

The ThermoPower Library

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Power Plant Dynamic Modelling at DEI - Polimi

1985-1993

- LEGO simulation environment (developed by ENEL)
 - Modular modelling, solver for index-1 DAE's, models implemented in FORTRAN
 - Wide availability of tested models, very low flexibility and extensibility, extremely old-fashion development environment (native FORTRAN code)

1993-2003

- ProcSim simulation environment (Maffezzoni, Leva, Bartolini)
 - Modular modelling, specialized implicit Euler solver for thermo-hydraulic system equations, models implemented using LabVIEW
 - Very good run-time user interface, good availability of models, efficient, low flexibility and extensibility

2003-

- ThermoPower library, using Modelica (Casella, Leva)
 - Object-Oriented paradigm, using the Modelica language
 - Maximum flexibility and extensibility, growing model base, highly readable models

Scope of the Library

Support for the generation of power plant models:

- Modularity
- Dynamic models
- Degree of detail suited to *system* studies (not for *component* studies)
 - Non-linear, first-principles models
 - Lumped-parameter models
 - 1D Distributed parameter models
 - NO 3D CFD models

Usage

- Dynamic plant simulation
- Computer-aided design of control strategies and controller architectures
- Validation and tuning of control systems
- Simulation study of large plant maneuvers (e.g. start-up)
- Plant maneuver optimization

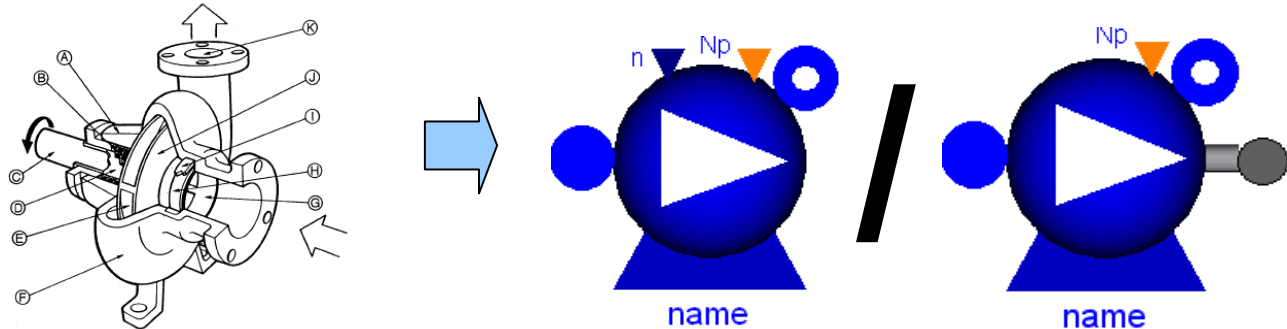
Type of plants:

- Traditional fossil-fired Rankine cycle
- Gas Turbine plants
- Combined cycles
- Combined heat&power plants
- Nuclear plants (gen III & IV)
- Organic Rankine Cycle plants
- Solar plants

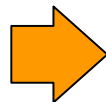
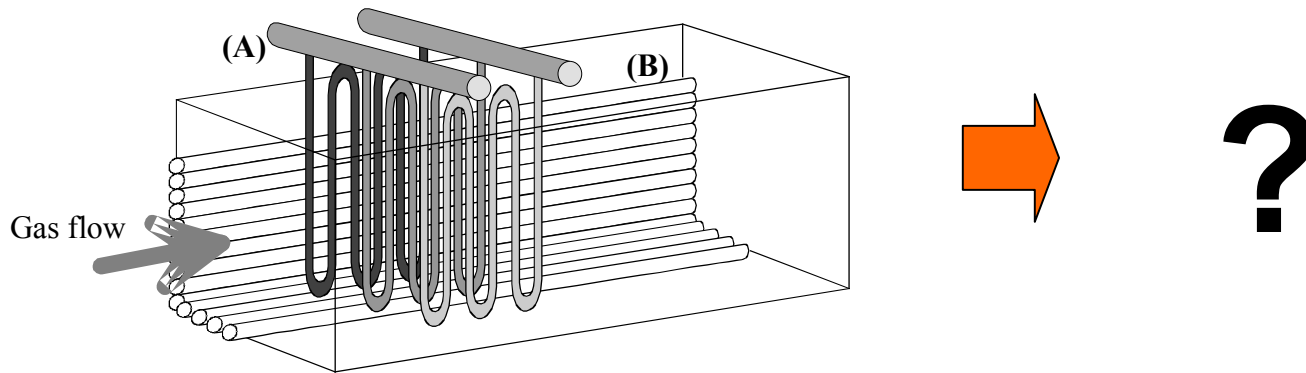
Issues with Object-Oriented Modelling of Power Plants

ISSUE #1: Abstract model structure

- Some components have clearly defined interfaces (flanges, shafts, etc.)



- Other components have a far less obvious structure

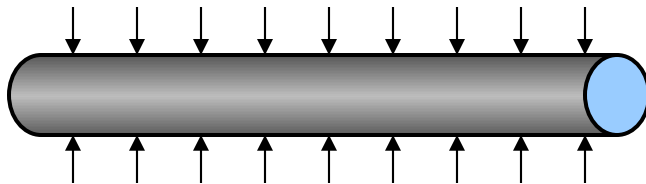


The basic models must allow to describe complex heat transfer configurations

Issues with Object-Oriented Modelling of Power Plants

ISSUE #2: Many completely different models to describe the same physical object

Liquid-filled pipe, with heat transfer through the lateral boundary



- One-phase vs. Two-phase
- Nature of the fluid
- Radial velocity distributions
- Compressibility and inertial effects
- Pressure wave propagation
- Discretization method for the PDE
- Etc. etc. ...
-



It is hard to define standard o basic thermo-hydraulic models for general-purpose use

Structure of the Library – I

Problems with extensive use of inheritance

- Difficult to define a hierarchy of heterogeneous models
- Modifying the “ancestor” equations can lead to hard-to-understand consequences on the “siblings”
- The equations of a single model are scattered through many classes, thus hampering:
 - readability
 - modifiability / extensibility

Judicious use of inheritance

- Flat library structure
- Inheritance is used to:
 - change the fluid property model
 - define families of very similar components (e.g. pumps, valves)
 - add advanced features to already functional components

Modelling assumptions are selected through conditional equations, depending on boolean/integer parameters \Rightarrow low number of models with many options, e.g:

- Options for the computation of the friction losses
- Dynamic term in the momentum balance equation
- Geometric characteristics
- Type of initialization
- ...

Structure of the Library – II

Type of fluids

- Water / steam for the steam side of the generation processes (fluids other than water may be used)
- Ideal gases (air, natural gases, flue gases etc.)

Models of the same component (e.g. a valve) with different fluids

- Choice 1: independent models
- Choice 2: generic model + extensions with fluid-specific equations
- Problem: changing the fluid, the modelling assumptions can vary drastically
- The reuse of part of the equations actually make things more confusing

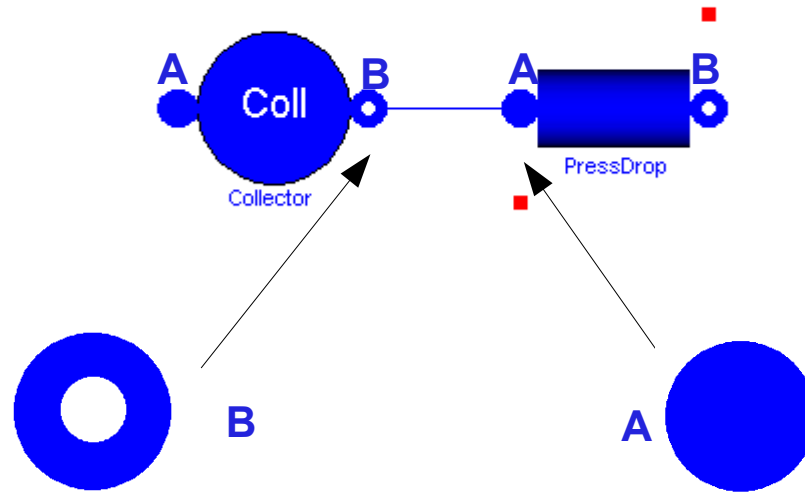


 Two separate categories of models: water/steam and ideal gases

 Within each family, the fluid model is replaceable

Old Design of Flange Connectors (ver. 2.x)

- Thermodynamic conditions are specified with a minimum number of non-redundant variables (Pressure, mass flow rate, specific enthalpy).
- Maximum independence from how the internal equations of each component are written (encapsulation).
- Support of reverse flow



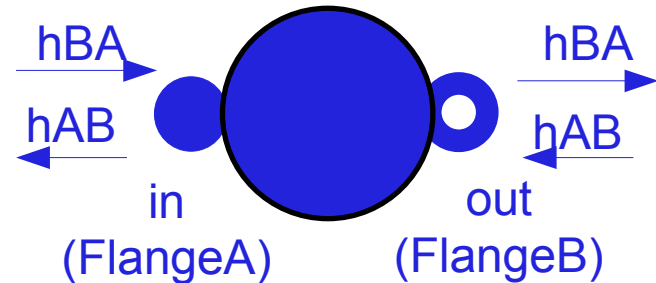
```
connector WaterFlangeB
  Pressure p;
  flow MassFlowRate w;
  output SpecificEnthalpy hBA;
  input SpecificEnthalpy hAB;
end WaterFlangeB
```

```
connector WaterFlangeA
  Pressure p;
  flow MassFlowRate w;
  input SpecificEnthalpy hBA;
  output SpecificEnthalpy hAB;
end WaterFlangeA
```


Using Flange Connectors: a Simple Example

```
model SimpleMixer
  parameter Volume V=0 "Inner volume";
  FlangeA in;
  FlangeB out;
  Pressure p;
  Density rho;
  Mass M;
  Energy E;
  SpecificEnthalpy h,hi,ho;

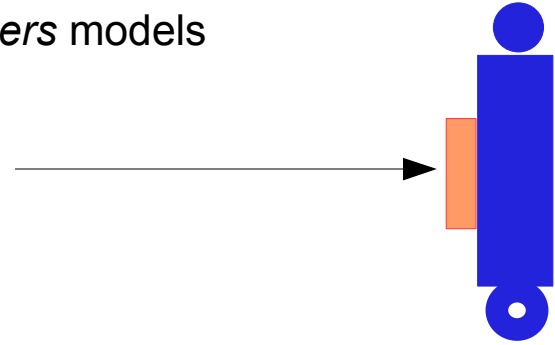
  equation
    rho = rho_ph(p, h);
    M = V*rho;
    E = M*h - p*V;
    der(M) = in.w+out.w;
    der(E) = in.w*hi+out.w*ho;
    hi = if in.w >= 0 then in.hBA else h;
    ho = if out.w >= 0 then out.hAB else h;
    in.hAB = h;
    out.hBA = h;
    in.p = p;
    out.p = p;
end SimpleMixer;
```



DHT Connectors (Distributed Heat Transfer)

Describe the heat transfer between *distributed parameters* models

```
connector DHT;  
  parameter Integer N=2 "Number of nodes";  
  Temperature T[N];  
  flow HeatFlux phi[N];  
end DHT;
```



Extended DHT connector with heat transfer coefficient
(computed internally based on the fluid conditions)

```
connector DHThtc;  
  extend DHT;  
  CoefficientOfHeatTransfer gamma[N];  
end DHThtc;
```

Computing the Fluid Properties: Modelica.Media

The fluid properties are computed using the models contained in the standard Modelica.Media library. The fluid property models and computational routines are contained in *replaceable packages*.

Usage example::

```
model Mixer
  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium;
  Medium.BaseProperties fluid;
  ...
equation
  // The fluid properties are determined prescribing two thermodynamic
  // variables + the composition (for multiple-component fluids)
  // pressione, temperatura e composizione
  fluid.p = p;
  fluid.T = T;
  fluid.Xi = Xi;

  // all other base properties (u,d,T) are automatically computed by
  // the fluid model
  h = fluid.h;
  d = fluid.d;

  // it is also possible to compute additional fluid properties, using
  // the thermodynamic state vector contained in the fluid model
  lambda = Medium.thermalConductivity(fluid.state);
  ...
end Mixer;
```

Computing the Fluid Properties: Modelica.Media

- The models are written for a generic fluid (PartialMedium, or PartialTwoPhaseMedium);
- When models are instantiated, it is possible to redeclare the medium package to specify the required fluid model (which *extends* PartialMedium or PartialTwoPhaseMedium)

```
model Plant
  Mixer M1(redeclare package Medium = Modelica.Media.Air.MoistAir);
  Mixer M2(redeclare package Medium = Modelica.Media.IdealGases.FlueGas);
  ...
end Plant;
```

- La standard Modelica.Media library contains several ready-to-use models
 - IAPWS IF97 water/steam properties
 - Accurate Ideal gas models (based on NASA data)
 - Humid air
 - Incompressible fluids, with table-based properties
 - ...
- It is possible to develop new fluid models in Modelica (using the interfaces defined in Modelica.Media.Interfaces)
- It is also possible to use FluidProp models, through the ExternalMedia interface.

Features of ThermoPower ver. 3

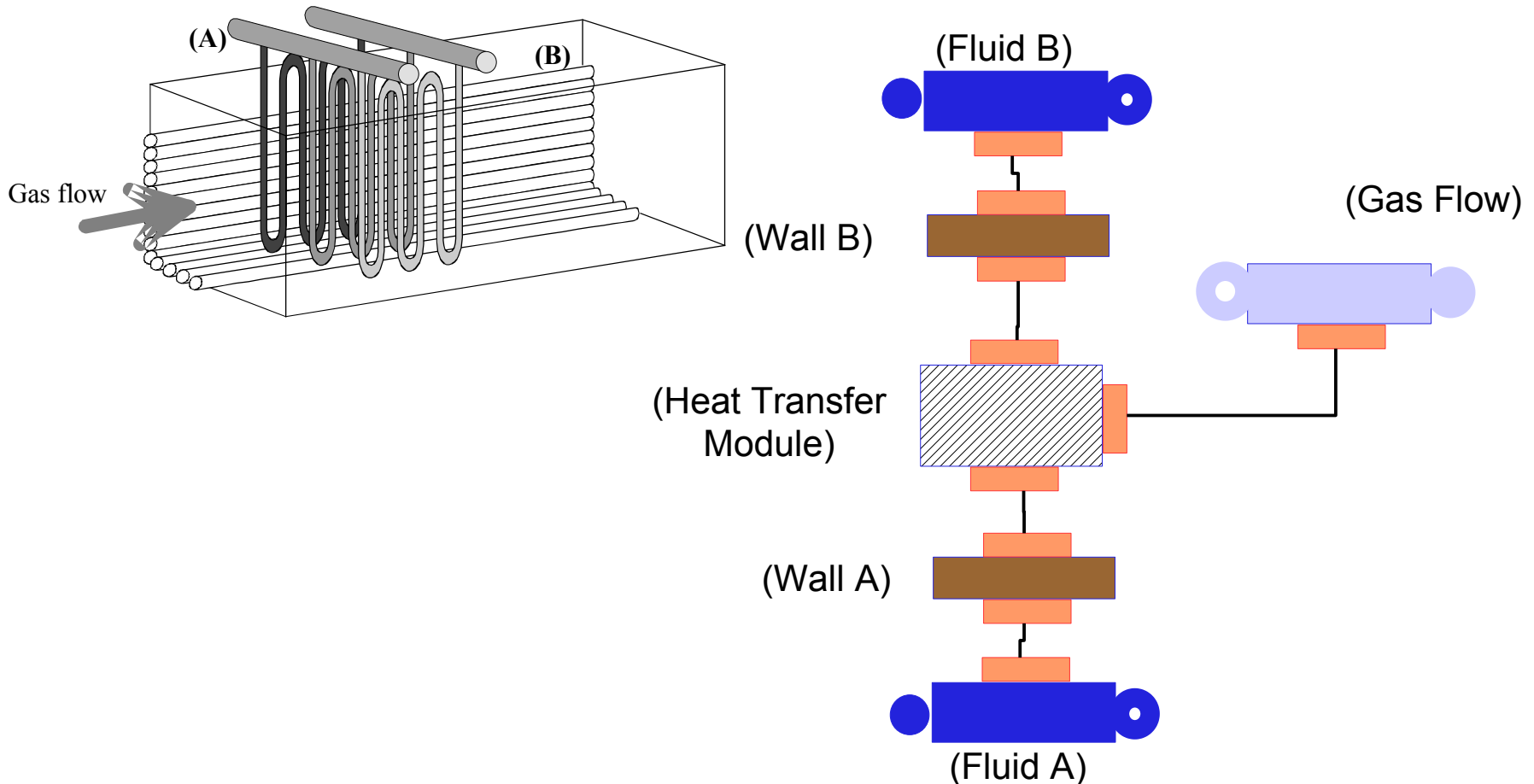
- Uses Modelica Standard Library 3.x
- Standard Modelica.Fluid connectors are now used
 - same mathematical structure
 - no more complementary ports
 - compatible with Modelica.Fluid components
- Homotopy operator used for more robust initialization
 - requires homotopy() support
 - if not available, dummy homotopy() function must be loaded
- Not yet released officially (later this year)
- Development version available on SVN (anonymous read-only checkout):

<https://thermopower.svn.sourceforge.net/svnroot/thermopower/trunk>

Complex Heat Transfer Configurations

Complex configurations like the one shown here can be modelled.

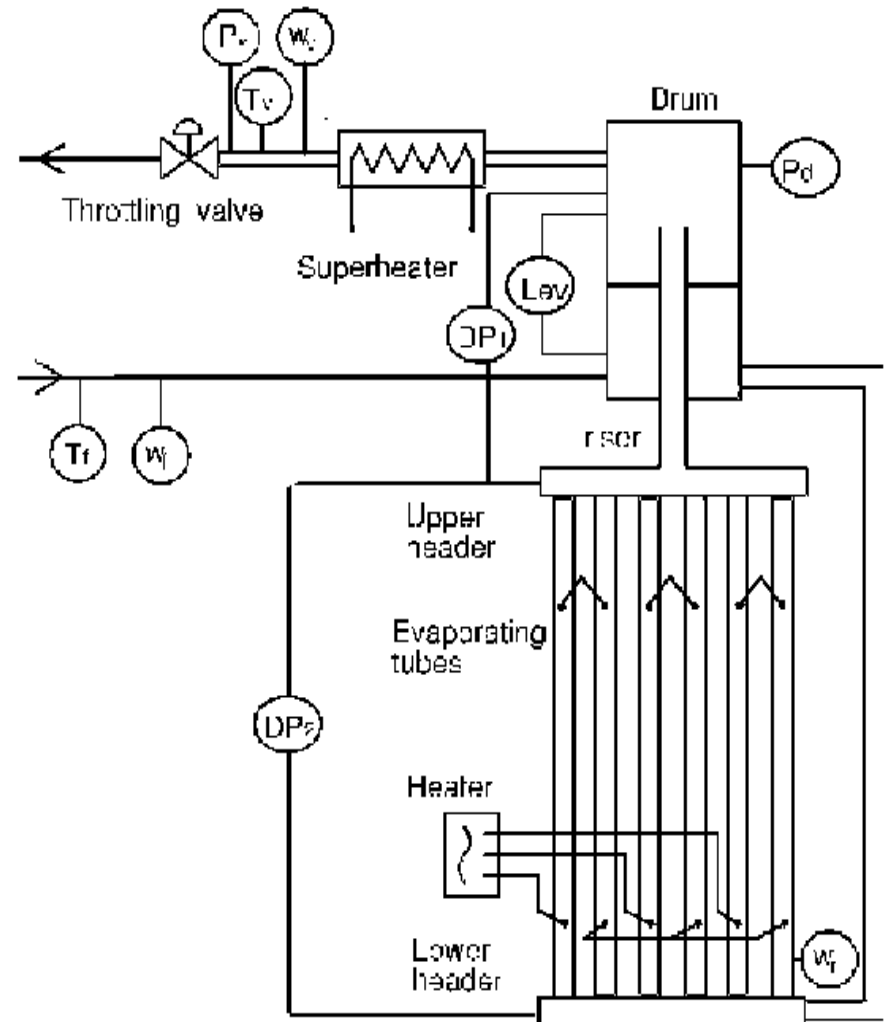
The modeller must write specific code for the heat transfer module. The wall models and the Flow1D models are taken straight from the library



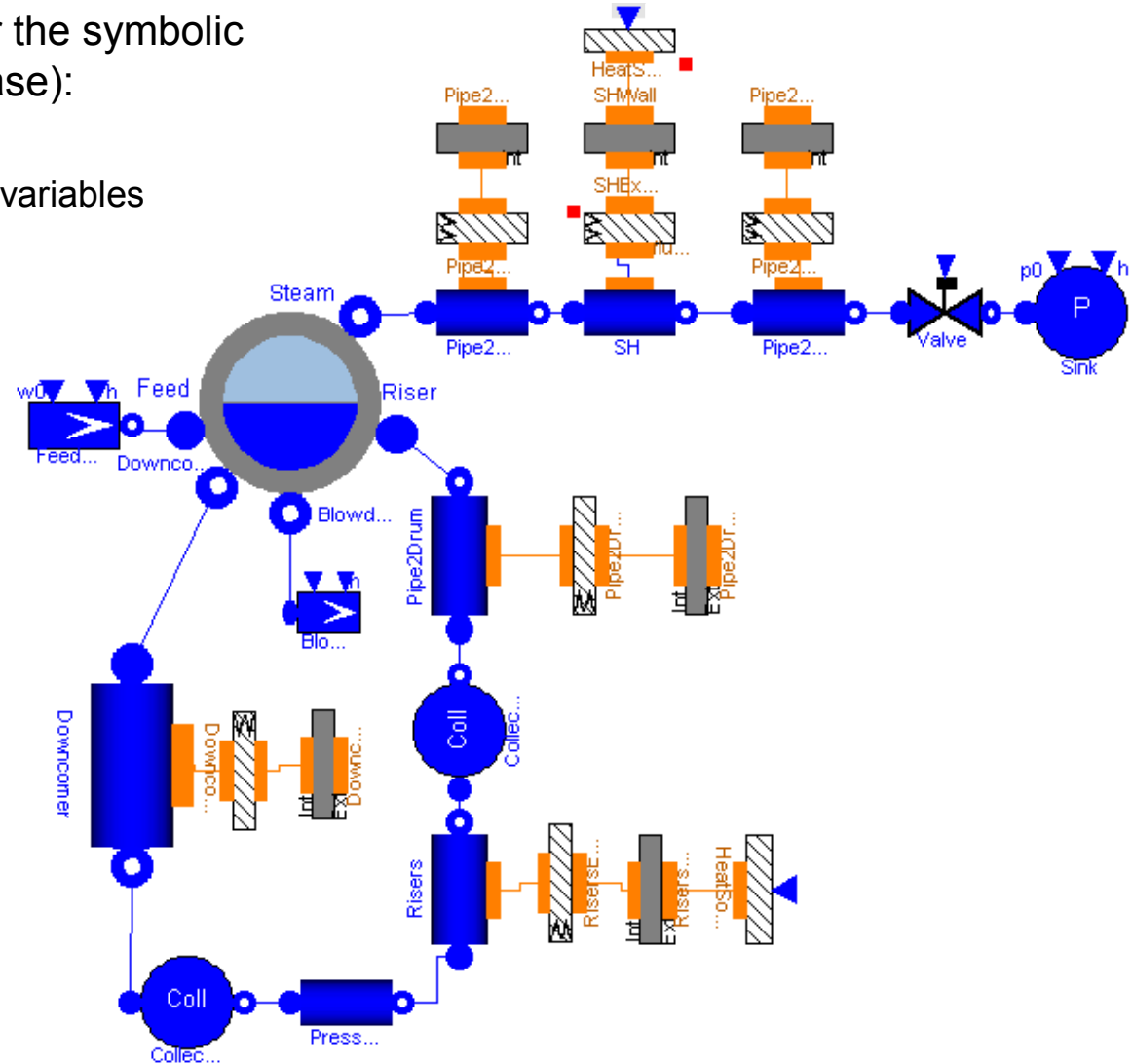
Applications of the ThermoPower library

CISE

- First real-life application
- Simulation of a lab model of a steam generator (100 kW, electrically powered)
- Available data:
 - Dimensional data
 - Open-loop transient recordings
- Medium complexity, in terms of number of components
- Maximum achievable degree of detail of the single components

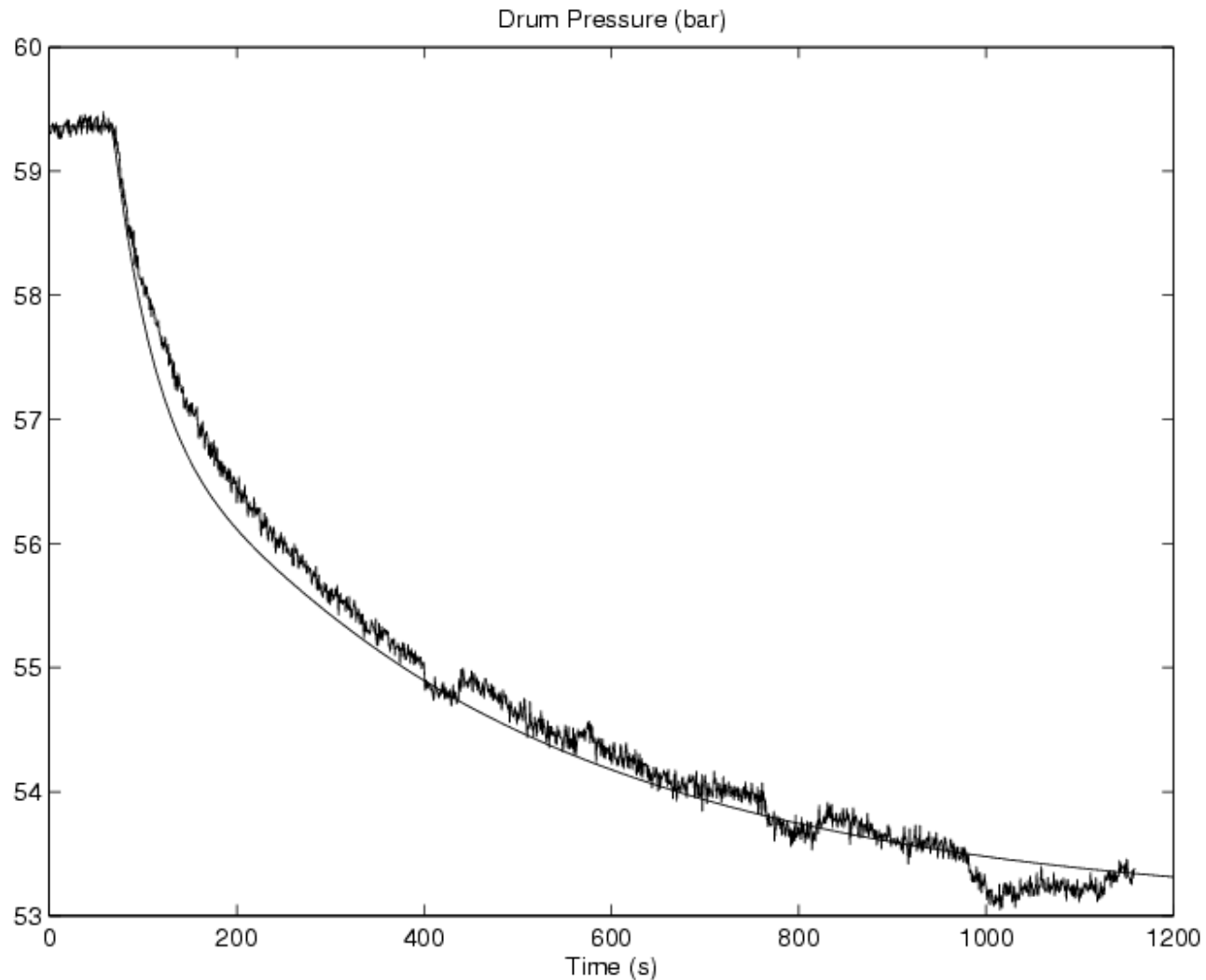


- Model diagram
- Complexity (after the symbolic manipulation phase):
 - 50 states
 - 300 algebraic variables



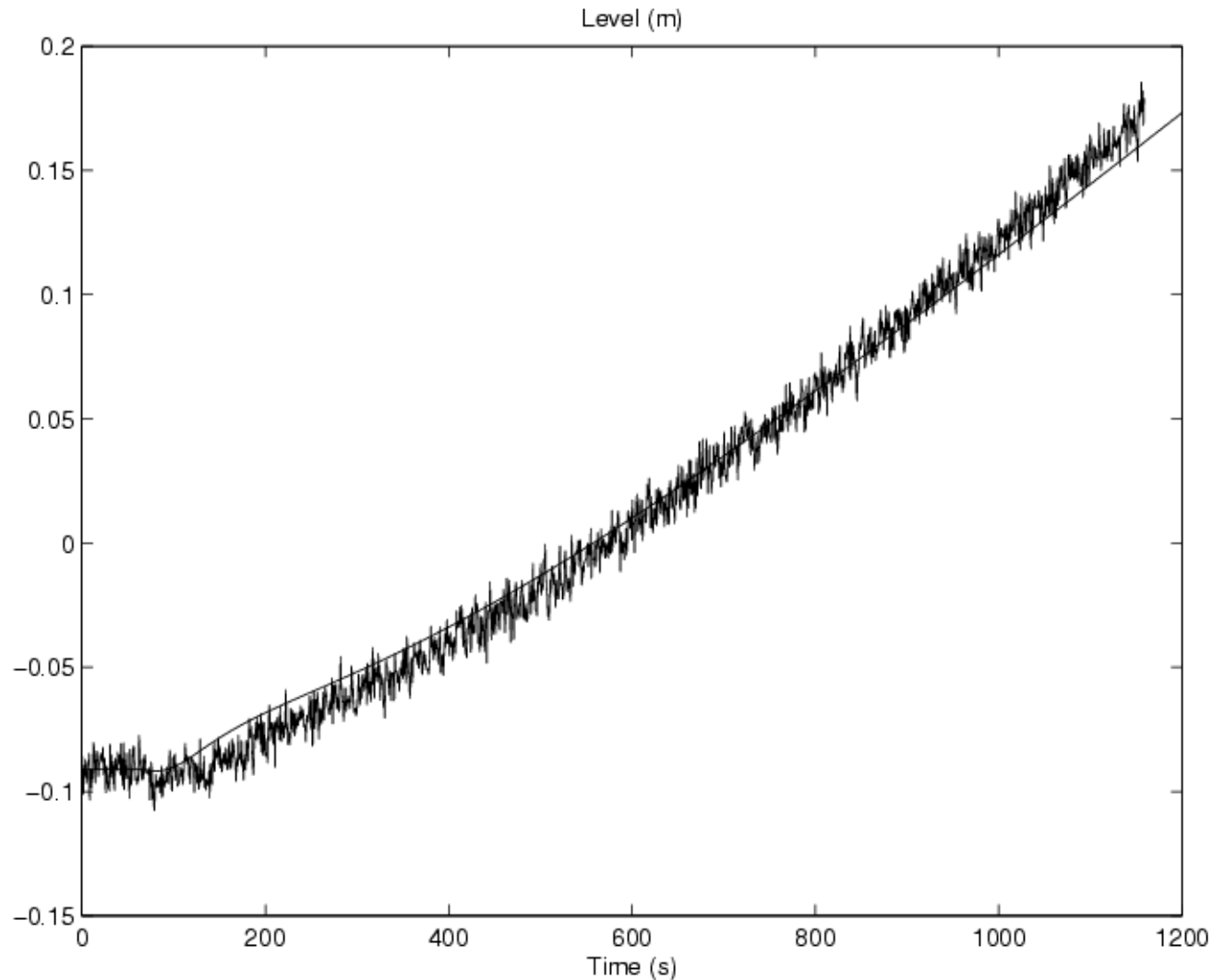
CISE - Validation

- Pressure: 60 bar
- Step reduction of the power to the evaporators



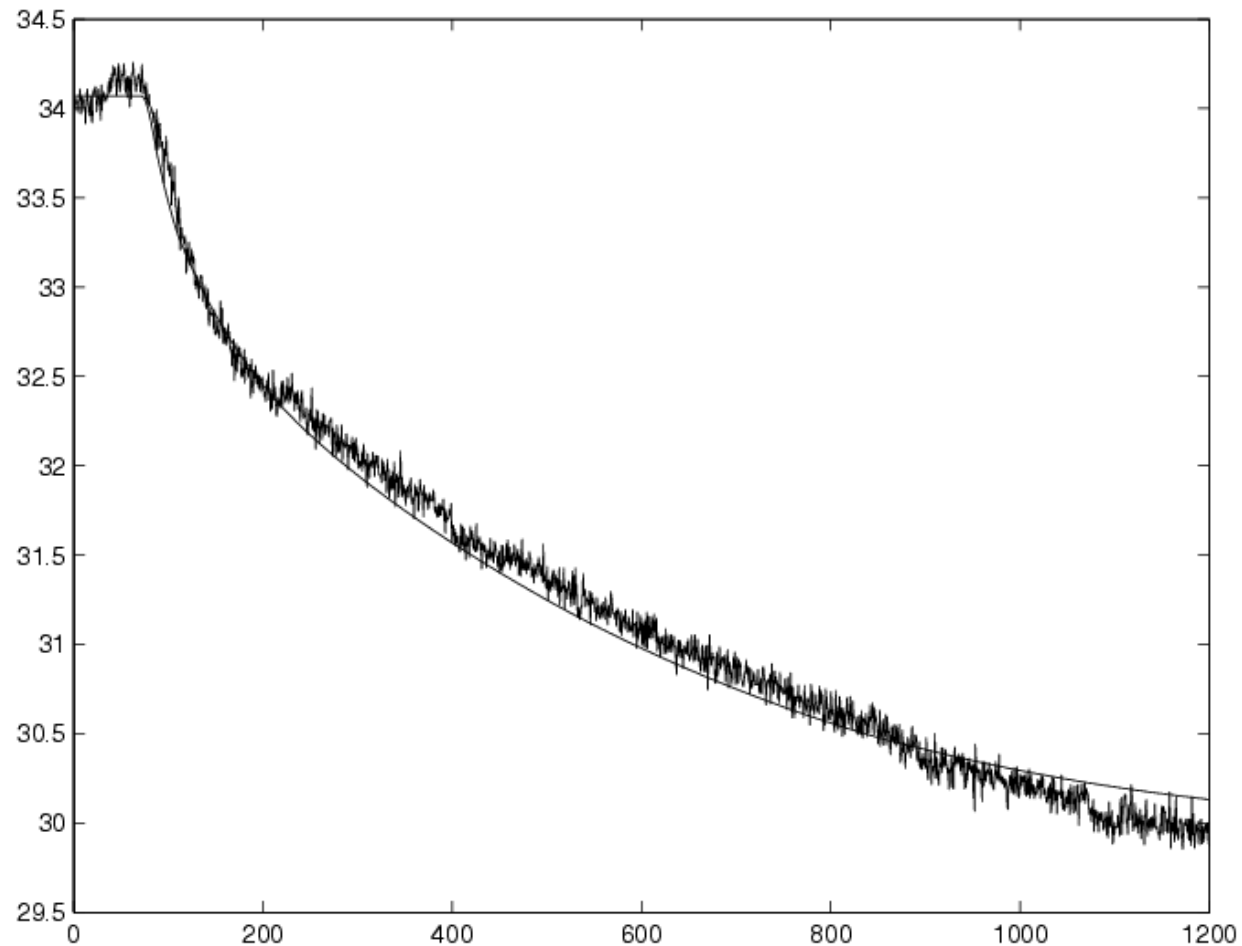
CISE - Validazione

- Pressure: 60 bar
- Step reduction of the power to the evaporators



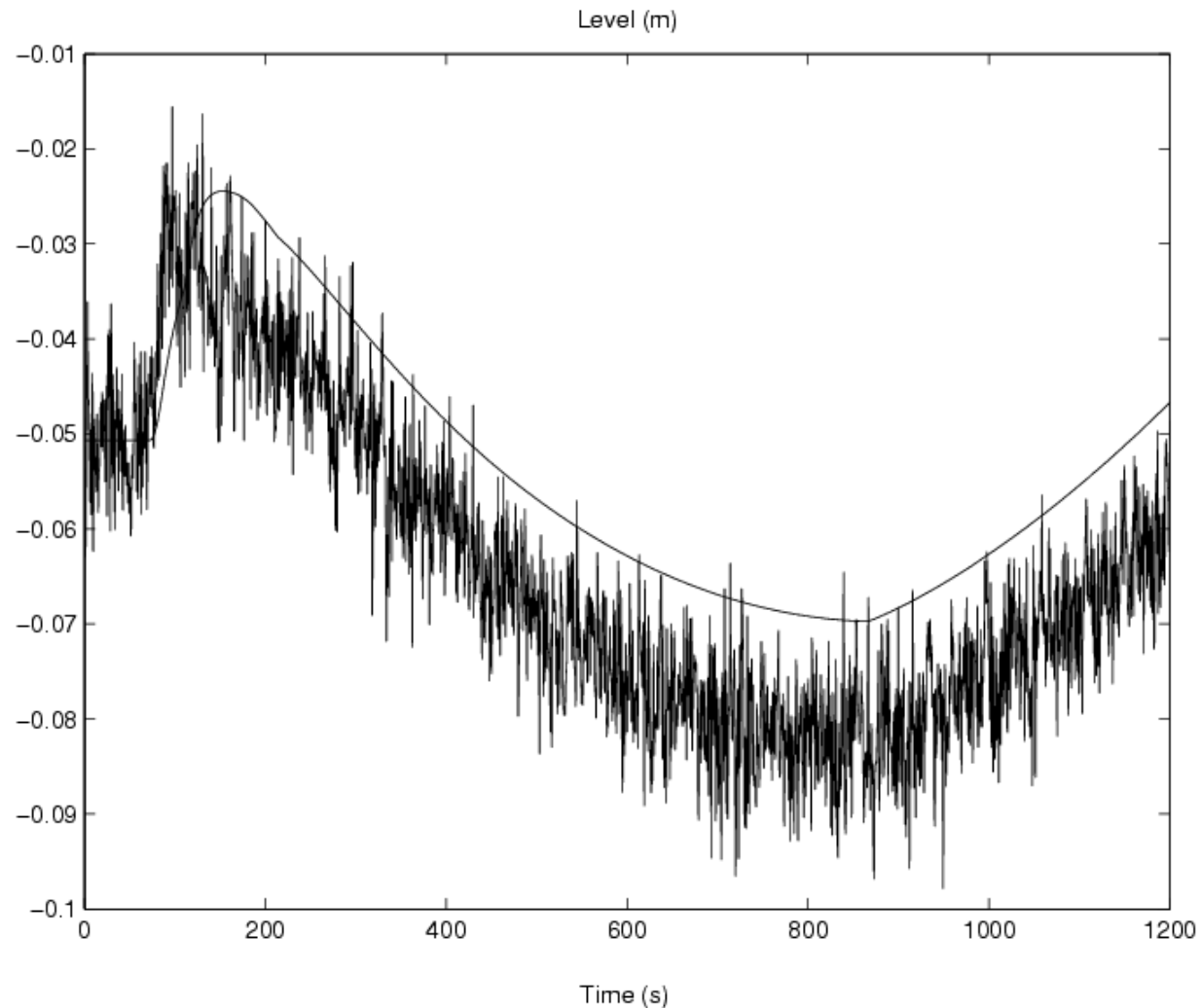
CISE - Validazione

- Pressure: 30 bar
- Step increase in the steam valve opening



CISE - Validazione

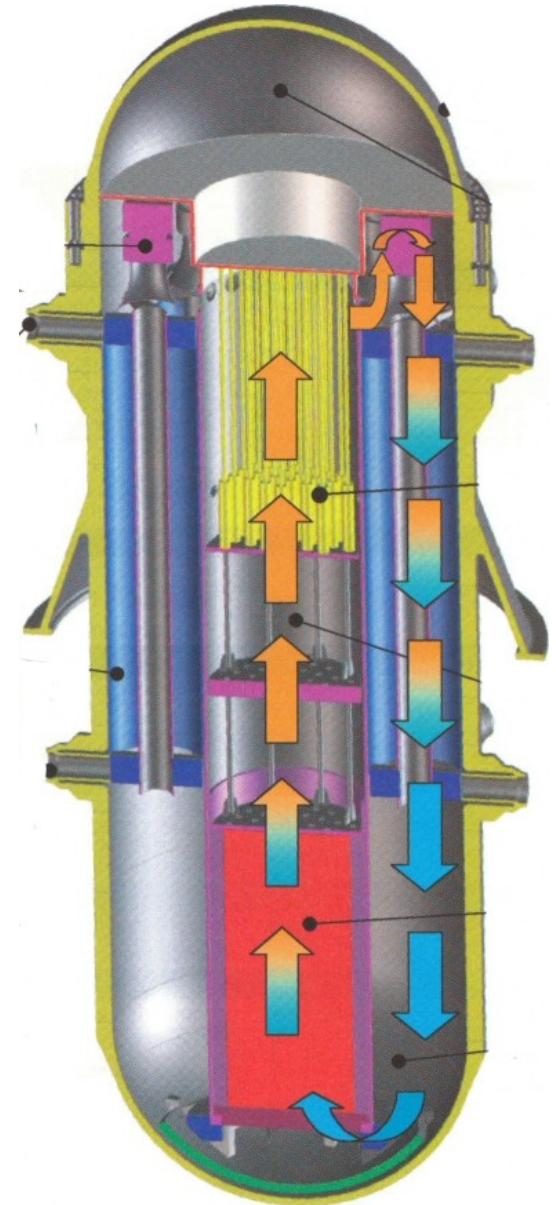
- Pressure: 60 bar
- Step increase in the steam valve opening



IRIS

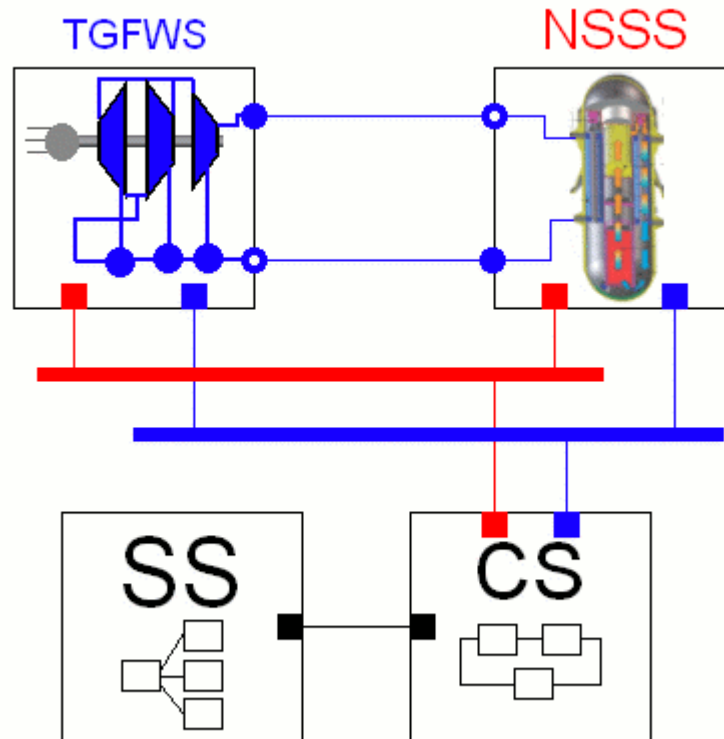
IRIS

- First industrial application: IRIS consortium (PoliMi + Westinghouse + others)
- Study of the control system for a new generation PWR nuclear plant
- “Lightweight” models needed to support the control design activities
- Integration of the ThermoPower and NuKomp libraries for the modelling of the nuclear core (Fourier equations for the fuel rods + point neutronic kinetics)
- Set up of a *family* of consistent plant models
 - Accurate reference model, to be compared with detailed simulation code results (RELAP)
 - More/less detailed control system models
 - More/less detailed turbine + feedwater train models
 - More/less detailed models of the steam generator
 - Modelli for very fast simulations



IRIS

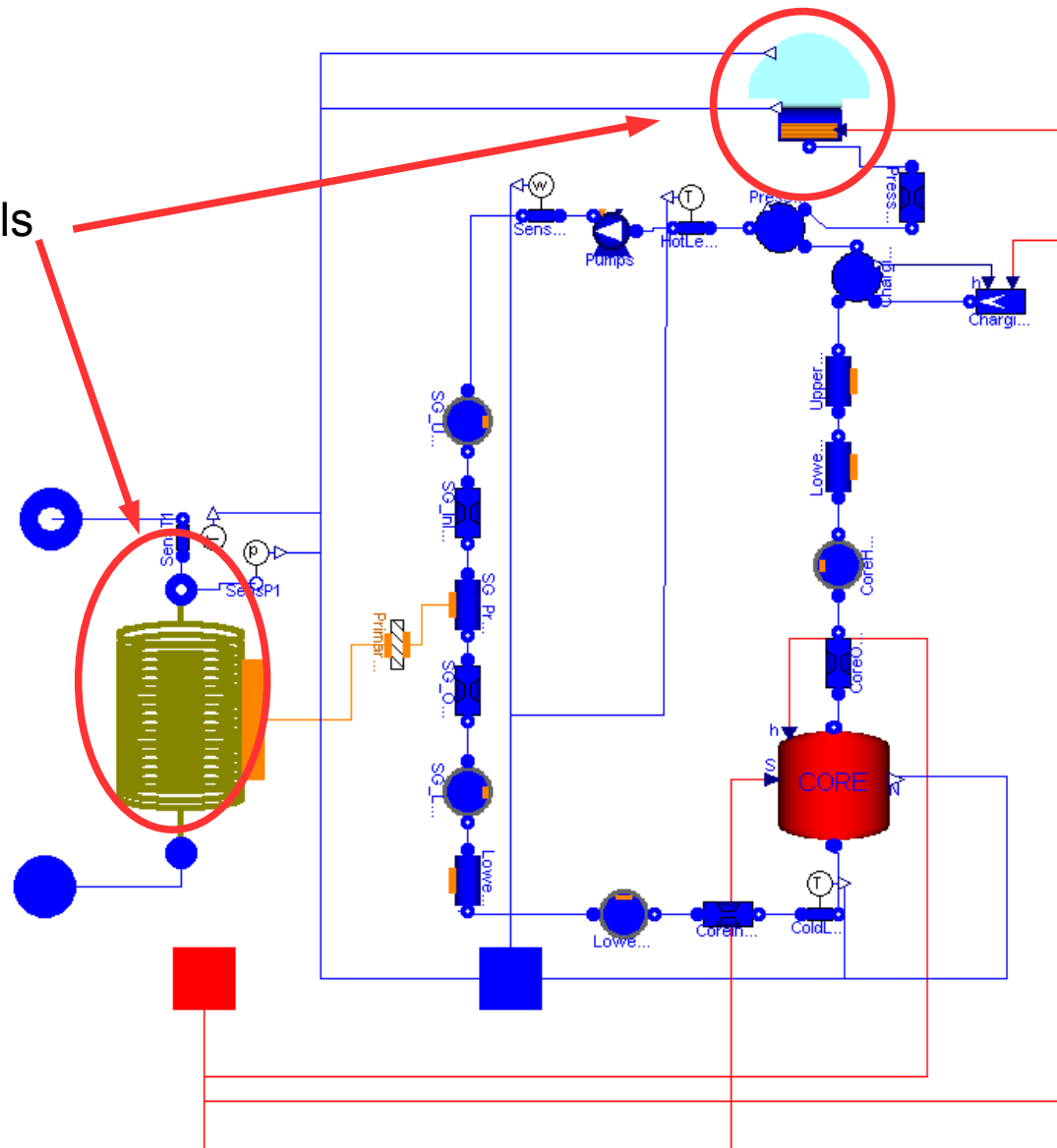
- Base model: four empty units (partial models) connected together.
- Actual simulators are obtained by instantiating the base model and replacing the units with one of their available implementations



IRIS

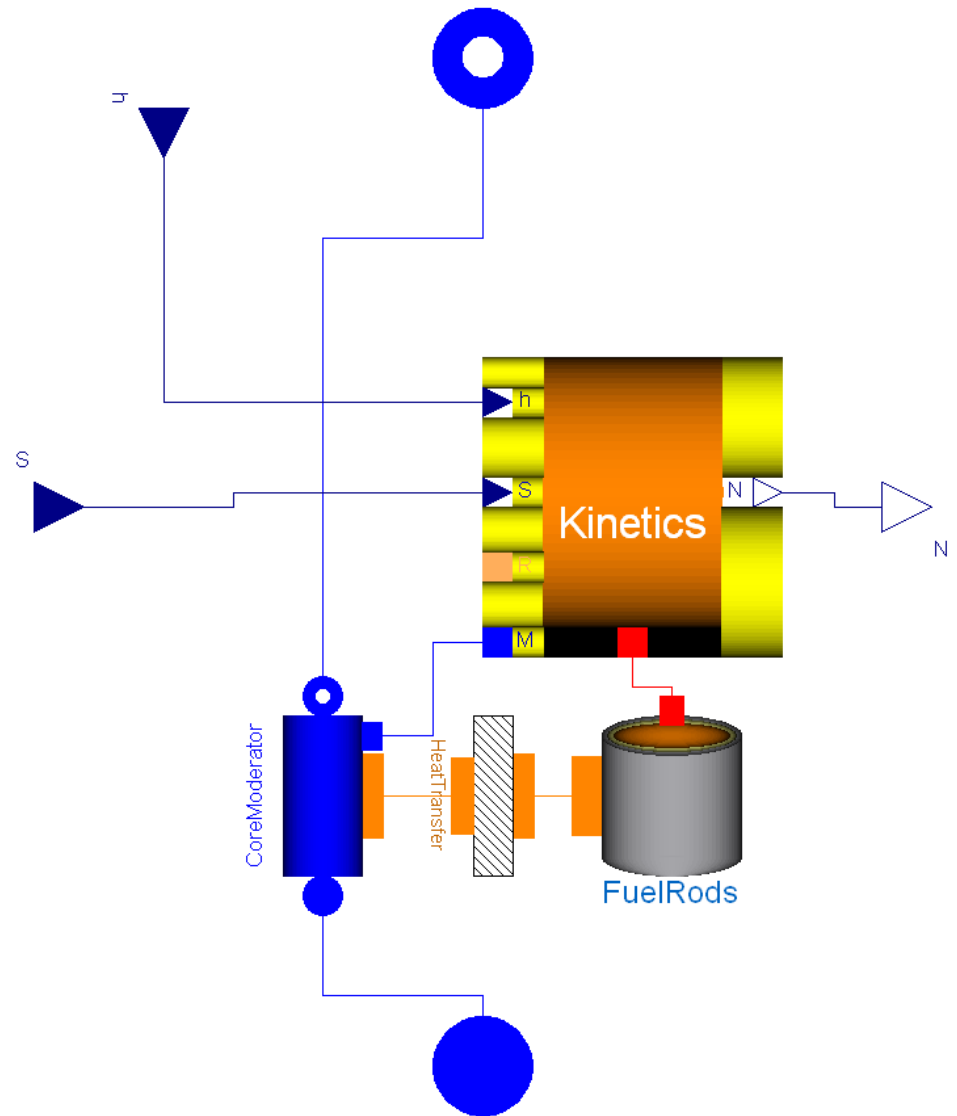
- NSSS diagram

Replaceable models



Core diagram:

Integration of ThermoPower and
NuKomp components



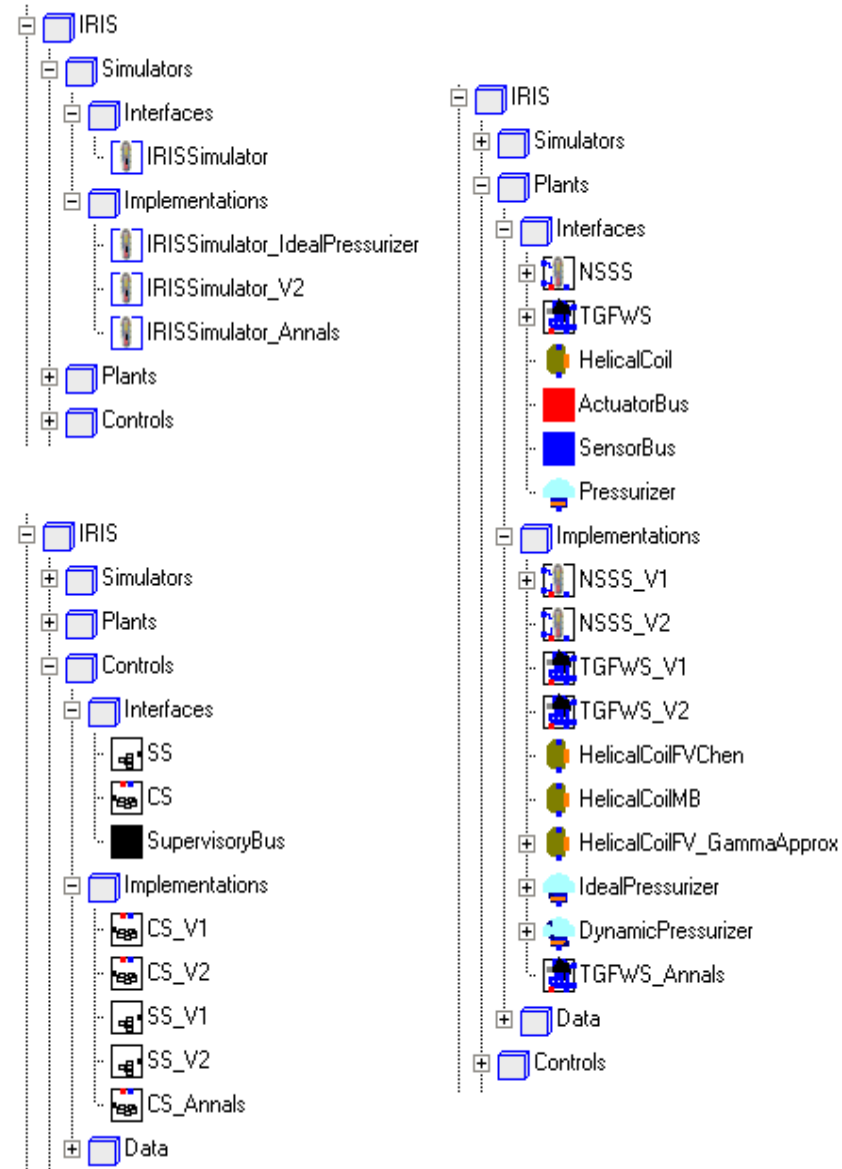
IRIS

- “Library of simulators”
 - Interface (empty shell with connectors) for each unit
 - Many implementation for each unit
 - Common repository of geometric and design data
 - Replaceable fluid models
- Instantiation of a specific simulator
 - *A' la carte* choice of details

```

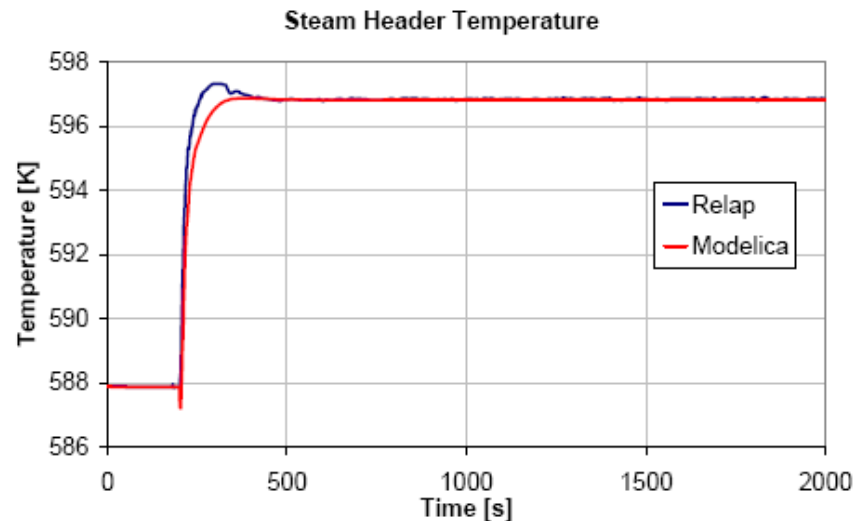
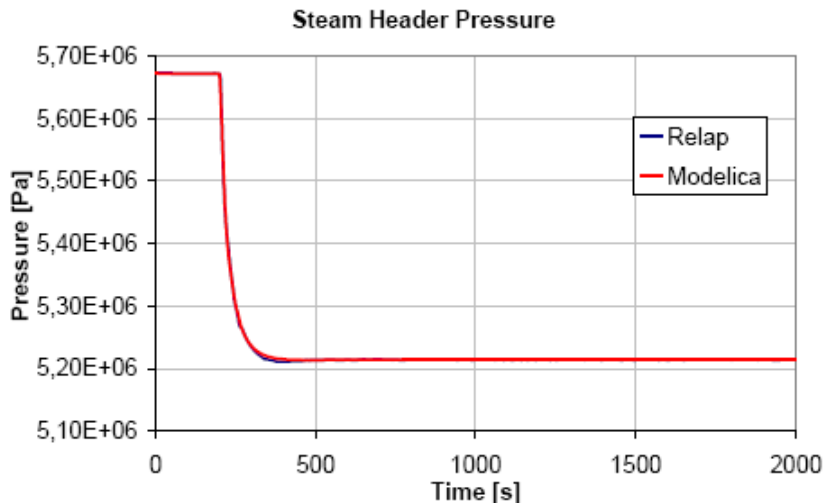
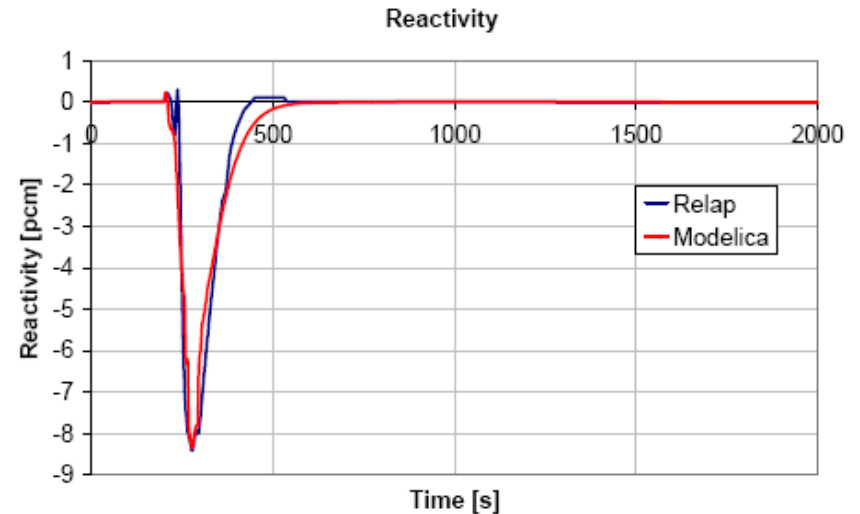
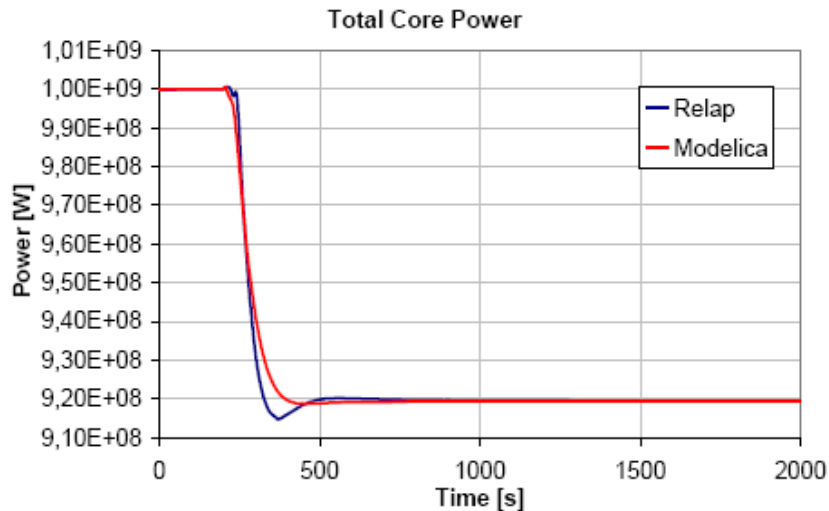
model IRISSimulator_V2
  extends IRISSimulatorBase(
    redeclare Plants.NSSS_V1 NSSS(
      redeclare package PrimaryMedium =
        Media.SimpleIncompressibleWater,
        Core(N = 7),
      redeclare Plants.HelicalCoilFVChen
        HelicalCoil(N=15)),
    redeclare Controls.CS_V2 CS,
    redeclare Controls.SS_V2 SS,
    redeclare Plants.TGFWS_V1 TGFWS);
end IRISSimulator_V2;
  
```

- All the implementable simulators are **consistent by design!**



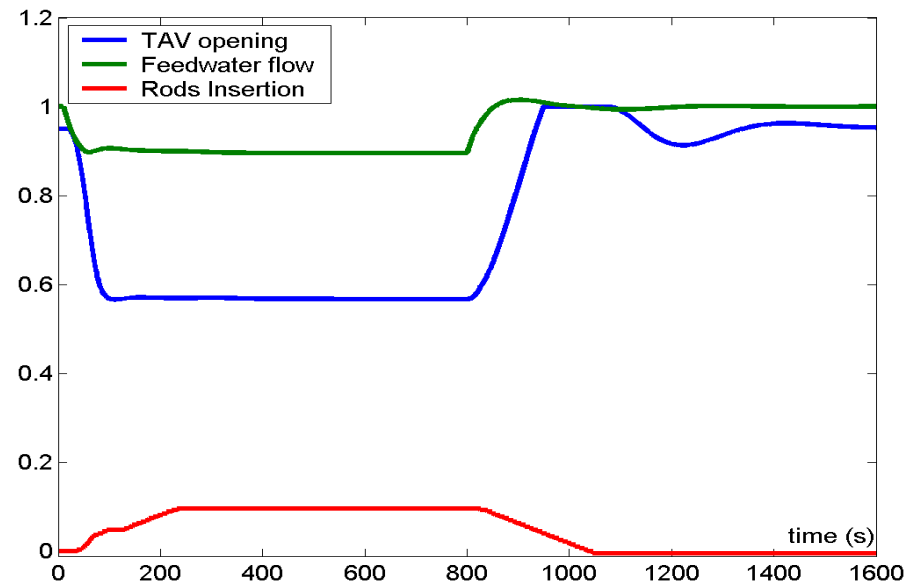
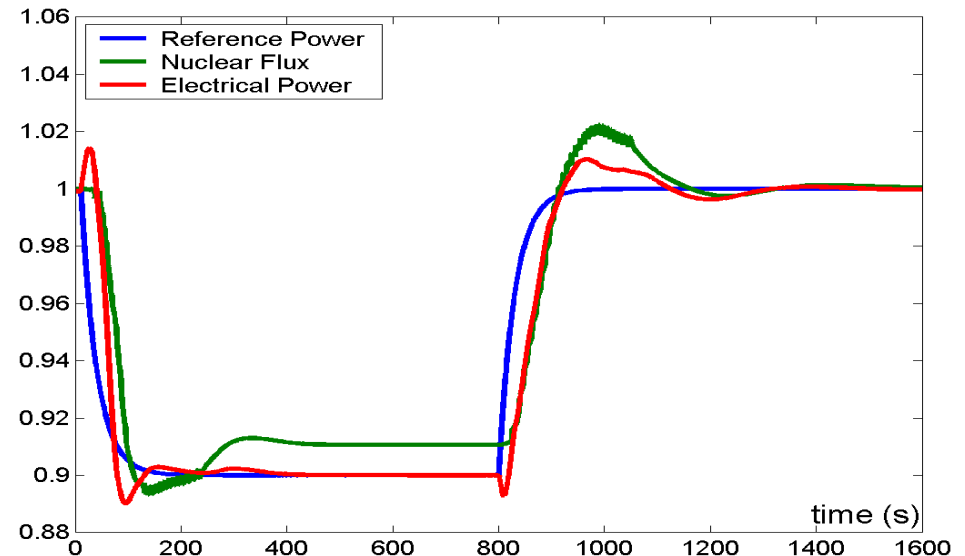
IRIS – Validation vs. RELAP code

- The model has been validated in open loop against results obtained from a RELAP model (good for accident simulation and safety analysis, but very slow)



IRIS – Test of Closed-Loop transients

- Simulations carried out with a simplified model of the digital control system (5 main control loops)
- In the future: multi-mode controller, including start-up and shut-down
- Using an incompressible fluid model for the primary loop, a non-stiff model is obtained
- This can be simulated using a fixed-time-step forward Euler algorithm, resulting in 20X real-time simulation speed.



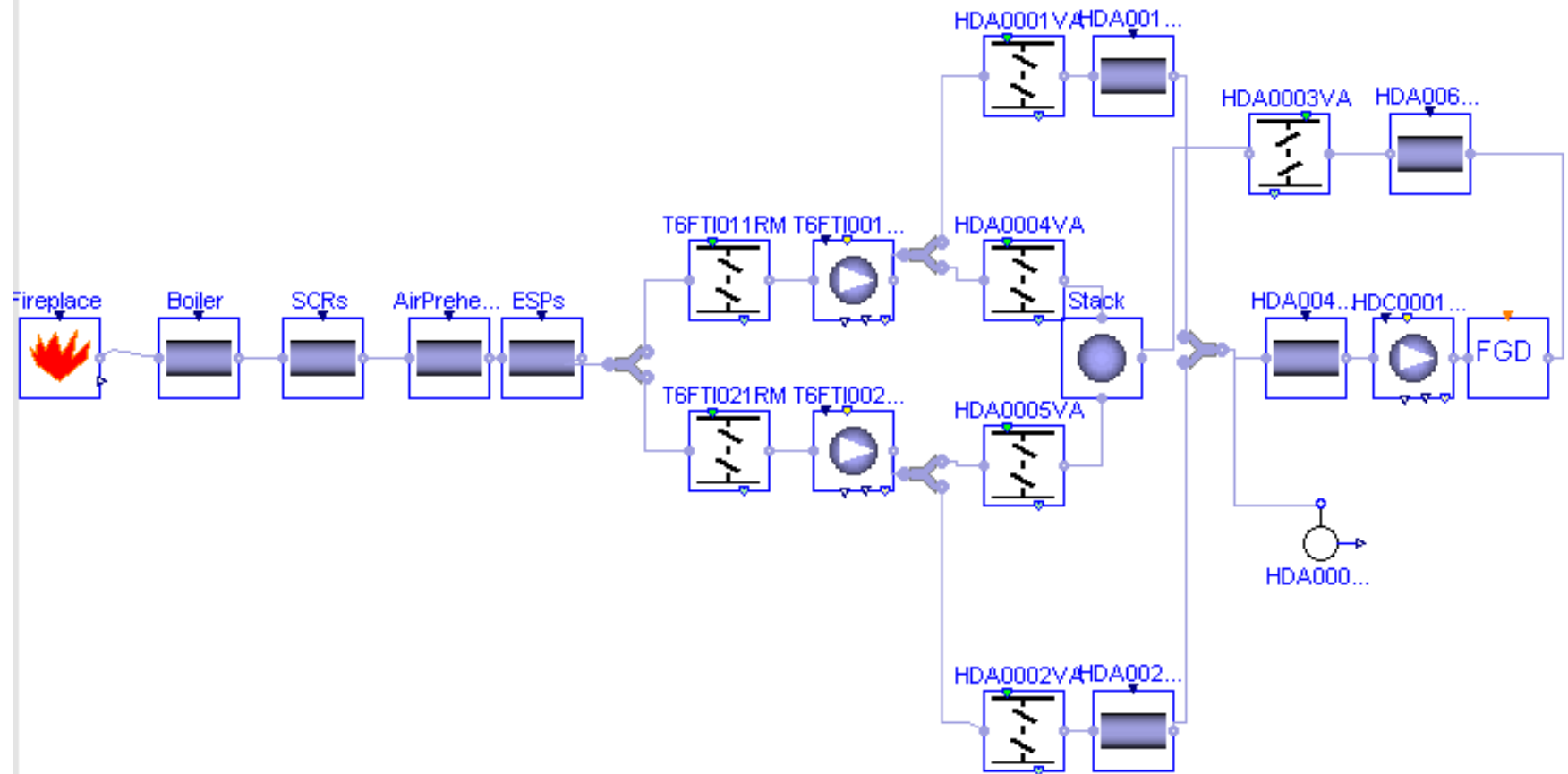
FLUE-GAS PATH SIMULATOR

Flue-Gas Path Simulator

- Study of the pressure control system in the flue gas circuit for a revamped coal-fired power plant
 - SCR unit
 - De-NOx unit
 - De-SOx unit
 - Booster fan
- A CFD study was available for some selected *static* operating conditions; it was then necessary to check if the control system can carry out all the foreseen maneuvers without tripping the plant:
 - Load level increase / decrease due to dispatching
 - Insertion / Exclusion of the De-SOx unit
 - Fan unit trip
- Highlights:
 - Ad-hoc con know-how proprietario (operating curves)
 - Very detailed modelling of the logic control system

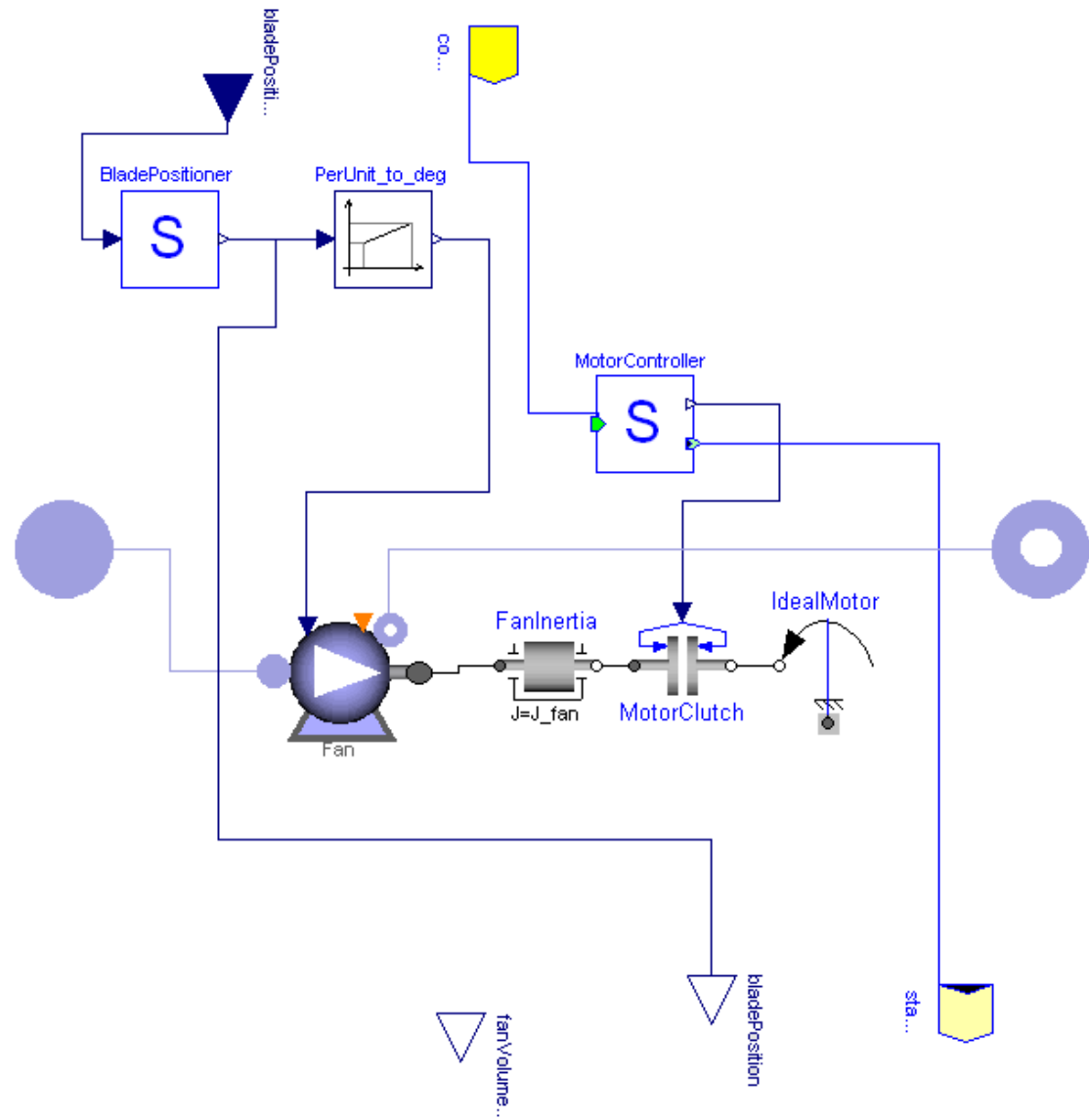
Flue-Gas Path Simulator

- Plant model: high-level diagram



Flue-Gas Path Simulator

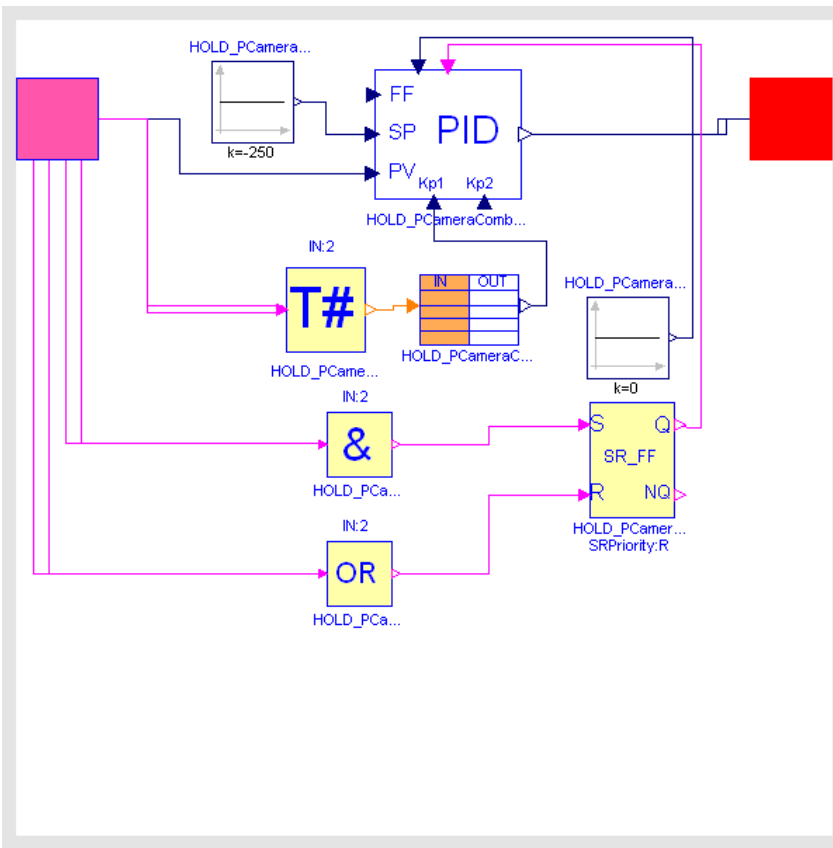
- Model of a fan unit



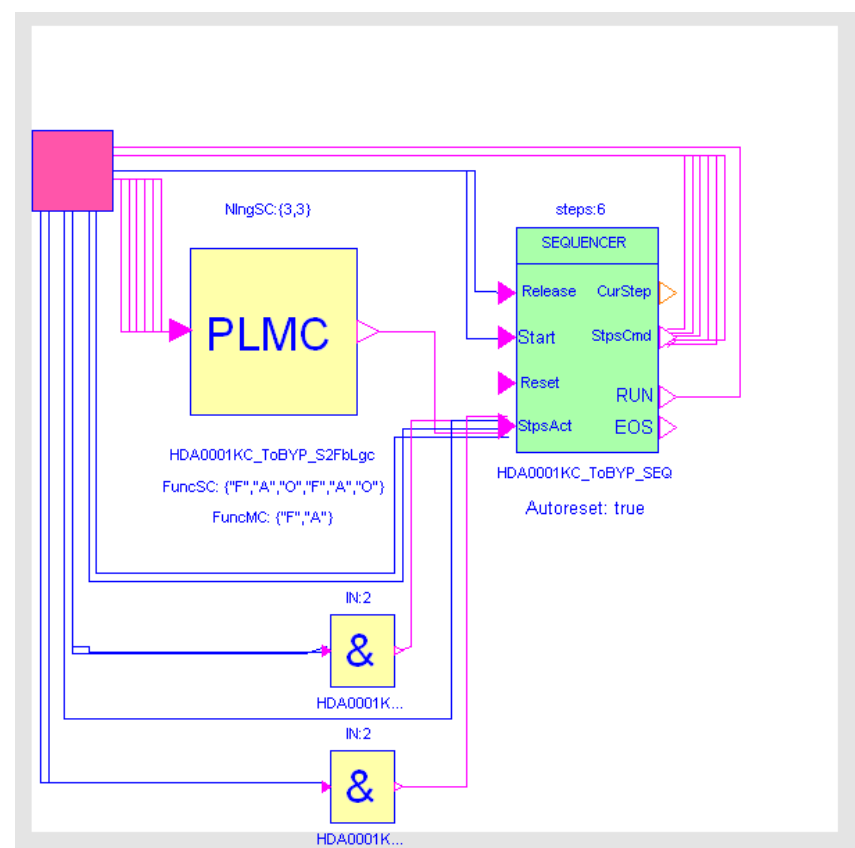
Flue-Gas Path Simulator

- Control system block diagrams
- Each logic blocks is specified through an algorithm

Furnace pressure control



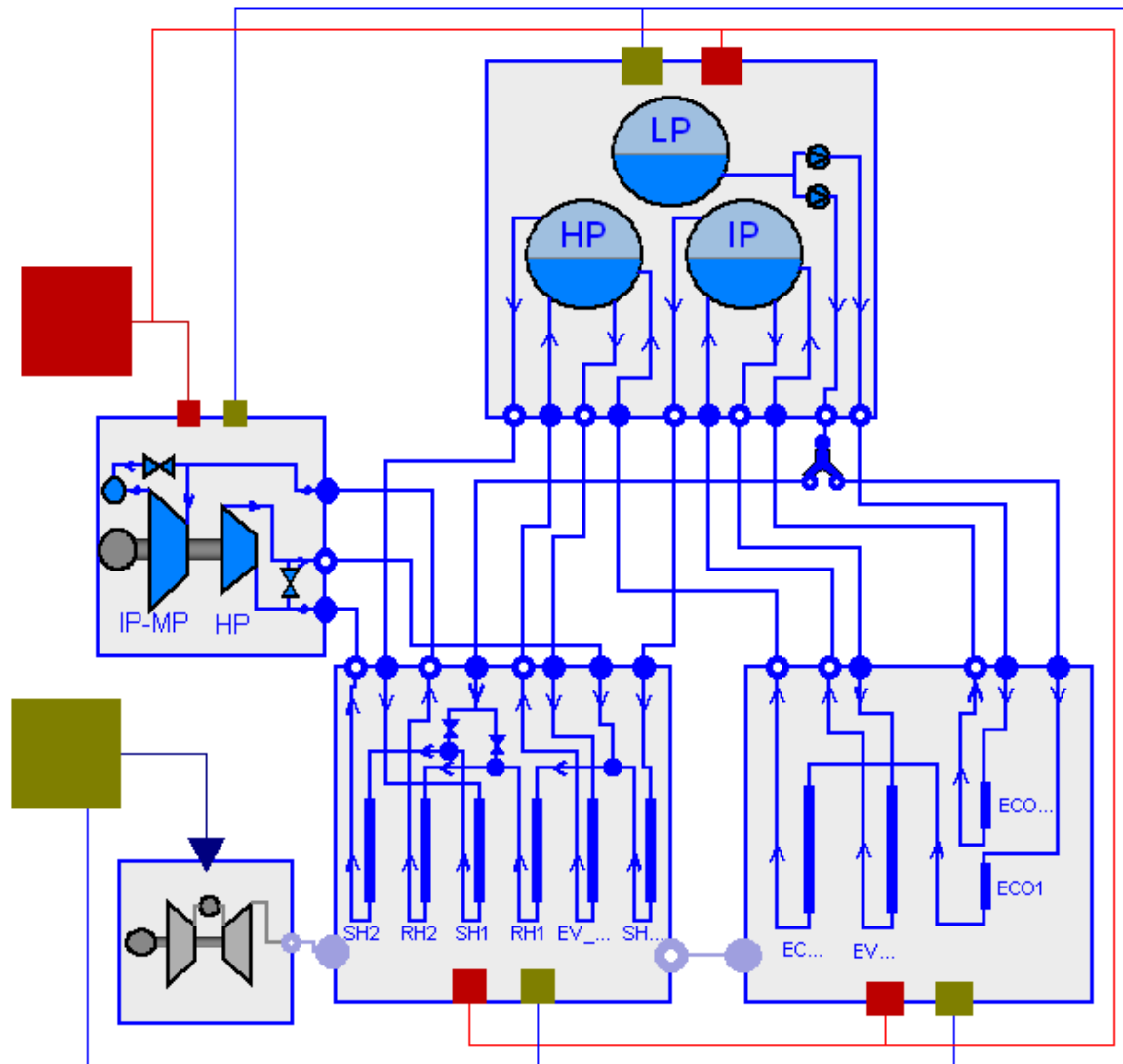
Bypass insertion sequencer



CESI - CC

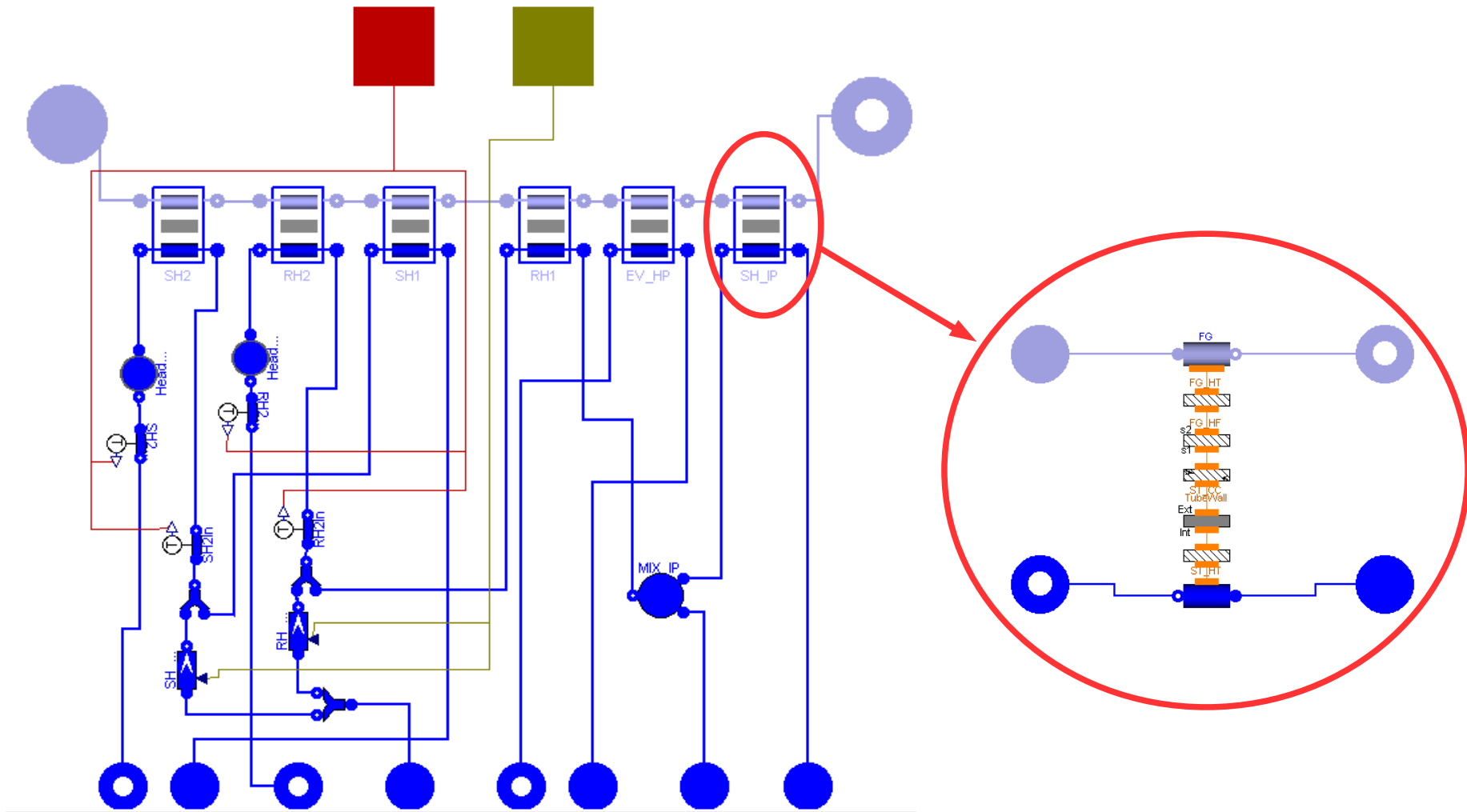
- Development of a dynamic model for a typical Combined-Cycle unit, to study fast start-up strategies
- The model includes the computation of the thermal stresses in the most critical points of the plant (steam turbine shaft)
- The control strategy must be selected in order to minimize the start-up time (from shut-down plant up to full load), without exceeding the maximum allowed stress levels.
- The strategies have been determined by trial-and-error. In the future, the model could be coupled to an optimization software, to compute the optimal control signals automatically
- Also, simplified versions of the model could be used to build model-based controllers (e.g. predictive controllers)
- Highlights:
 - High complexity (large number of components)
 - Start-up conditions included (low or zero flow rates, very low pressures, etc.)

- High-level structure of the plant simulator



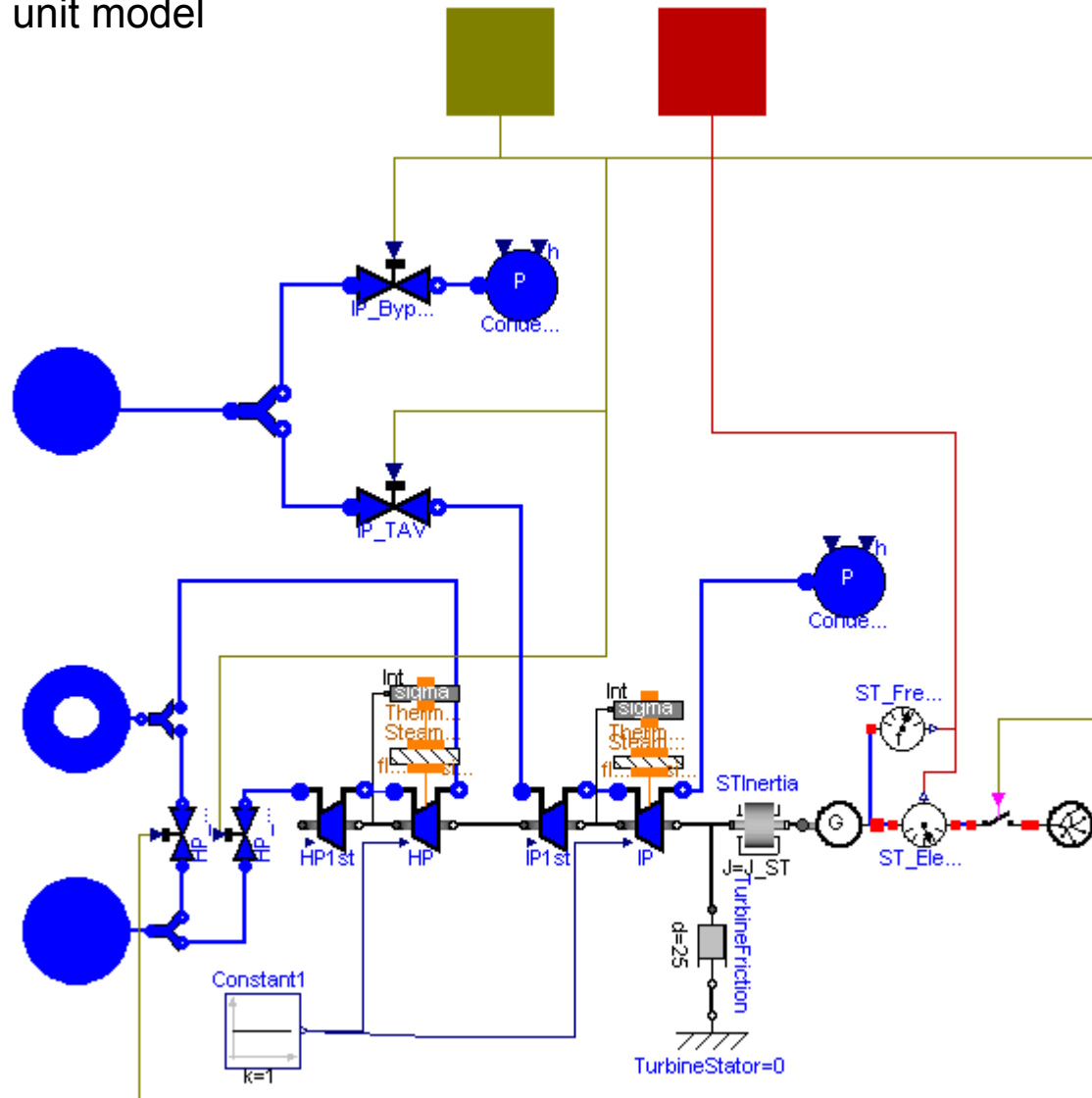
CESI - CC

- Heat recovery boiler model



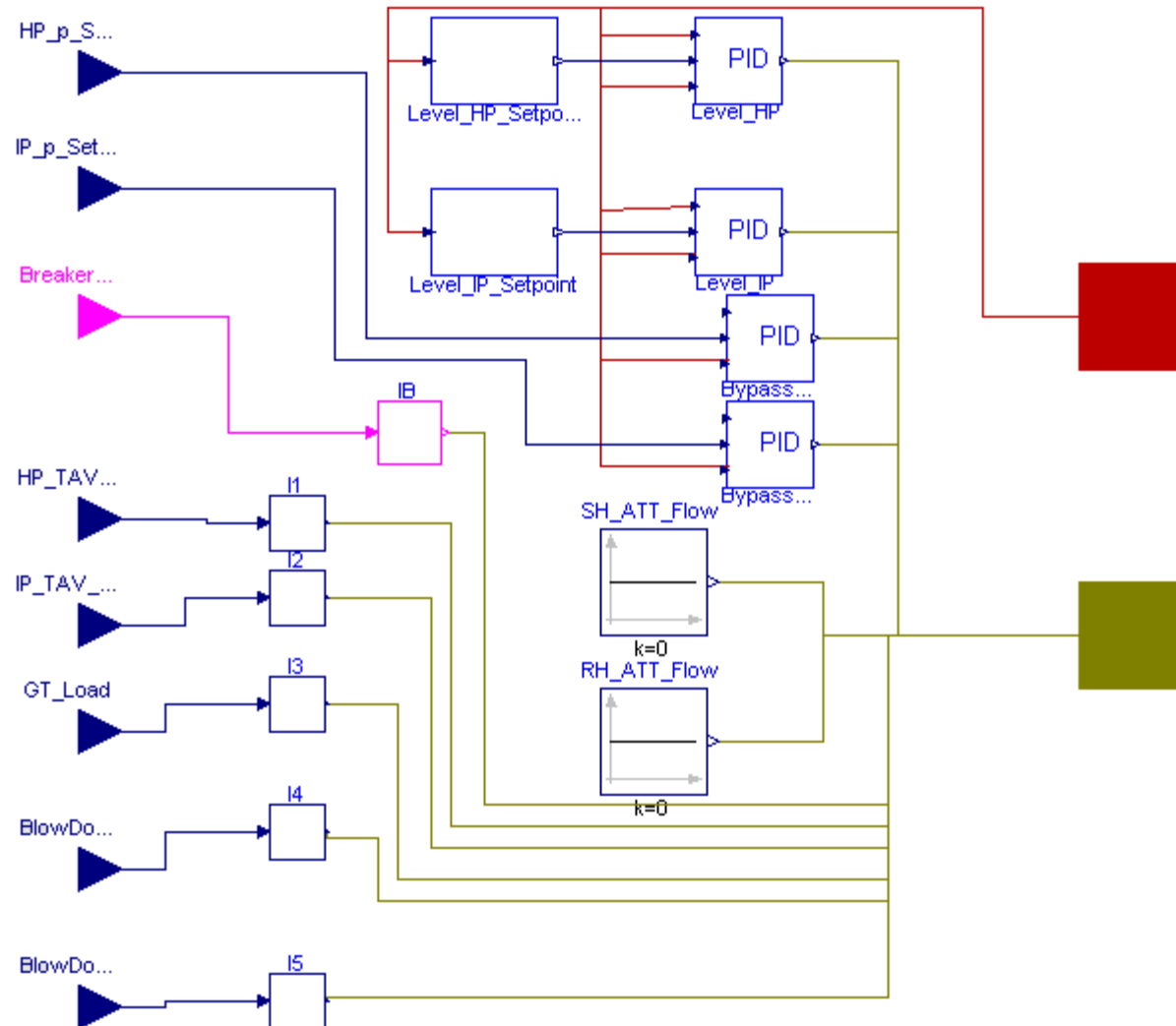
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-
- | Age Group | Percentage |
|-----------|------------|
| 18-24 | 10% |
| 25-34 | 15% |
| 35-44 | 20% |
| 45-54 | 25% |
| 55-64 | 20% |
| 65-74 | 15% |
| 75-84 | 10% |
| 85+ | 5% |



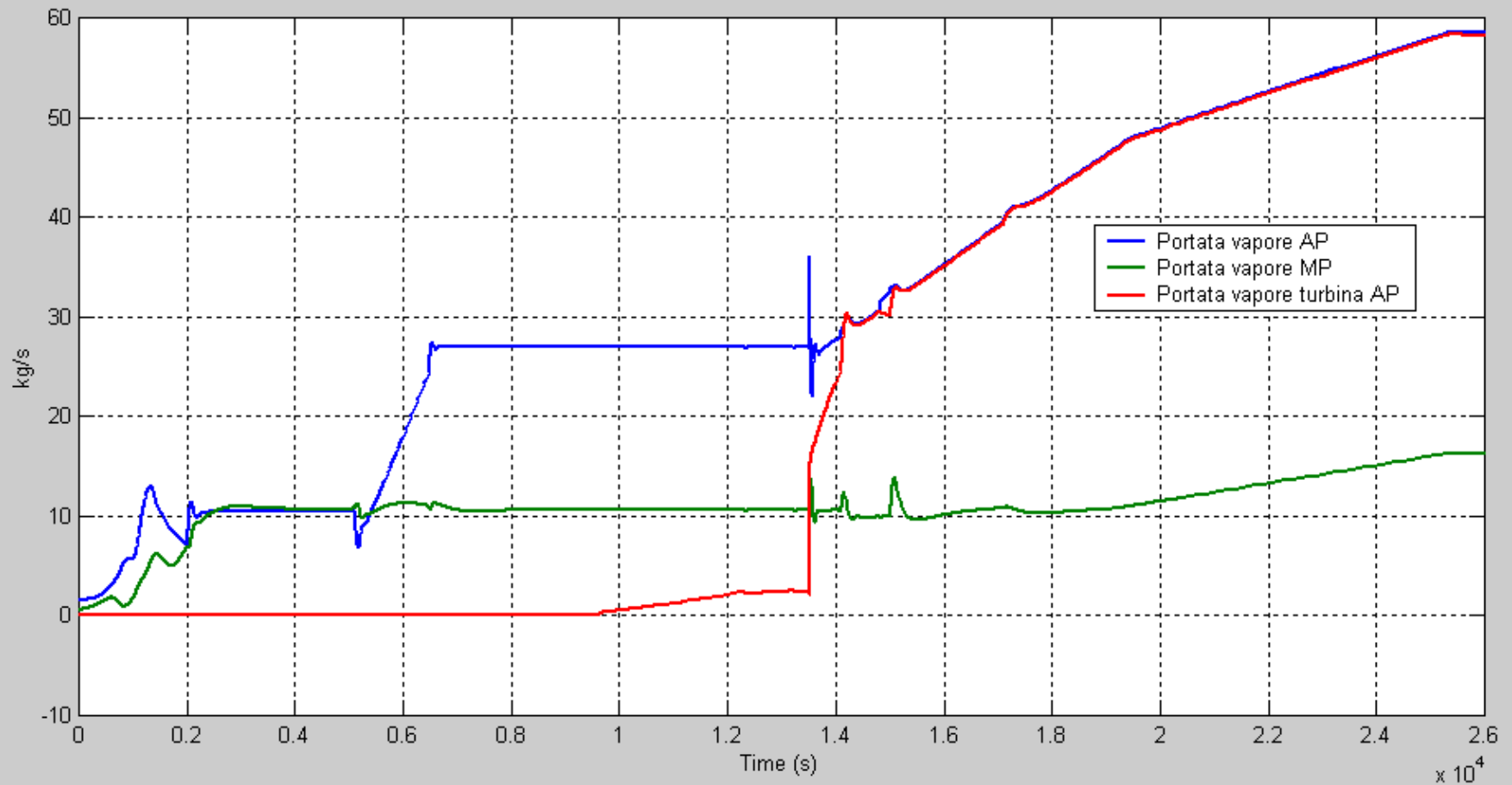
CESI - CC

- Low-level controllers



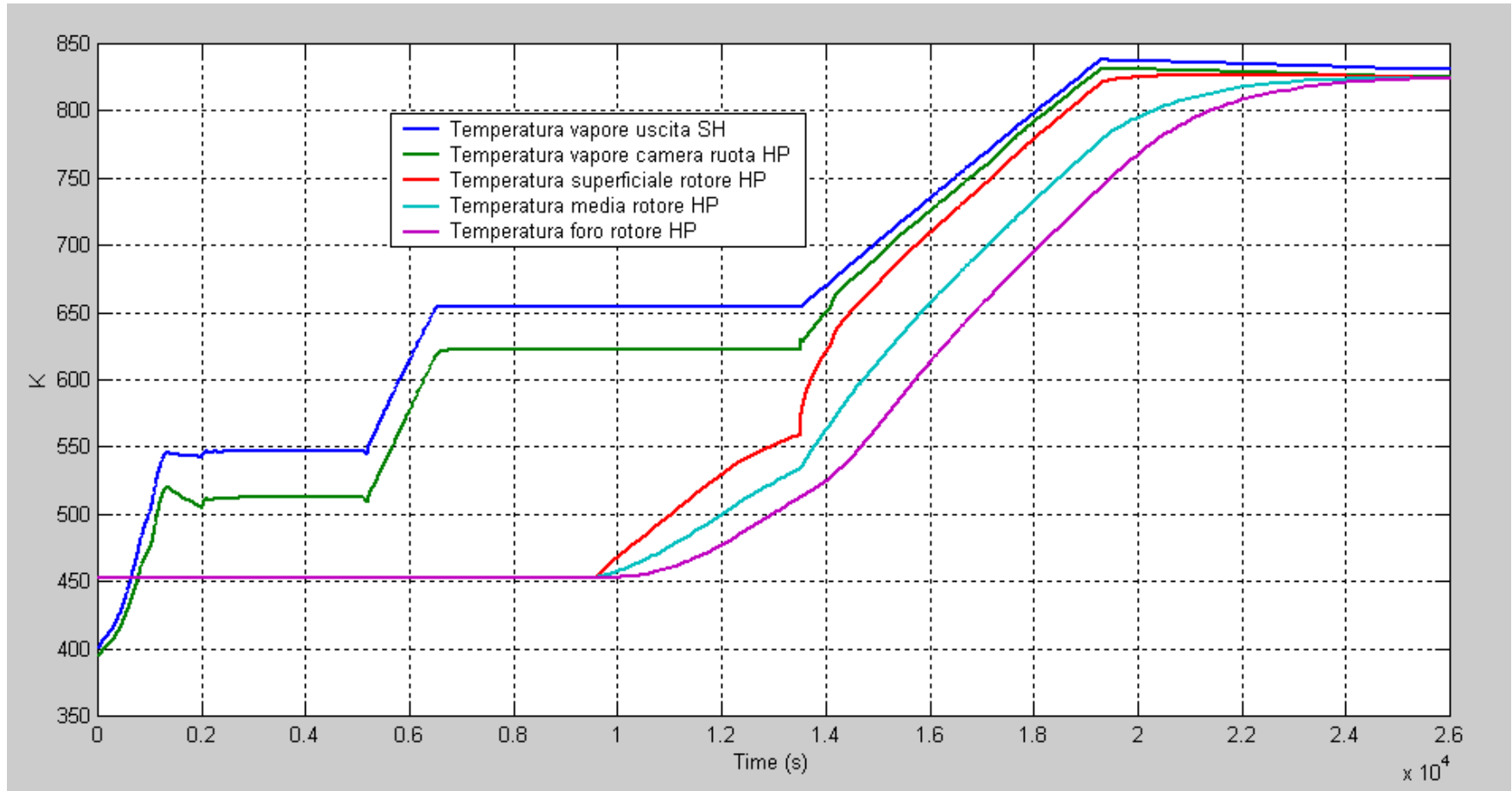
CESI – CC: Simulation Results

- Reference start-up transient: steam flow rates



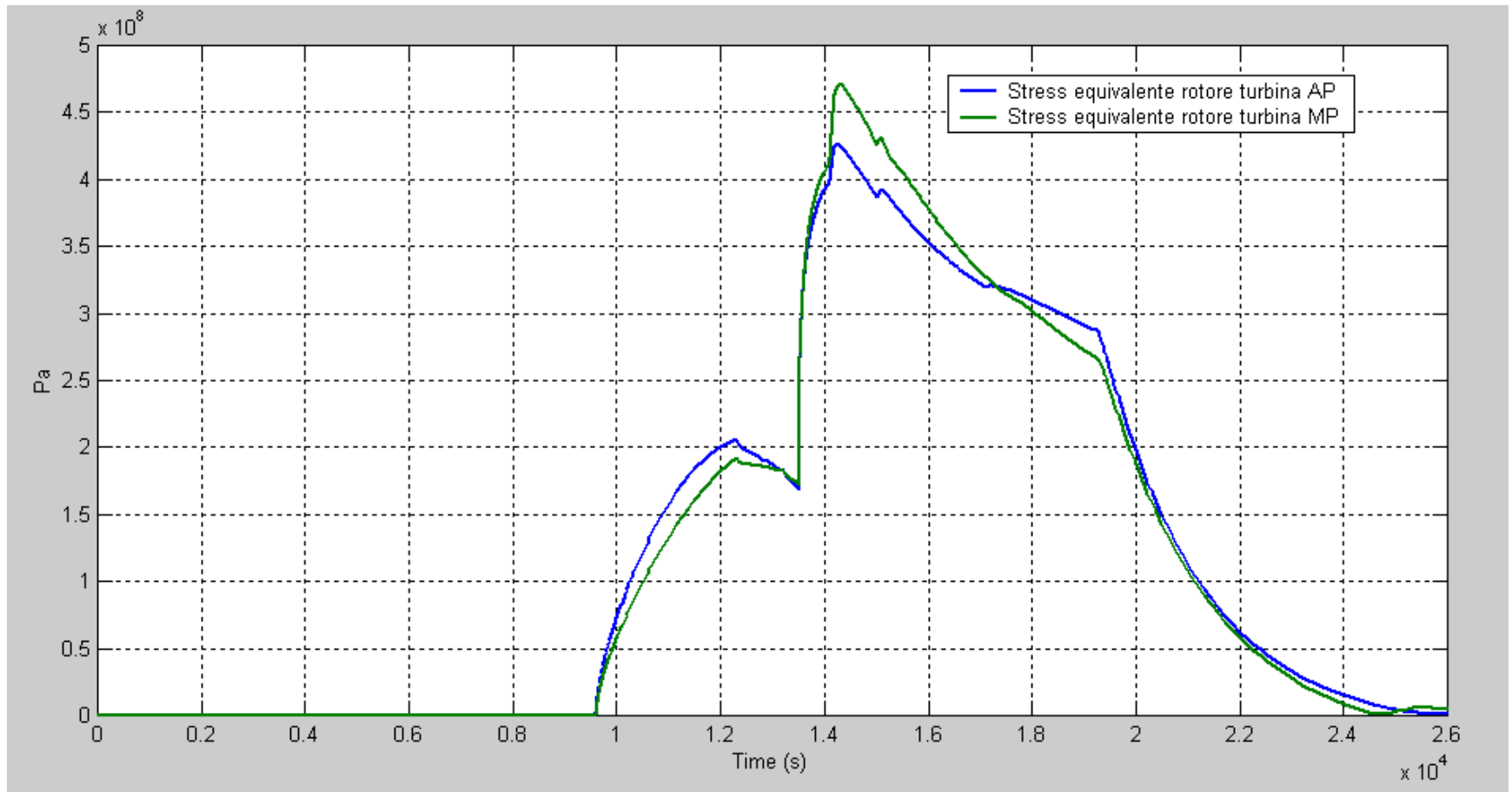
CESI – CC: Simulation Results

- Reference start-up transient: steam and HP turbine rotor temperatures



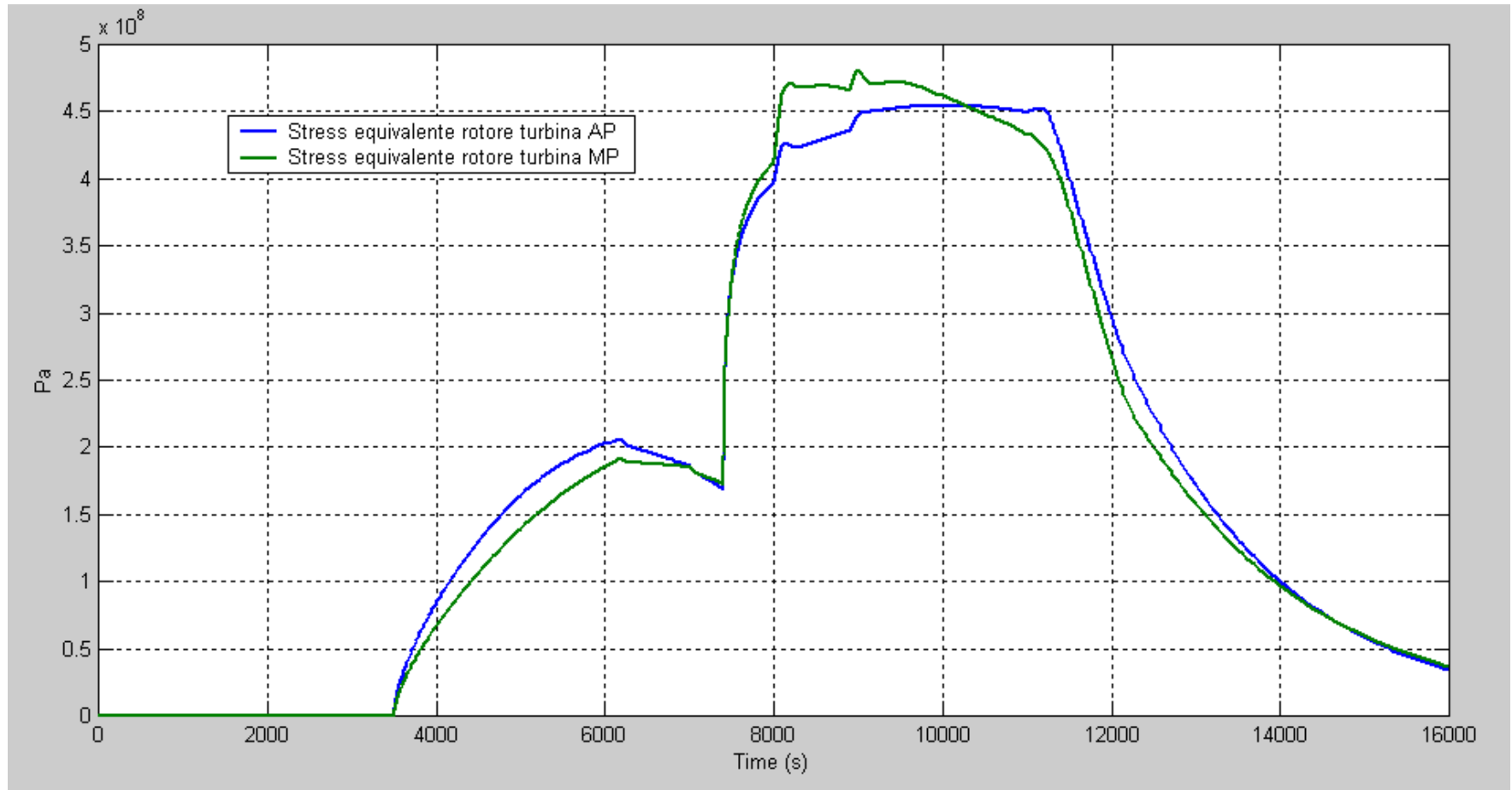
CESI – CC: Simulation Results

- Reference start-up transient: thermal stresses on HP and MP turbine rotors



CESI – CC: Simulation Results

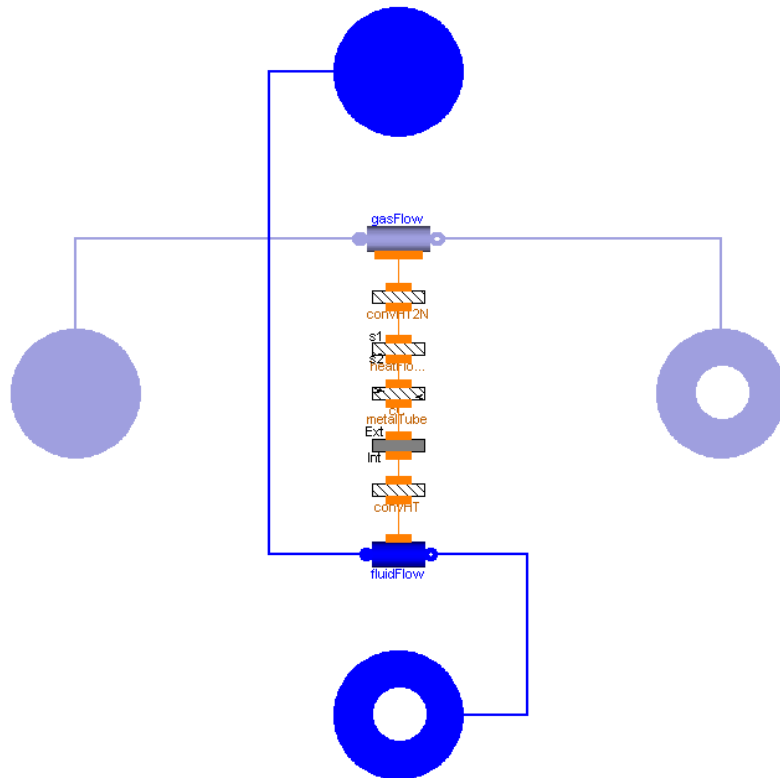
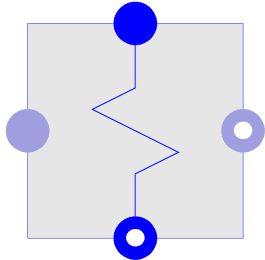
- Minimum-time start-up transient:: thermal stresses on HP and MP turbine rotors



Modelling of Combined-Cycle Power Plants

- Circulation type for evaporators
 - forced circulation
 - natural circulation
 - once-through (seldom used)
- Cycle configuration
 - two pressure levels no reheat
 - three pressure levels w/ reheat
- Steam turbine configuration
 - Arrangement of HP/IP/LP stages
 - Single- or double-flow
- Plant configuration
 - Single shaft (1 GT/HRSG, 1 ST on same generator shaft)
 - Double shaft (1 GT/HRSG, 1 ST on separate generator shafts)
 - Triple shaft (2 GT/HRSG, 1 ST, three generator shafts)
 - ...
- Goal of the **PowerPlants** package in ThermoPower:
 - provide abstract interfaces for all these categories
 - provide template pre-built models for at least some cases
 - avoid repetitive and tedious work when setting up a new model

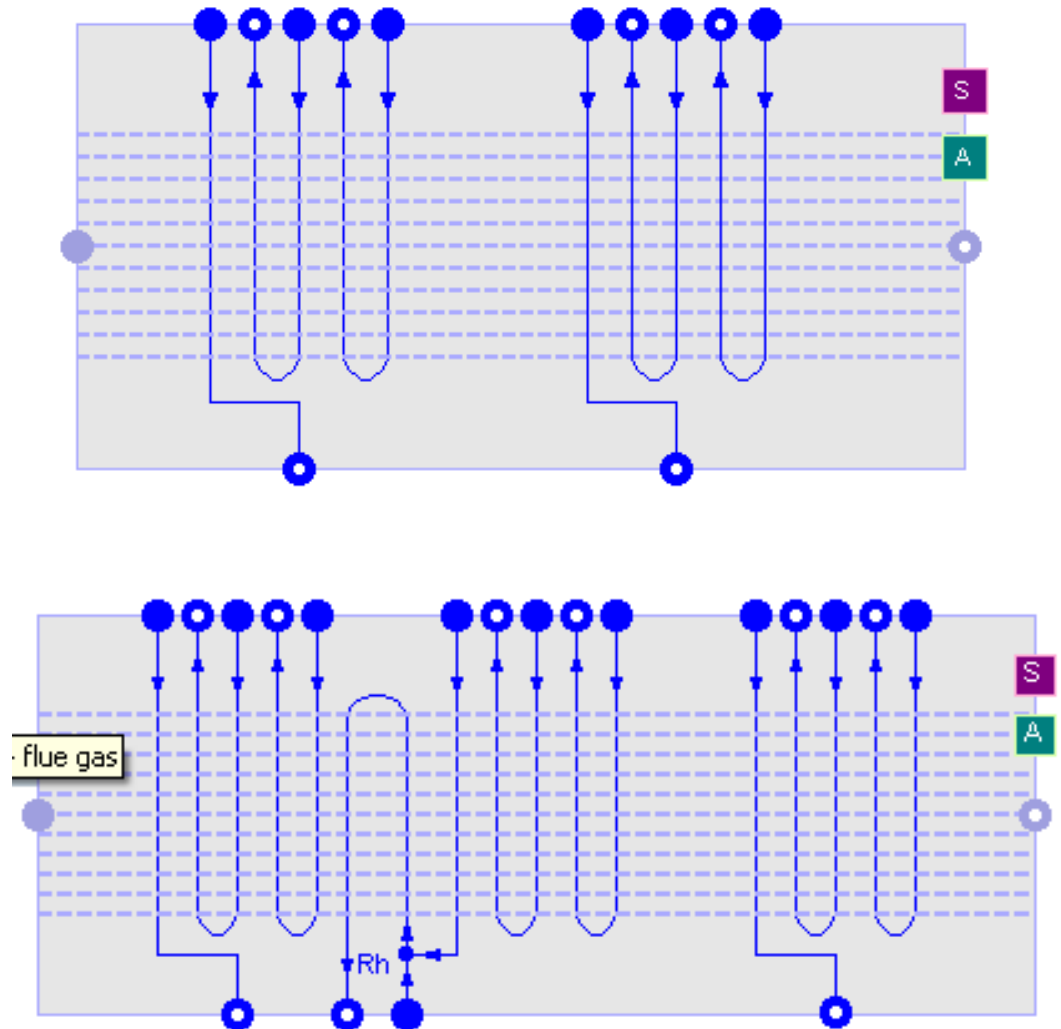
Heat exchanger unit



- Interface has 4 connectors
- Different implementations using basic components from the library
 - 1 phase / 2 phase
 - heat transfer phenomena
 - fixed/varying h.t.c.
 - convection
 - radiation
 - ad-hoc correlations

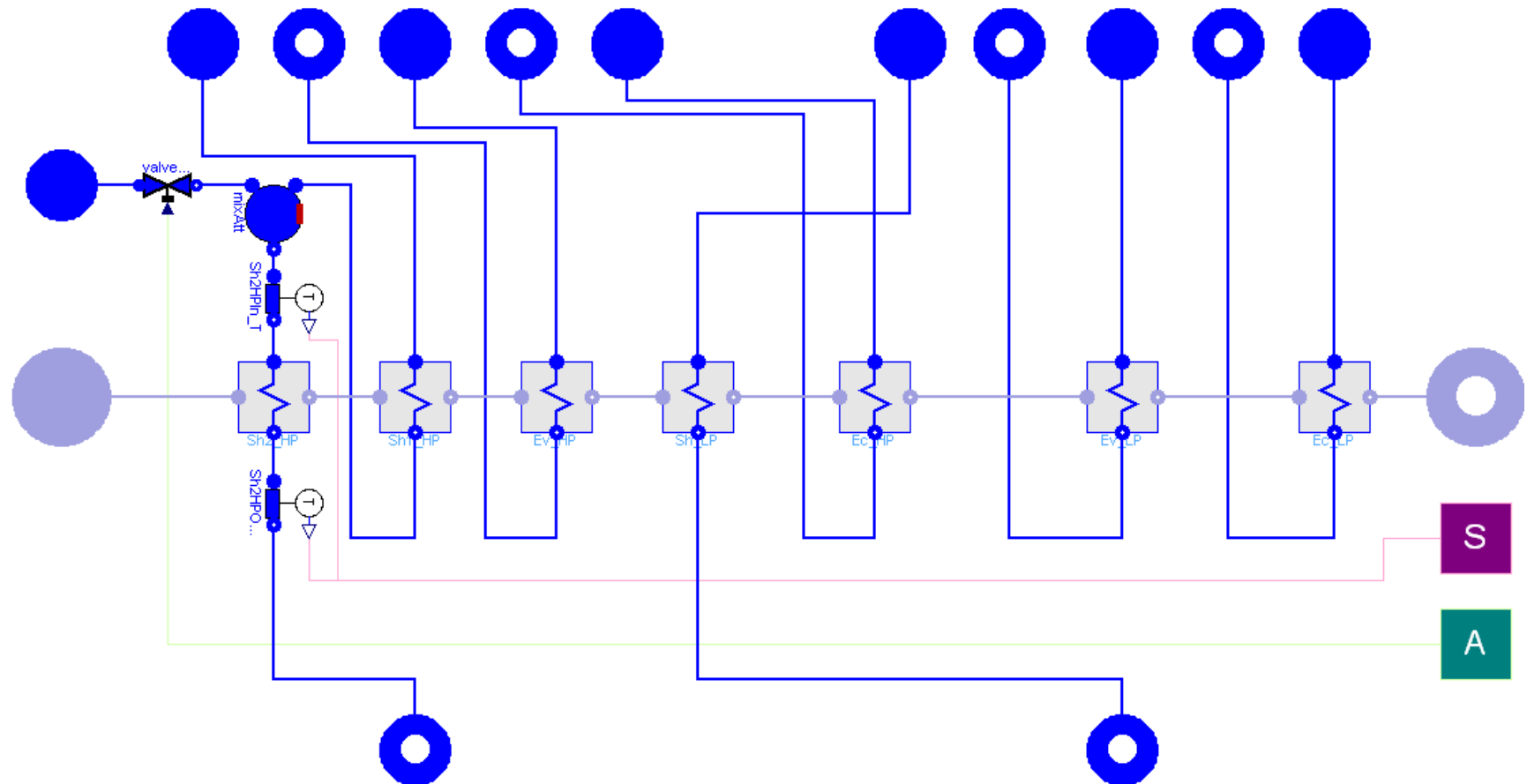
Heat Recovery Steam Generator body

- Two or three levels of pressure
- Two interfaces defined accordingly



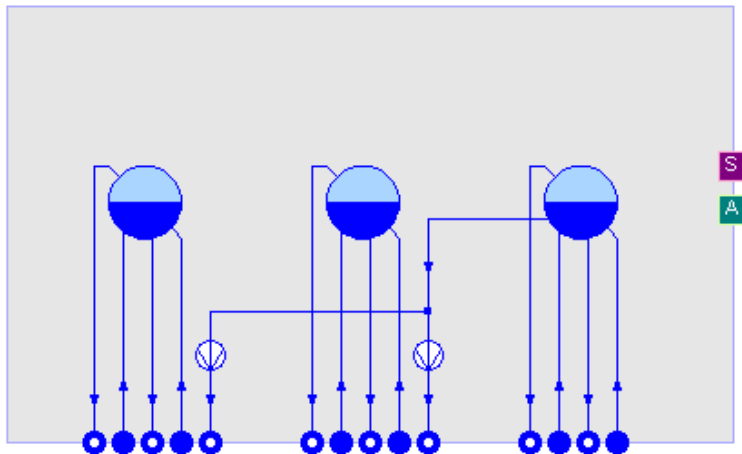
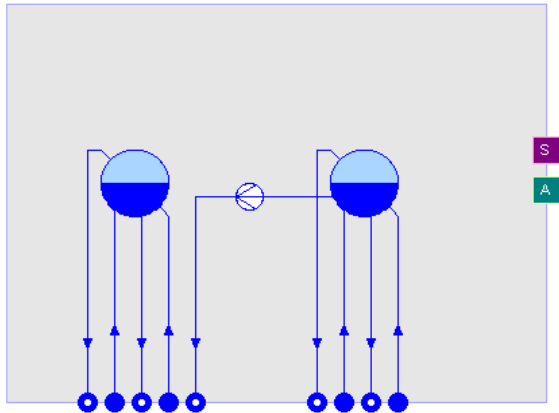
Heat Recover Steam Generator body

- Example implementation of two-levels of pressure HRSG

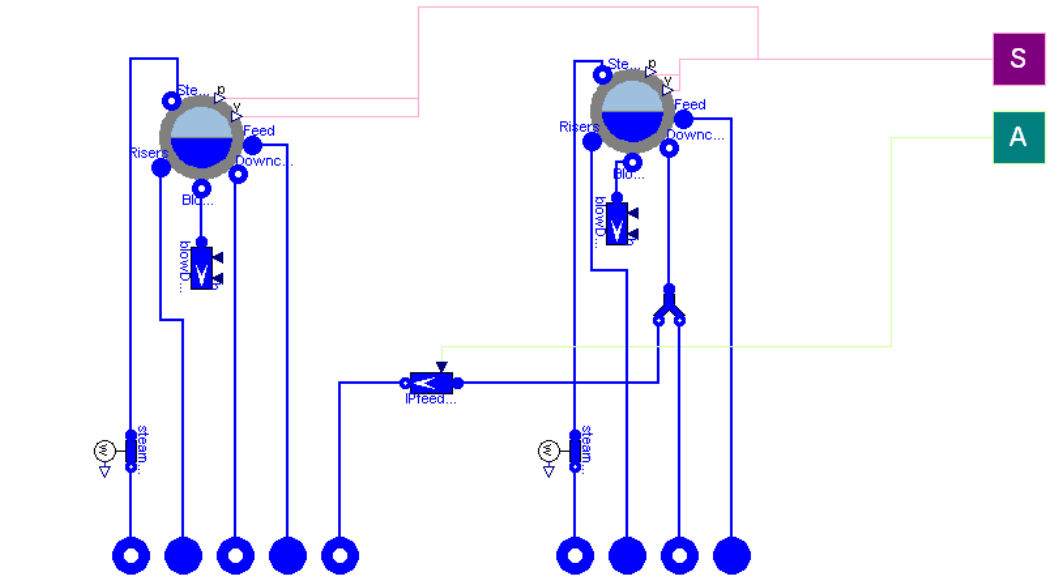


Drum units

- Two and three levels of pressure interfaces

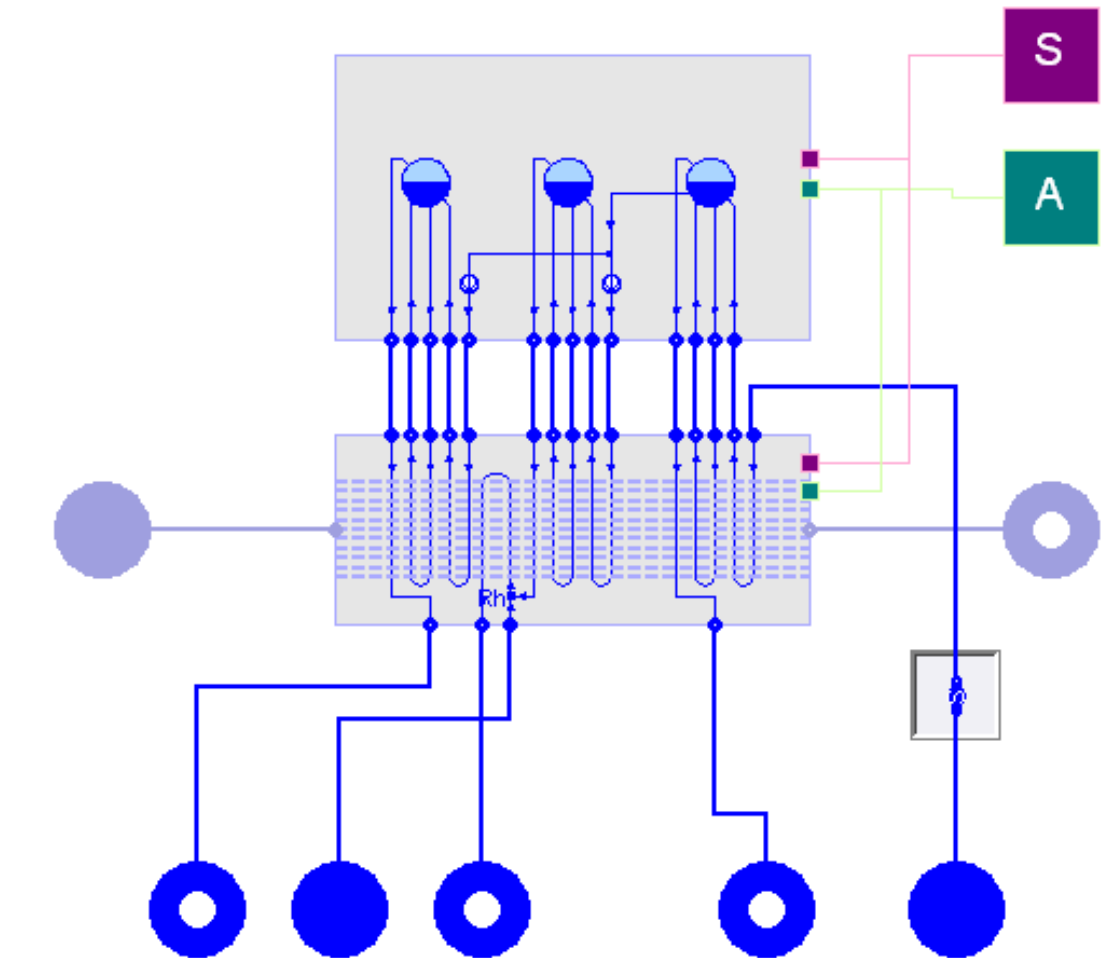
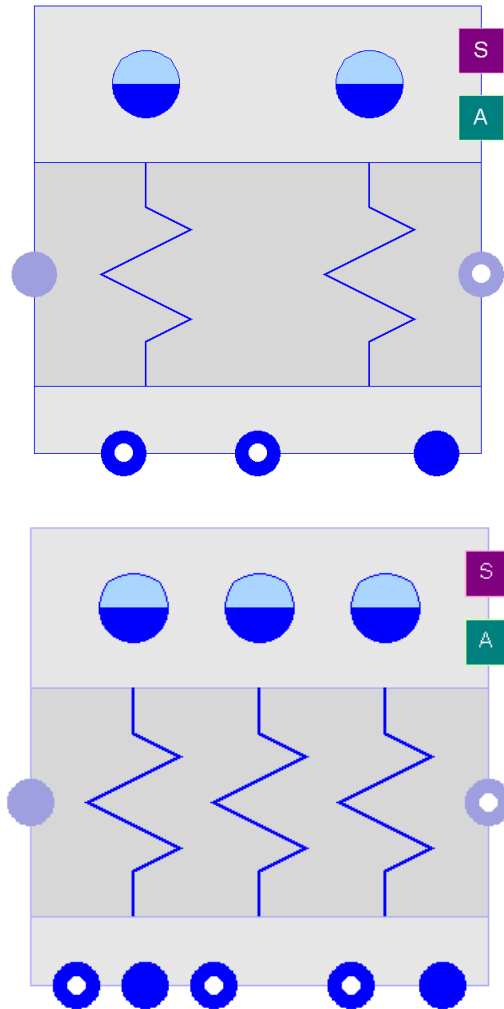


- Different implementations
 - natural circulation (no pumps)
 - forced circulation (w/ pumps)



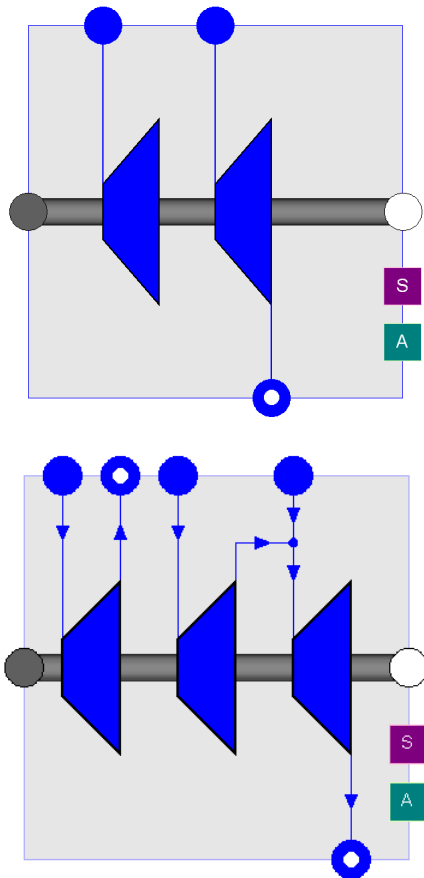
Complete HRSG unit

- Interfaces defined for two and three levels of pressure
- Example implementations built with HRSG body and drum units

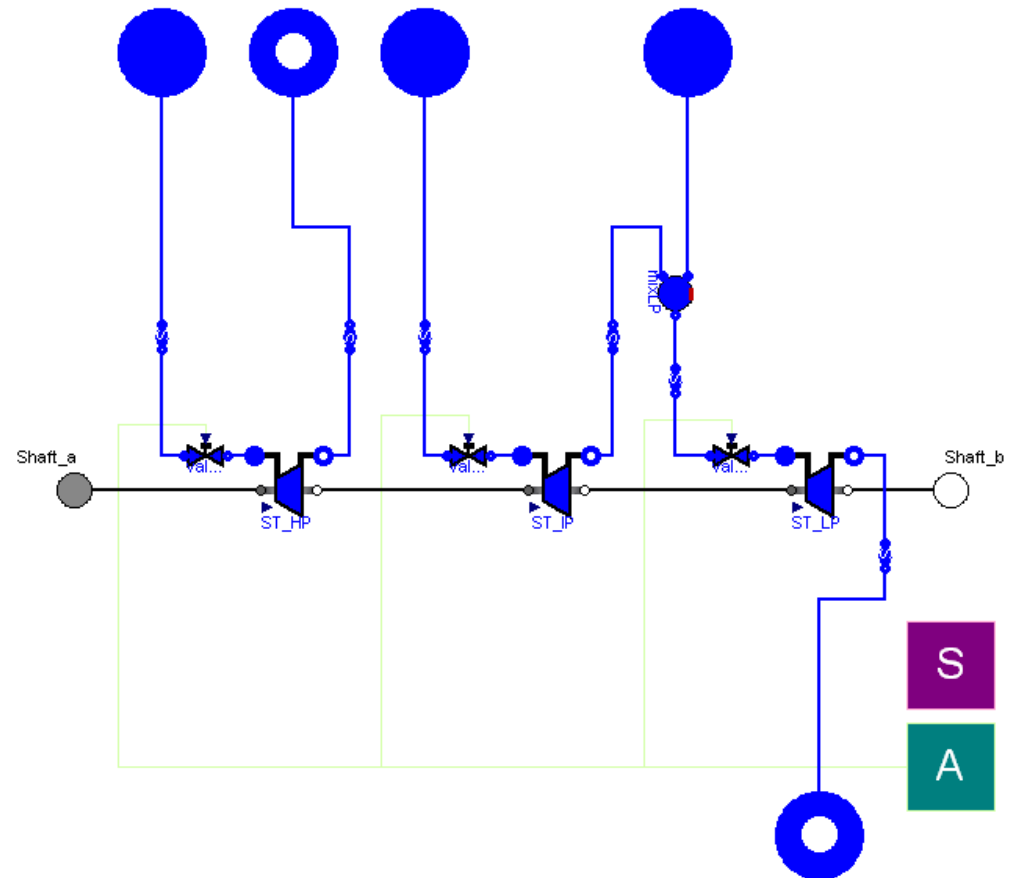


Steam turbine unit

- Interfaces for
 - two levels of pressure, no reheat
 - three levels of pressure w/ reheat

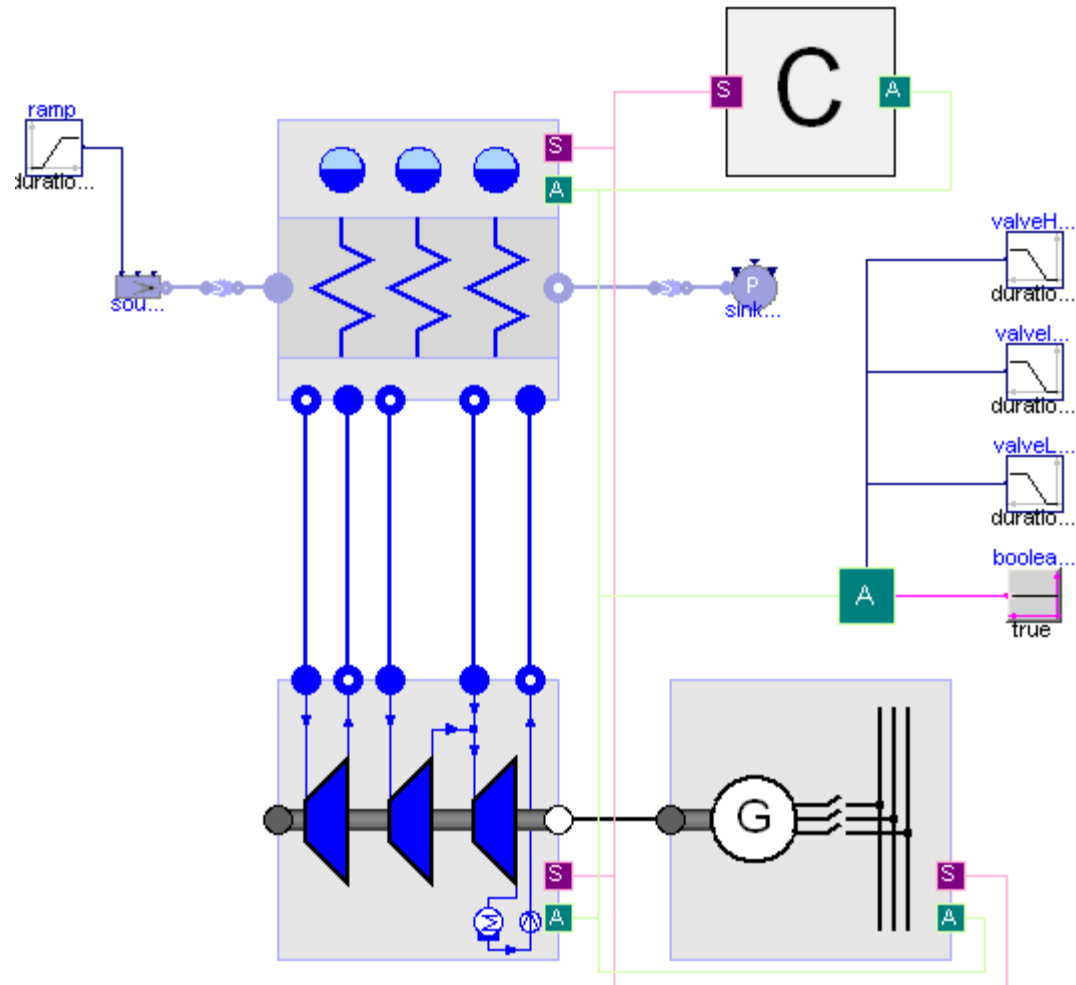


- Different implementations
 - simpler model for normal operation only
 - complete model including bypass paths for start-up simulation



Complete plant model

- Using the unit models defined before, one can easily assemble a complete plant model with any specific configuration



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