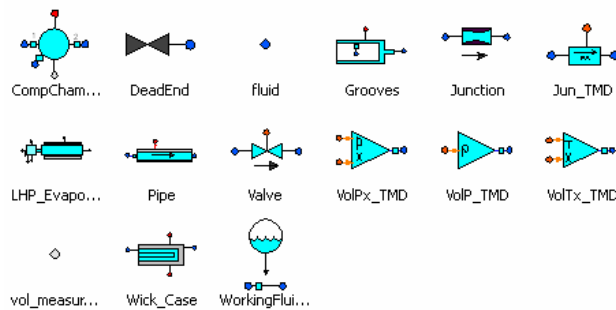


Figure 5. Palette of LHP_SS Library.

The following main assumptions have been made for the LHP component modelling of the TPCS library:

- The 1D fluid flow model is a homogeneous equilibrium model. It is considered that the two phases are in equilibrium assuming equal phase velocities, temperatures and pressures
- The calculated thermodynamic properties correspond to the two-phase mixture and they are obtained by interpolation using the tables built from NIST (National Institute of Standards and Technology) routines
- The LHP components can exchange heat with the environment by convection and radiation, and they can exchange heat with other external components (such as saddles) by conduction
- The fluid model is based on the one-dimensional fundamental conservation equations applied to control volumes, i.e. the transient mass, momentum and energy conservation equations are solved using a staggered grid. The fluid part of each LHP component is subdivided into individual control volumes
- The compressibility and transient effects are taken into account. The viscous effects are taken into account through the pressure drop calculations, which include empirical correlations for the pressure drop in a porous medium

- The gravity effects due to the different orientations of the LHP have been taken into account in the formulation

A detailed description of the mathematical model behind this library can be found in Ref. 5.

The assumptions considered in the LHP_SS library are the same as those considered in the library TPCS except for the transient phenomena. The mathematical model of this library is based on the steady-state energy balance equations at each component of the LHP. The pressure drop is computed at each LHP component and the location of the liquid-vapor interface in the condenser or in the transport lines is obtained.

B. Components

The main components of a LHP system appear both in the TPCS library and the LHP_SS library. A brief description of these components is given below:

- **CompChamber:** it represents Compensation Chamber of Loop Heat Pipe (LHP). The two-phase compensation chamber stores excess liquid and controls the operating temperature of the loop
- **Transport lines and Condenser:** these components are discretised into several control volumes (nodes) in order to increase the accuracy of the model results. The formulation used takes into account the effects due to phase changes
- **WorkingFluid:** this component allows the working fluid of the LHP to be specified
- **Grooves:** it represents circumferential and axial grooves in the evaporator with various shape of cross area, i.e. either triangular or rectangular
- **Wick_Case:** it represents the evaporator wick case. The following parts are included in the evaporator wick case: metal case, grooves, primary wick and core. The wick in the evaporator is made of fine porous material for the purpose of developing a capillary pressure to circulate fluid around the loop
- **LHP_Evaporator:** it is a topological component that mainly consists of the CompChamber, Grooves and Wick_Case. The compensation chamber is located close to the evaporator. In fact, the compensation chamber is usually included as an integral part of the evaporator, and a secondary wick is used to connect these two elements
- The TPCS library also includes some thermal components that represent a radiator plate, a thermostat and a radiator conductor that can be used by the LHP_SS library

C. Example

As mentioned above, the TPCS library is being used for the design and performance prediction of the LHPs manufactured by IberEspacio. Fig. 6 shows an illustrative example of a LHP model built with the TPCS library.

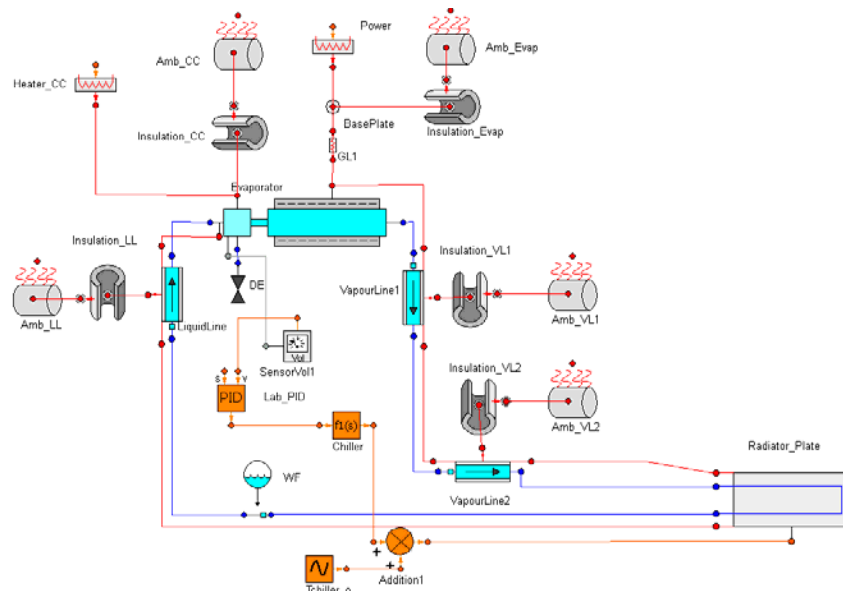


Figure 6. EcosimPro simulation model of a LHP.

The model consists of the evaporator, condenser and transport lines. The evaporator has a double-sided mounting flange attached to the cooled unit. The condenser has a single-sided mounting flange attached to the heat sink. The LHP is charged with high purity ammonia through a filling tube.

TPCS components interact with components of the EcosimPro professional standard THERMAL libraries (like the cylinder wall with a 2D spatial discretisation or the natural convection units simulating the heat exchange with the atmosphere) and CONTROL (such as PID, sensors, transfer functions, etc).

The model allows the tuning of the PID parameters to the specific power levels to be tested. The PID controller sets the cold plate temperature, which is responsible for the compensation chamber control.

The condenser component (“Radiator_Plate”) is divided into several condenser lines and plates modelled with a 2D spatial discretisation thermal network. Fig. 7 depicts the topological distribution of the components that represents the “Radiator_Plate” component included in the LHP example.

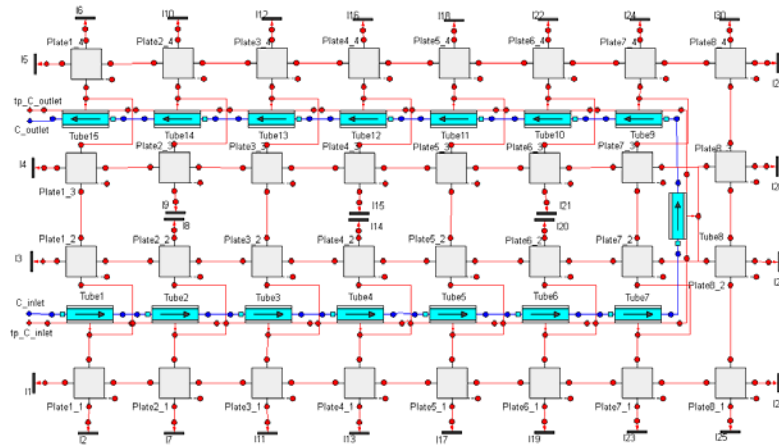


Figure 7. EcosimPro model of LHP condenser.

V. Applicability of the new features to ECLSS and LHP modelling

A. Optimization

Some parameters of LHP and ECLSS models are either very difficult or impossible to predict or to know. Thus, some of these parameters should be experimentally correlated. For example, the low power startup simulations in LHPs are usually problematic and an experimentally-fitted heat leak correction factor is necessary to reproduce the startups. In addition, external and internal heat transfer coefficients may be experimentally correlated. As a result, experimentation remains indispensable to validate the startup simulation results.

The new optimization capability of EcosimPro would help adjust these model parameters to make the process more automatic and less manual.

With this tool users can obtain optimum values for the required variables of any EL model. All users have to do is select a model and its corresponding partition, and from that moment the wizard will ask for all the information necessary to resolve a given optimization problem. Basically, the user’s tasks are to specify the objective function (the error between the experimental results and the results predicted by the model), to select the solver to be used, the decision variables (for example, the heat leak correction factor in LHP models), the constraints and another series of useful options.

The user can choose between two available methods in order to solve the dynamic optimization problem:

- A deterministic method: SQP (Sequential Quadratic Programming)
- A stochastic method: PBSA (Population Based Stochastic Algorithm)

Experimental correlation remains an important component for accurate prediction of transient LHP and ECLSS operation. Once the model is experimentally validated for a specific design operation point, it can be used to analyse the system under more complex operational conditions. The new optimization tool in EcosimPro will make this procedure easier for the user.

B. Custom Attribute Editor

This editor (Fig. 8) can be used to arrange the data and construction parameters of the components in these libraries. The user will thus be capable of finding the data that need to be modified in each system at a single glance.

For instance, the components of the Cabin component from the ECLSS library could be grouped in different tabs as shown in the following figure:

- Chemical Component: to specify the working fluid
- Geometry: to define the component geometry
- Properties: to define the various experimental coefficients associated to the component
- Init Conditions: to define the input conditions of the component

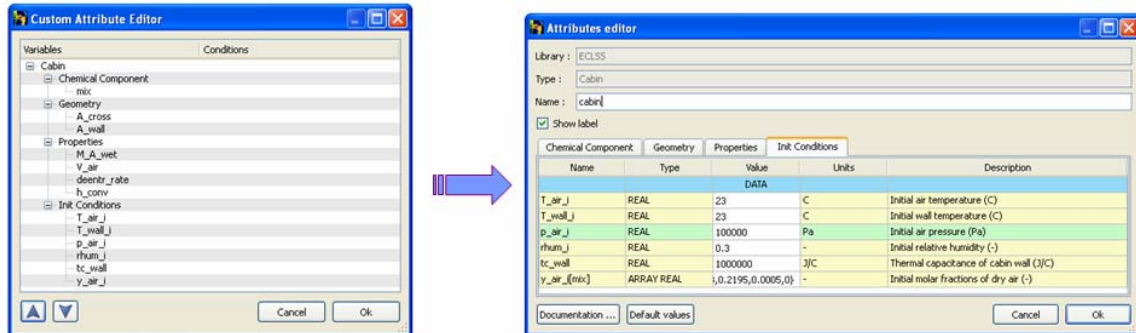


Figure 8. Custom Attribute Editor of the Cabin Component in ECLSS library.

C. Properties Editor

Another capability that would facilitate comparing the results of the model and the experimental results of the real system is the possibility of assigning aliases to the different model variables. Thus, the same name could be used in the model for the measurements of the test setup sensors so as to reduce the confusion when comparing the same variable. Furthermore, it would make it easier for users exclusively in charge of simulating the various simulation cases and using the results to interpret and represent the results of the model.

The debugging of steady-state simulations can be improved by selecting the TRACE property that displays the value of the variable in each iteration.

These features will help the user attempt the experimental validation of the model comparing the model predictions and the experimental results of the LHP hardware. Fig. 9 depicts the customisation of the properties editor of the evaporator component in a LHP model.

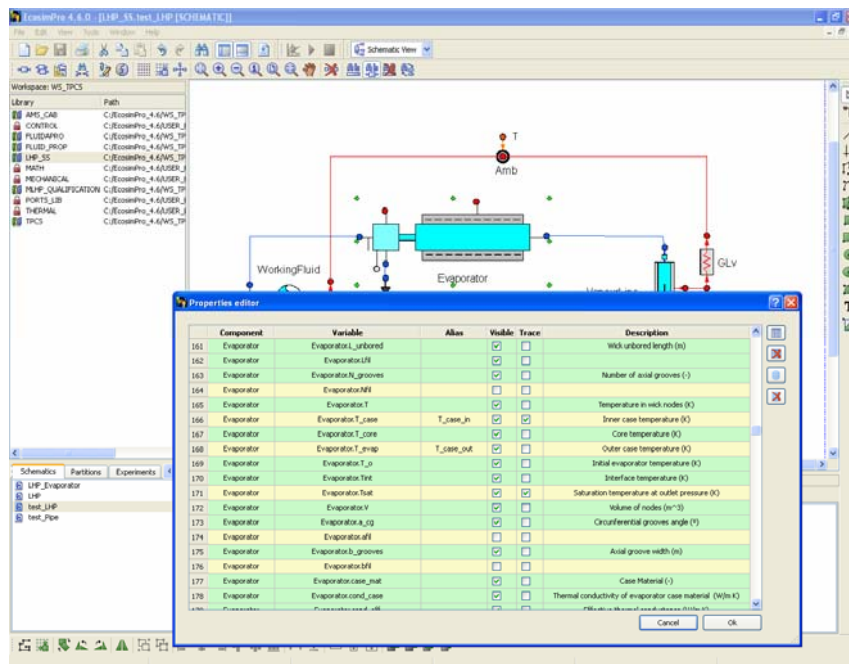


Figure 9. Properties editor of the Evaporator component.

D. New Debugging Capabilities

As mentioned above, there is a library for the calculation of steady state LHPs, known as LHP_SS. The purpose of this library is to calculate the performance and preliminary design of the LHPs. The new version of EcosimPro facilitates the simulation model debugging process for the user if any model convergence problems are encountered:

- Information of the calculation process
- Traceability of the critical variables for model convergence
- Possibility of selecting different convergence criteria
- Analysis of external function performance

E. Deck

The use of the deck allows ECLSS models and LHPs to be sent so they can be run by final users that do not have EcosimPro installed. Additionally, the decks allow model information to be encapsulated, so the final user only has permits to modify input data and to view simulation results that have been specified previously or that have been defined by the deck generator. This ensures that the confidential information in the model remains hidden for the final user.

For instance, the generation of an LHP model deck would provide the final hardware user with a tool to predict the equipment performance without accessing data or correlations that are considered confidential for the equipment supplier.

Fig. 10 shows a LHP model and how a deck is generated. In this example some variables can be modified by the deck user (ambient temperature, radiator sink temperature, temperature initialization) and only others variables are visible.

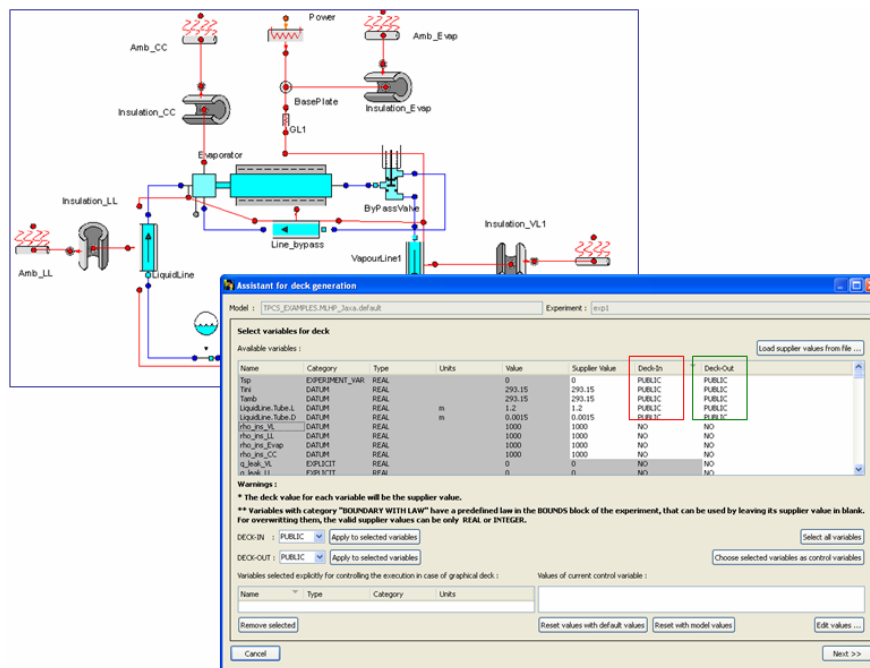


Figure 10. Example of a deck of LHP model.

F. Other features

The new version of EcosimPro allows the user to have several simulation cases associated to an experiment. This improves the organisation of the studies or analyses performed and could be useful to adapt the simulation model to experimental or model parametric analysis data.

The user can create experiment directories under each experiment. This makes easier to have multiple experiments associated to an experiment.

Finally, it is important to bear in mind that EcosimPro generates C++ classes, so it would be possible to use this model for predictive control. Closed Environmental Life Support (CELS) systems use this control strategy to regulate the growth of biomass in bioreactors.

VI. Conclusion

EcosimPro is an appropriate simulation tool for the detailed modelling of different areas as biological systems, control, hydraulic, mechanical and thermal areas. This is due to its multidisciplinary character and object-oriented characteristics. It is important to highlight that EcosimPro is an open-source tool, which allows the user to modify existing component models or to create new ones.

EcosimPro 4.6 simplifies the users tasks of modeling and simulation thanks to its new debugging and language capabilities, the new wizards and the new features of the attributes editor and property editor of components.

The tool called Deck allows the users to generate an executable program of their models where the users can encapsulate the information defining the input and output variables available for the final customer of the deck.

In addition the new version of EcosimPro enables the connection of a simulation model to an optimization tool. This new feature may be very useful for the experimental correlation of model parameters.

Acknowledgments

The authors are really grateful to IberEspacio and EA staff for their support in the preparation and review of this paper.

References

- ¹Pin, O., "Using EcosimPro for Thermal and Thermo-Hydraulic Analysis in ESA", *Proceedings of the 31th ICES Conference*, 2001-01-2409
- ²Pérez Vara, R., Mannu, S., Pin, O., and Müller, R., "Overview of European Applications of EcosimPro to ECLSS, CELSS and ATCS", *Proceedings of the 33th ICES Conference*, 03ICES-405
- ³Cobas-Herrero, P., García-Gutiérrez, B., Perez-Vara, R., Avezuela, R., and Gregori, C., "An ESA State-of-the-Art Simulation Tool for Space Applications", *9th International Workshop on Simulation for European Space Programmes, SESP 2006*
- ⁴Müller, R., et al., "Comparing EcosimPro and ESATAN Modelling", *Proceedings of the 32th ICES Conference*, 2002-01-2447
- ⁵Kaya, T., Pérez, R., Gregori, C., and Torres, A., "Numerical simulation of transient operation of loop heat pipes," *Applied Thermal Engineering*, Vol. 28, No 8-9, June 2008, pp. 967-974.
- ⁶Avezuela, R., Funke, H., and Witt, J., "Simulation Model of the Air Revitalization System for ISS," *Proceedings of the 35th ICES Conference*, 2005-01-2860
- ⁷Kaya, T., and Hoang, T. T., "Mathematical Modeling of Loop Heat Pipes," *AIAA*, June 1999, AIAA 99-0477.