Cryogenic Dynamic Modelling and Simulation at CERN

Presented by Enrique Blanco (BE-ICS-AP) on the original presentation made by Benjamin Bradu (TE-CRG-OP)
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  - QRL
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- **Summary**
Introduction...
What is dynamic process simulation?

- **Simulation** = mimic the reality in a computer
  - Need to model your system first!

- **Dynamic** = evolution over time

- Applied on cryogenic **processes**:
  - Macroscopic modelling from a process point of view (0D/1D)
  - Use of an object-oriented modelling approach
    - Active equipment: valves, heaters, turbines, etc.
    - Passive equipment: pipes, HX, phase separators, etc.
  - Simulate all pressures, temperatures, mass flows over a cryogenic installation

≠ CFD simulation (different objectives, different techniques)
Empresarios Agrupados

EcosimPro | PROOSIS, Modelling and Simulation Toolkits and Services

For today’s engineering firm, using simulation tools to improve the design process of new products has become an absolute necessity. Systems simulations allow companies to reduce design and manufacturing costs while shortening development times.

The simulation toolkits developed by EA Internacional over the last 20 years have aided many companies in this respect. Check out our products webpage and see if there is a toolkit there that meets the specific needs of your firm. Our products have been tested in complex projects in the fields of space, aeronautics and power, water and process sectors since 1990. They are currently the simulation toolkits of choice in many disciplines at organisations such as the European Space Agency (ESA).

EcosimPro/PROOSIS models are being used for:

- Digital Twins of process plants, aircraft engines, rockets, etc.
- Engineering for design of products
- Health Monitoring
- Optimisation
- Virtual Commissioning
- Hardware-in-the-loop
- etc

EA Internacional can provide a full range of consulting services to your firm, including training courses adapted to your company's needs and support for modelling your systems. We invite you to visit some of the industrial cases developed using our toolkits in recent years.

More Info ➤

PROOSIS

PROOSIS is a state-of-the-art tool for 1D modelling of aeronautical gas turbines based on EcosimPro. It provides additional capabilities for representing and designing new propulsion systems.

More Info ➤
EcosimPro (Libraries)
EcosimPro (Graphical design)
EcosimPro (Interfaces)
EcosimPro (Libraries)

https://www.ecosimpro.com/products/

1. **Power Plant Transient Simulation Toolkit (PPTS)**
   - PPTS (Power Plant Transient Simulation), currently an EA International in-house toolkit, provides modeling components to represent the dynamics of typical hardware and controls of a power plant.
   - More Info

2. **Solar-Thermal Power Plant Simulation (ST_PPTS)**
   - ST_PPTS (Solar Thermal Power Plant Transient Simulation), currently an EA International in-house toolkit, allows the dynamic simulation of the plant operation modes of parabolic through power plants with optional thermal energy storage and fossil fired backup systems.
   - More Info

3. **Power Plant Thermal Balance Simulation Toolkit (THERMAL_BALANCE)**
   - THERMAL_BALANCE toolkit is used to carry out steady state thermal balance studies in typical power generating plants (Coal, Combined Cycle, Nuclear, Thermosolar, etc.). It also enables performing studies with slow dynamics where model boundary conditions change with time.
   - More Info

4. **Gas Turbine Engine Simulations For Power Generation Applications (GTE_TURBOSHAFT)**
   - The GTE_TURBOSHAFT is a toolkit for simulating gas turbine turboshaft engine configurations typically used in industrial applications (e.g. for power generation or mechanical drive) and for marine vessel propulsion. The user can perform both design point and off design calculations as well as to study transients and perform advanced calculations for the control and monitoring of the engine.
   - More Info

5. **Dynamic Fluid Networks Simulation Toolkit (FLUIDAPRO)**
   - FLUIDAPRO is a toolkit to model and simulate complex dynamic fluid networks (gas, liquid and two phase flow regimes for ideal or real fluids), coupled to heat transfer effects and control loops.
   - More Info

6. **Thermo-Hydraulic Transient Simulation Toolkit (PIPELIQTRAN)**
   - PIPELIQTRAN is a toolkit to model and simulate complex dynamic fluid networks (gas, liquid and two phase flow regimes for ideal or real fluids), coupled to heat transfer effects and control loops.
   - More Info
Why using it for cryogenics?

- **Train operators / Design Engineering**
  - Safe training with no risk on the process
  - Simulate failure scenarios (e.g. turbine or compressor trips)
  - Simulate occasional events (e.g. cooldown phases)

- **Validate new control strategies**
  - No disturbance on the process
  - Fair comparison between strategies
  - Time saving

- **Perform virtual commissioning**
  - Debug safely the control programs
  - Fast validation of complex starting/stopping sequences
  - Commissioning control systems offline
  - Reduce commissioning time with the real plant
How does it work?

Model each cryo component individually + fluid properties

Build your complete model by assembling elementary components + Parametrize each component with your specifications (pipe diameter, valve size, etc.)

Include basic control in model OR: couple it to real control system

Define boundary conditions over time

Simulate
The CERN approach...
What do we do at CERN?

- Modelling and simulation software
  - EcosimPro (Empresarios Agrupados)

- Cryogenic Library
  - CRYOLIB (see next slide)

- Coupling with control system
  - Stand Alone simulation in EcosimPro with simplified control
  - PROCOS: Process and Control system coupling
CRYOLIB

- **CRYOLIB**: a commercial library for modelling and simulation of cryogenic processes with EcosimPro.

- **History**
  - **2001**: CRYO_HE: First modelling of cryogenic helium components with EcosimPro (CERN).
  - **2007→2009**: CRYO_CERN: Development of a full helium cryogenic library and simulation of main CERN cryogenic plants (CERN).
  - **2011**: CRYOLIB v1: Commercialization of a cryogenic library based on CRYO_CERN using all fluids and including reverse flow (Knowledge Transfer from CERN to Empresarios Agrupados).
  - **2017**: CRYOLIB v2: Improvement of speed computation and many bug resolutions (Empresarios Agrupados).
Variational approach

- Some parameters are difficult to find in large cryogenic systems
  - Geometrical parameters (length, pipe shape, HX parameters, etc.)
  - Thermal parameters (insulation)
  - “Secret” parameters (turbines)

- Generally, manufacturers guarantee a nominal operation point:
  - Static calculations performed by manufacturers

- If $X$ depends on an unknown constant $K_1$: $X = K_1 \cdot f(P,T)$,

- Known design point: $X_d = K_1 \cdot f(P_d,T_d)$.

- Ratio between both: $X = X_d \cdot \frac{f(P,T)}{f(P_d,T_d)}$.

- Non-linearity of ‘$f(P,T)$’ is kept and unknown constants are removed
PROCOS: PROcess and COntrol Simulator

- **Data Server**: SCADA (PVSS)
- **Supervision Layer**
  - SCADA
  - PLC
  - Siemens PLC
  - Unity (PLC simulator)
  - Simatic WinLC (PLC simulator)
  - OPC client

- **Control Layer**
  - PLC (Field bus)
  - Technical network Ethernet / MOD or S7

- **Field Layer**
  - Real process
  - I/O (OPC)
  - I/O (Field bus)

- **C++ application**
  - C++ class EcosimPro model
  - EcosimPro algorithm

- **Process model (EcosimPro)**

- **Cryogenic Process Simulator (CPS)**
Applications to CERN cryogenic systems…
CMS refrigerator

- CMS cryoplant
  - Cooldown CMS magnet (225 tons)
  - Air Liquide – 1.5 kW @ 4.5 K
  - 3310 Algebraic equations
  - 244 Differential equations
  - Simulation speed during cool-down: x15

- Validation of a complete system
- Simulation architecture validation
CERN Central liquefier (TCF50)

- CERN central helium liquefier (B165)
  - Provide liquid helium for small CERN experiments
  - Commercial Linde TCF 50 – 70 Lhe / hour
  - 2060 Algebraic equations
  - 170 Differential equations
  - Simulation speed during cool-down : x20

- VIRTUAL COMISSIONING
  - Test and improve PLC code
  - Bad calibration of sensors
  - PLC-coding errors
  - Sequence errors (timers, thresh
  - New turbine starting sequence
  - PI tuning
LHC 4.5 K helium refrigerator

- 4.5 K LHC refrigerator
  - Linde 18 kW @ 4.5 K
  - 6100 Algebraic equations
  - 500 Differential Equations
  - Simulation speed: x3

- Operator training tool
- Improvement of controls using simulation
  - High Pressure control optimization
LHC 4.5 K helium refrigerator

Temperature after last Heat Exchanger

Cool-down cold-box alone

Heater in the phase separator

Cool-down cold-box alone

Total massflow (g/s)

Cool-down cold-box alone

TS diagram reached with LHC (16 kW @ 4.5 K)
LHC 1.8 K refrigeration unit

- 1.8 K refrigeration unit
  - Air-Liquide 2.1 kW @ 1.8 K
  - 3500 Algebraic equations
  - 320 Differential equations
  - Simulation speed during pumping: x80

- Operator training tool
- Improvement of controls using simulation
  - New Cold-Compressor speed management
LHC 1.8K refrigeration unit

Final pumping of LHC sector 5-6 between 100 mbar and 16 mbar
LHC Cryogenic Distribution Line

- Modelling of the Very Low Pressure Line (line B) used to pump helium baths at 1.8 K
  - Modeling based on 1D Euler equations (3 PDE)

- Dynamic simulation of the helium flow along the 3.3 km line after a quench

- Simulation of the “heat wave” induced by a quench in the return pumping line
  - Comparison with a quench in the LHC sector 5-6 during hardware commissioning (May 2008)

\[
\frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \frac{M}{E} \end{bmatrix} + \nabla \cdot \left[ \begin{bmatrix} \rho \cdot \mathbf{V} \\ \rho \cdot \mathbf{V} \times \mathbf{V} + \mathbf{P} \cdot \mathbf{I} \end{bmatrix} \right] = \begin{bmatrix} 0 \\ 0 \end{bmatrix}
\]

107 mètres après le quench
LHC Beam Screens

- LHC beam screens
  - Minimize heat loads, remove resistive wall power losses and intercept synchrotron radiation/molecules
  - Supercritical helium flow at 3 bar from 4.6K to 20K
  - 2 cooling tubes of 53m long / 3.7mm diameter

- Modeling based on 1D Euler equations (3 PDE)

- Control improvements using simulation for beam induced heat loads (Feed-Forward)
Cryo Simulation Lab (Operator training platform)

- Linde 4.5 K refrigerator for LHC (18 kW@4.5 K)
- Air-Liquide 1.8 K refrigeration unit for LHC (2.4 kW@1.8 K)
- 18,000 Algebraic equations
- 1,240 Differential Equations
- Simulation speed: ~ x5

Simplified model of 1 LHC sector (3.3 km)
Summary

- Dynamic simulations are really helpful along projects

- **During the design phase**
  - Validation of dynamic behaviour
  - Setup of control schemes

- **During the commissioning phase**
  - Virtual commissioning
  - Tuning of control loops

- **During the operation phase**
  - Operator training
  - Control improvements
  - Cryoplant optimization
References


