



TANDEM

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Modelica models description for the 'TANDEM' Library

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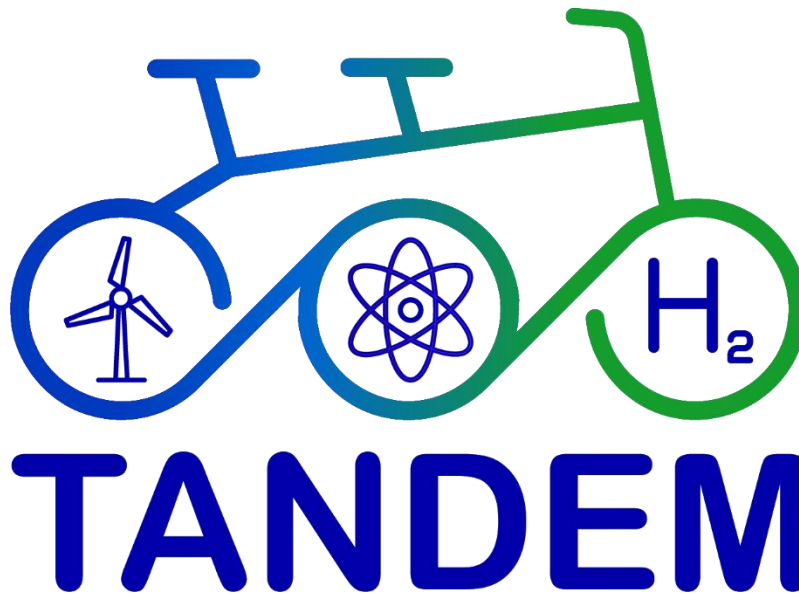
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Summary

The primary objective of the TANDEM project is to conduct a comprehensive assessment of the nuclear safety, techno-economic aspects, and operational feasibility of Hybrid Energy Systems (HES) incorporating Small Modular Reactors (SMRs) in the net-zero energy transition targeted by the EU policies. Because of the close emergence of Light-Water SMR technologies, the project focuses on the analysis of LW-SMR integration within two distinct configurations of representative hybrid energy systems, each tailored to match the energy transition needs and constraints for reaching net-zero greenhouse gas emissions as identified in different parts of Europe. Task 2.2 of the project had the objective of building an open-source Modelica library as a modelling tool dedicated to Hybrid Energy Systems. The library will be used to set-up an easy customizable simulator that can support techno-economical and safety studies. The library constitutes the deliverable D2.4 of the TANDEM project, and this document, deliverable D2.3, provides the associated documentation. It gives a detailed description of the components of the v1.0 of the library and the associated modelling assumptions. Some demo cases and/or benchmark results are also displayed.

Approval

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D2.3 - Modelica models description for the 'TANDEM' library

WP2 - Task 2.2

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Abbreviations and Acronyms

Acronym	Description
AMR	Advanced Modular Reactor
BOP	Balance of Plant
CCGT	Combined-Cycle Gas Turbine
CI	Conventional Island
HES	Hybrid Energy System
HOB	Heat Only Boiler
HP	High Pressure
HTSE	High Temperature Steam Electrolyser
I&C	Instrumentation and Control
LP	Low Pressure
LTE	Low Temperature Electrolyser
LW SMR	Light Water SMR
MP	Medium Pressure
MSR	Moisture Separator Reheater
NPP	Nuclear Power Plant
NSSS	Nuclear Steam Supply System

Acronym	Description
NTU	Number of Transfer Units
PEM	Proton Exchange Membrane
PWR	Pressurized Water Reactor
QS	Quasi-Static
RCS	Reactor Coolant System
SG	Steam Generator
SMR	Small Modular Reactor
ST	Steam Turbine
SOEC	Solid Oxide Electrolyser Cell
TEM	Thermal Energy Storage
WP	Work Package



Executive Summary

The primary objective of the TANDEM project is to conduct a comprehensive assessment of the nuclear safety, techno-economic aspects, and operational feasibility of Hybrid Energy Systems (HES) incorporating Small Modular Reactors (SMRs) in the net-zero energy transition targeted by the EU policies. Because of the close emergence of Light-Water SMR technologies, the project focuses on the analysis of LW-SMR integration within two distinct configurations of representative hybrid energy systems, each tailored to match the energy transition needs and constraints for reaching net-zero greenhouse gas emissions as identified in different parts of Europe.

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Keywords

Modelica, Model library, Hybrid Energy System, Simulator, SMR, cogeneration.



1. Introduction

This document constitutes the deliverable 2.3 of the TANDEM project, i.e. the documentation of the open-source Modelica-based TANDEM library. The latter, which constitutes the deliverable 2.4 of the project, has the objective of providing the bricks to build an easily customizable simulator of the *Hybrid Energy System*. For example it could be used to:

- Perform techno-economic studies taking into account the complex and dynamic interactions between the components of the HES.
- Provide realistic physical conditions at the coupling interfaces (SMR secondary circuit) for safety studies assessing the impact of cogeneration.

This document has the objective of documenting the library v1.0 (*Open Source "TANDEM" Library, 2024*)¹ and providing the user with the useful information to start using it. It completes the online documentation within the library with some complementary information, in particular:

- some demo cases results;
- some comparisons versus numerical or experimental results.

Considering the hybrid energy system configurations in TANDEM, the district heating (DH) configuration and the energy hub (eHub) defined in the deliverable 1.4 (Konsta VARRI et al., 2023), the required components have been developed in the library. The objective is to simulate operating scenarii for the two HES configurations; in particular low and high penetration of SMR have to be modelled to assess the impact of nuclear cogeneration on some techno-economic and environmental key parameters (Miriam Minchole Lapuente et al., 2023). Together with the SMR, other production units (for example Combined Cycle Gas Turbine (CCGT), nuclear Heat Only Boilers (HOB), renewables...) may be considered, but also storage units and heat pumps according to forecasted European trajectories.

To accurately evaluate the interactions between their components, the TANDEM library targets a dynamic representation of the main components. In its first version, the effort has been put on some key components; other "minor" components (especially electricity only users) have been modelled with a simplified approach because of their limited impact on the global system. This also limits the complexity of the simulator. In the future, the library may keep evolving to:

- improve the modelling of some components,
- include new HES components (e.g. methanation)

¹ The TANDEM library is available at <https://gitlab.pam-reted.fr/tandem/tandem>

- and provide models for alternative technologies.

Concerning this last item, for example, the TANDEM library is focused today on pressurized-water SMRs technology, because of its maturity of PWRs and the development status of such reactors in Europe; however, Advanced Modular Reactors (AMR) could be included in HES considering a longer-term deployment. Another example concerns hydrogen production technology, which is rapidly evolving: SOEC and PEM are provided today in the library but additional technologies may be considered in the future.

The library is not developed from scratch but it is supported by well-established Modelica libraries:

- ThermoPower (Casella & Leva, 2006) and ThermoSysPro (El Hefni & Bouskela, 2019)

Respectively developed by Politecnico di Milano and EDF R&D, these two libraries are mainly dedicated to power plant modelling; they include components such as heat exchangers, turbines, pumps... For the core modelling of the nuclear reactor, the ThermoPower library is complemented with some components from the NuKomp library have been used (Cammi et al., 2011).

- CEA_Energy_Process_Library

Developed by the CEA, the goal of this MSL compatible library is to gather various models focused on energy processes (electrolysis, fuel cells, chemical conversion to molecules of interest, gas storage etc.) but most importantly a great diversity of fluid medium and components.

- Buildings (Wetter et al., 2014)

As an exhaustive library dedicated to building modelling, it has been used within the TANDEM library for the electrical grid.

- WindPowerPlants (Eberhart et al., 2015)

This library has been developed at the Technical Engineering College (TGM) and is used in TANDEM to model the contribution of energy generation from the wind power plants integrated into the hybrid energy system, starting from wind data. A detailed description of the library's structure and underlying assumptions is available in (Eberhart et al., 2015).

Concerning its usage, the TANDEM library will be used to build customizable simulators of physical behaviour for different HES configurations. The simulator will then be used to perform techno-economical studies taking into account the complex physical interaction of the system

components focussing on different timescales: from load variations (characteristic time of a few minutes) to seasonal variations (characteristic time of several months). It will also be used to provide realistic physical conditions at the coupling interfaces (SMR secondary circuit) to safety codes for safety studies. For example, the TANDEM Modelica modes can be used to simulate a rapid load variation for a heat user and to see how it propagates through the CI-BOP to the nuclear island; such a coupled simulator (Modelica + safety codes) could also be used, for example, to evaluate the potential benefits of having additional systems (e.g. heat storage) to *smooth* fast turbine transient (e.g. islanding), by absorbing part of the positive or negative load variation and thus easing the nuclear island transient. Finally, the simulator can be used to optimize the design of the system (set points, components sizing...) or its operation (controls, operating procedures...): on the entire system level or focussing on a single component while taking into account its interactions with the other connected components.

The next chapters of this document provide a detailed description of all the components contained in the first version of the library.

2. Nuclear Steam Supply System

This *package*² provides the dynamic model of light-water cooled Small Modular Reactor (SMR), based on the European SMR (E-SMR) design as proposed by the Euratom ELSMOR project (Lansou et al., 2023): see Figure 1 for a schematic view.

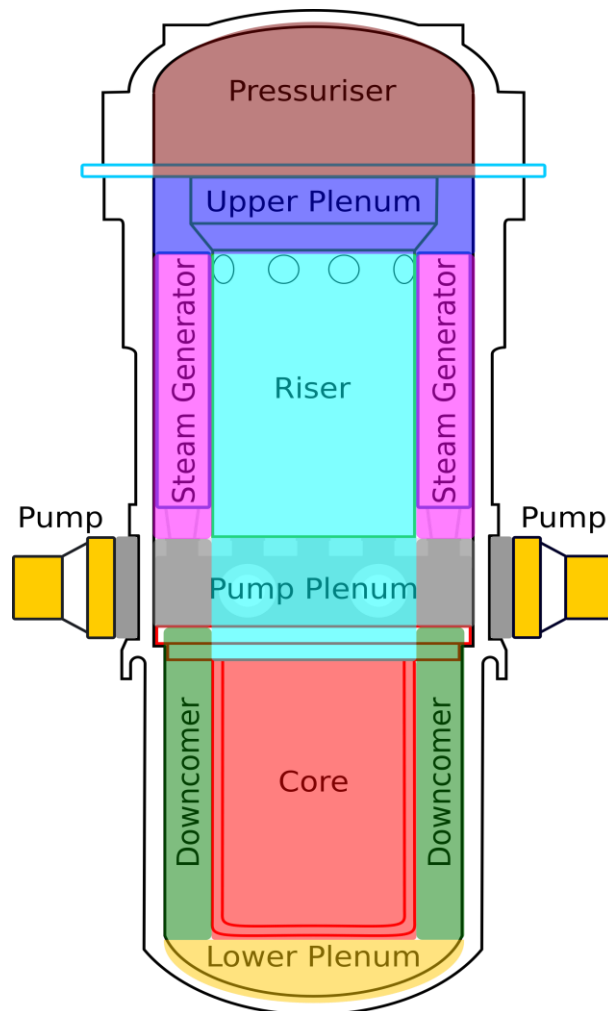


Figure 1. Schematic view of the E-SMR layout.

Moreover, the dataset encompassing the main geometrical and operational parameters developed within the scope of this project has been considered as a reference. The key parameters of the reactor are reported in the following table:

² *Package* is the Modelica keyword for directory or (sub)library.

E-SMR parameters	Value
Thermal Power	540 MW
Core inlet temperature	300°C
Core outlet temperature	324.5°C
Nominal pressure	150 bar
Nominal coolant flow rate	3700 kg/s

Table 1. E-SMR parameters.

The E-SMR is an integrated desing SMR, with the main NSSS components packed within the reactor pressure vessel. The primary coolant is heated in the core and flows through the riser to the upper plenum. This is connected to the pressurizer, which features a hemispherical shape, and to the steam generator inlet. The reactor has been designed with six compact steam generators and two additional safety heat exchangers, although these are modelled here as SG bypass only (no thermal exchange). Six spool-type pumps, located at the steam generator outlets, force the flow of the coolant through the downcomer to the lower plenum at the core inlet.

Two versions of the NSSS model are proposed, based on the ThermoSysPro and the ThermoPower libraries. The rationale behind developing two models for the same component in parallel is, on the one hand, to benchmark the two models by comparing the simulation outcomes, and on the other hand, to enable the user to select the model that is more appropriate for its application (depending for example on the required type of coupling (thermal or fluidic) or on the desired compromise between computational speed and dynamic representation). The two models are based on a similar modelling approach, adopting point kinetics equations for the neutronics and a one dimensional thermal-hydraulic model to simulate the coolant flow through the NSSS components, despite some differences in terms of underlying assumptions. The following table highlights the main differences:

Model assumption	ThermoSysPro	ThermoPower
Core power contributions	Neutronic and radioisotopes decay power	Only neutronic power
Xenon poisoning reactivity feedbacks	No	Yes
External reactivity insertion	Through control rod insertion speed	Direct external reactivity input
Pressurizer model	Non-equilibrium (two regions)	Equilibrium
Mass and energy balance equations	Dynamic energy balance	Dynamic (compressible fluid)

Table 2: Main differences between the NSSS models in ThermoSysPro and ThermoPower.

ThermoSysPro model

The models are assembled using components from the ThermoSysPro library, developed by EDF. The *NSSS_ThermoSysPro* package contains several versions of the NSSS model, with different interfaces (thermal and fluid connections) for the coupling with other components. The complete **model of the NSSS is also present, with the fluid interface for the connection to the BOP, as shown in the figure below:**

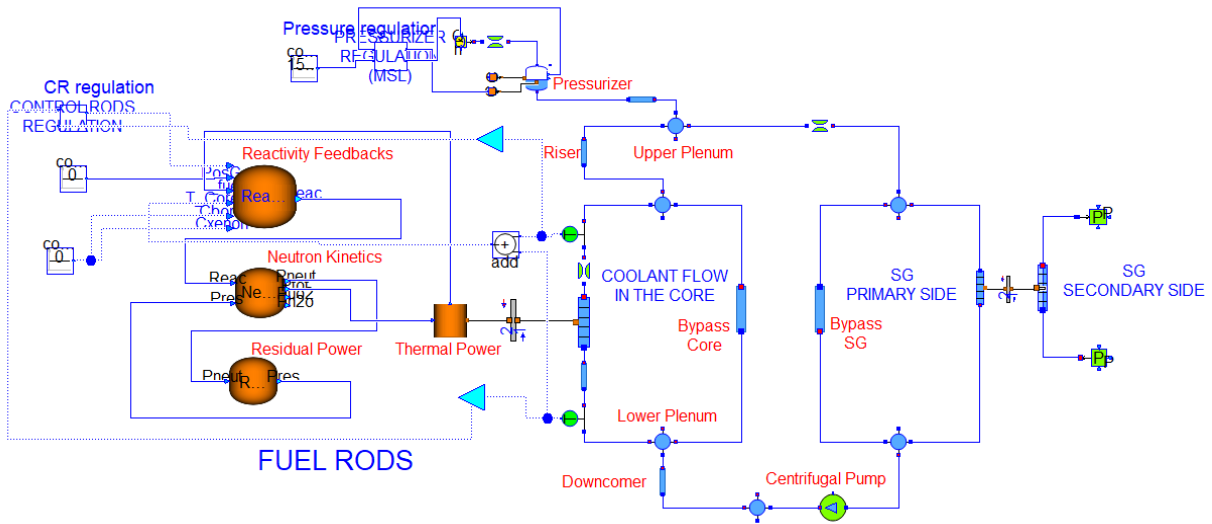


Figure 2: Example of NSSS model in ThermoSysPro.

Package description

The package is divided into different subpackages, as described below:

- The main package, which contains the *NSSS complete* model, and the models with the different interfaces available: the *NSSS_primary_base* model presents a thermal interface (*Thermal_Port* class in ThermoSysPro) and does not include the secondary side of the steam generator; the *NSSS_secondary_base* model instead includes the secondary side of the steam generator and the fluid interface.
- The *DEMOS* package, that contains some steady state examples of the models with different interfaces: the *NSSS_Primary* model that only includes the primary side of the steam generator, the *NSSS_Secondary* which includes also the secondary side of the steam generator, and also an example of the model with the secondary side and the Modelica Standard Library connectors, useful if the model has to be linked to a model built with the Modelica Standard Library components.
- The *CONTROL* package, that includes the system regulation models and a stand-alone model that contains both regulation systems: the average temperature control system, that acts on the control rods velocity, and the pressurizer control system, that regulates the pressure in the pressurizer volume.

The main modelling assumptions of the NSSS model are the following:

Neutronics Assumptions

The ThermoSysPro classes that describe the power production in the fuel, the reactivity feedbacks and the heat transfer in the fuel are the *Reactivity_Feedbacks* module, the *Neutron_Kinetics* module, *Residual_Power* module and the *Fuel_Thermal_Power* module. In the *Neutron_Kinetics* module the point reactor kinetics equations are solved, with six groups of delayed neutrons. The *Reactivity_Feedbacks* module is used to model the feedback effects in the fuel due to the fuel temperature (Doppler effect), the moderator, the control rods and the presence of neutronic poisons as Xenon or Boron (the latter being considered null in the TANDEM scope). The Xenon concentration in the core is considered constant and null, and this feature could be improved to consider also the variation of Xenon concentration in the core. The control rods groups are only two, the grey (G) group and the regulating (R) group. The G group is considered still and completely extracted from the core; its position and velocity can be changed by the user if needed. Moreover, the control rod worth is considered constant and independent from the position. The core is initialized in critical condition (the total reactivity is zero). The *Fuel_Thermal_Power* module describes the dynamics of the thermal conduction in the fuel pellets and between the pellet and the cladding by solving the radial 1D heat transfer equation. In the computation of the temperature, the fuel pellet is considered as divided in six axial zones and in three radial zones. The *Residual_Power* module calculates the residual power produced in the core due to the decay of fission products, and it considers six radio-isotopes maximum.

Thermal-Hydraulic Assumptions

The thermal-hydraulic model of the coolants passage in the core and the steam generators are based on a user-defined axial discretization of tubes, with a 1D staggered grid scheme (the component used is the *DynamicOnePhaseFlowPipe* in ThermoSysPro); all the pipes and heat exchangers have a cylindrical geometry. The convection heat transfer coefficient is computed using the Dittus-Boelter correlation for the one-phase flow, and the Gungor-Chen correlation for two-phase flow in the secondary side of the steam generator. In ThermoSysPro, the *Volume* components solve the mass and energy balance equations to compute the pressure and enthalpy of the fluid in the cell, while the *Flow components* (pipe and singular pressure losses), solve the momentum balance equation to compute the mass flow rate at the boundaries of the cell. The friction pressure loss term is computed using the Darcy-Weisbach equation; the friction pressure loss coefficient is computed with the Idel'cik correlation.

The pressurizer presents a two-region physical model; the conservation equations are solved for the liquid and vapor phases. The liquid that enters the pressurizer from the hot leg of the reactor is assumed to enter the volume with an enthalpy equal to the saturation enthalpy at the pressurizer pressure (to take into account thermal stratification in the pressurizer and avoid the impact of subcooling liquid on the thermal equilibrium of the pressuriser). The water sprays of

the pressurizer inject water taken from an independent external source, and not from the cold leg of the reactor. This could mean that the pressurizer might fill up completely if the simulated transients are too long.

Control Strategy

The *CONTROL* package includes models of the system controllers, and in particular the *regulation_pressurizer* model that controls the pressure in the pressurizer, the *regulation_CR* model that regulates the average temperature of the coolant, and the comprehensive *NSSS_CONTROL_ThermoSysPro* model that includes both of them.

Pressure controller

The pressure inside the pressurizer is kept constant by controlling the temperature of the fluid in the volume, which is at the saturation temperature and hence is maintained in two-phase condition. If the pressure in the core decreases to a value that is lower than a certain turn-on value, electrical heaters inside the pressurizer are activated in order to increase the temperature (and the pressure) in the volume, and in case the pressure in the core increases with respect to the turn-on value, water sprays are activated in the pressurizer so that part of the vapor phase condenses into the liquid lowering the temperature (and pressure) in the volume. In this model, the regulation of the pressure inside the pressurizer is given by two electrical heaters and one spray valve. During steady state operations, the backup heater is closed and the variable heater is open to compensate heat losses. The backup heater follows a ON/OFF regulation strategy, modelled through the *Hysteresis* component in ThermoSysPro; the output signal of the *Hysteresis* is then converted into a 1 or 0 real value and multiplied by the power of the backup heaters. The variable heater and the water sprays present a proportional regulation strategy. The relief valve is not included in the model.

Average core temperature controller

For the regulation of the average temperature of the coolant in the core, two temperature sensors are inserted at the inlet and at the outlet of the core, then the average temperature in the core is computed and compared to the setpoint temperature of the coolant. The absolute error of the temperature, if bigger than the ± 0.5 °C deadband, is then multiplied by a constant gain ($32.24 \frac{cm}{min \cdot ^\circ C}$) to determine the control rod speed. The maximum velocity of the bars is set to 72 cm/min. Since the reactivity of the bars is proportional to their position in the core, and the velocity of the bars is the derivative of the position of the rods, the control on the temperature is not only proportional, but it can be considered proportional-integral.



ThermoPower model

The models are based on components from the ThermoPower library, developed at Politecnico di Milano. The *NSSS_ThermoPower* package offers various versions of the NSSS model, allowing users to select the most suitable according to their specific needs. In particular, the models have different degrees of detail (e.g., in terms of bypass flows) or different interfaces to facilitate the coupling with other models. In the figure below, the detailed NSSS model with a fluid exchange interfaces is proposed.

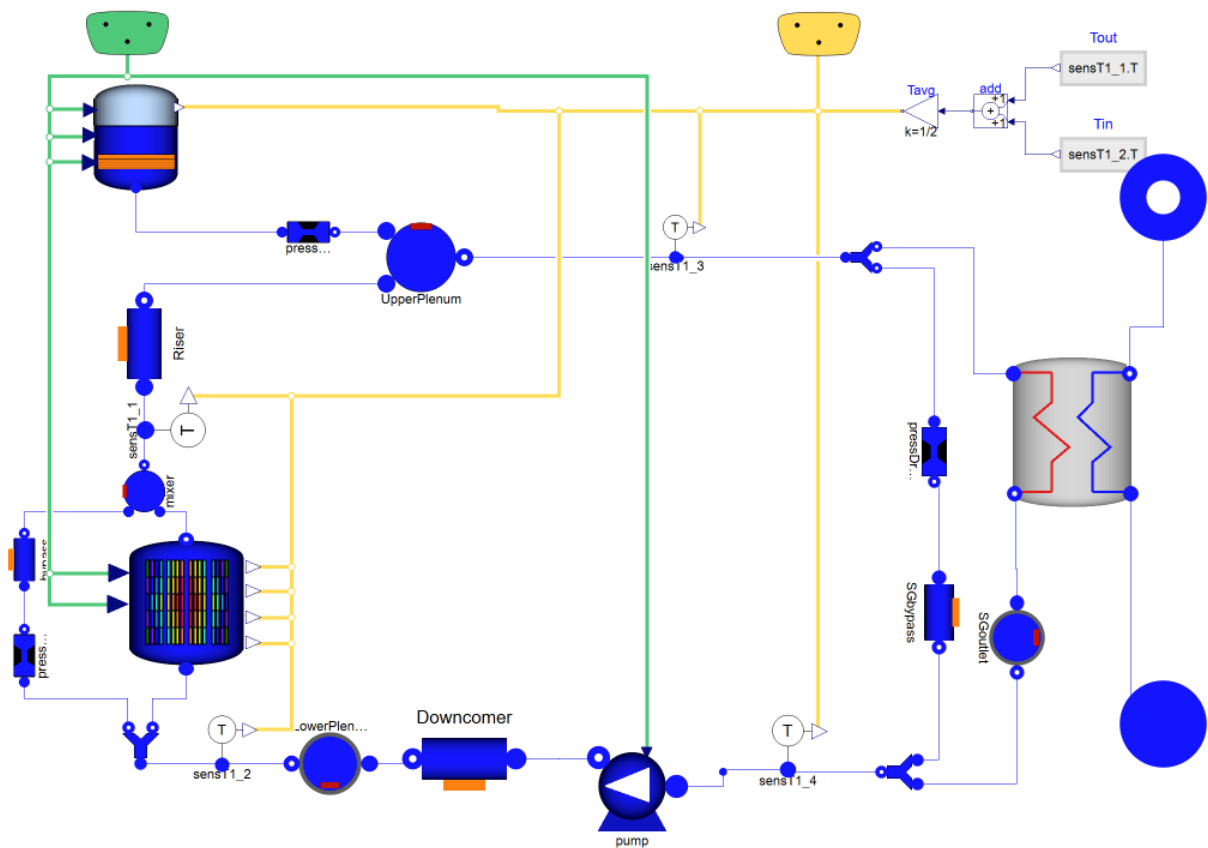


Figure 3: Example of NSSS model in ThermoPower.

Package description

The package is structured as follows:

- The *Test* package contains some test cases for the various versions of the NSSS model, showcasing its dynamic response after a perturbation of a variable exchanged at its interface (e.g., thermal power exchanged in the steam generator or secondary coolant flow rate).

- The main models have either a thermal or a fluid exchange interface. A simplified version, without core and steam generator bypass flows, is provided for both versions.
- The novel components developed for the NSSS model, namely the core, the pressurizer, and the steam generator, are collected in the *Components* package.
- The *Control* package delivers the controller components to regulate the pressure in the NSSS by acting on the pressurizer sprayers and electrical heater, and an example of core average temperature control program. These examples of controllers can be coupled to the NSSS model through dedicated connectors.
- Records for the neutronic parameters, together with some examples of initial conditions for the temperature distribution in the fuel rods to support the initialization of the models, are available in the *Data* package.
- The *Interface* package encompasses the partial models with the connectors and parameters that will be used for the different NSSS and controller models.
- The units that were not available in the Modelica Standard Library, such as those related to the neutronic modelling of the core, are included in the *Units* package.

Component description

The core, pressurizer, and steam generator models included in this package were developed specifically for the TANDEM library. The other components used for the simulation of the primary coolant flow within the NSSS, e.g., the riser, upper plenum, lower plenum, downcomer, etc., stem from the *Water* package of the ThermoPower library.

Core

The *Core* model is the first model available in this package and is based on three components gathered in the *BaseClasses* package:

- The *Flow1DFV_LiquidCoolant* component, employed to simulate the coolant flow through the core,
- The *NeutronicKinetics* component encompasses the neutronic model of the core,
- Lastly, the *Fuel* model provides the thermal analysis of the fuel rods.

The *Flow1DFV_LiquidCoolant* is based on ThermoPower's *Flow1DV* component. In particular, the latter component is extended with an additional connector (the *Moderation* connector in the *Interfaces* subpackage) to transfer the coolant average temperature to the *NeutronKinetics* block, which is required to estimate the moderator feedback contribution. As a result, the required parameters are those reported in the documentation of the ThermoPower component. *Flow1DV* also includes a connector exchanging thermal power and temperature, *DHTVolumes*, which is used to thermally couple the coolant flow through the subchannel to the fuel rod outer surface.

The *NeutronKinetics* model is required to simulate the neutronic behaviour in the core. It is based on point kinetics equations, with reactivity contributions from external sources (e.g., control rods), as well as reactivity feedbacks due to Xenon poisoning and fuel and moderator temperature. The reactivity contribution due to Xenon poisoning is computed by exploiting the decay laws of iodine-135 and xenon-135. On the other hand, the temperature feedbacks are driven by the fuel and moderator temperatures. Several options can be selected to specify the external reactivity insertion. Specifically, the external input can be considered as:

- the reactivity insertion, in pcm.
- the control rod displacement with respect to a reference position. In the model, the reactivity insertion is proportional to this displacement.
- the control rod position, which will be converted into the reactivity insertion through a sinusoidal relation.

The *NeutronKinetics* component interacts with the other core components through dedicated connectors included in the *Interfaces* subpackage, such as the aforementioned *Moderation* connector and the *Fission* connector, employed to exchange the fission power and the Doppler temperature (computed in the fuel rod's thermal model according to Rowland's model) with the *Fuel* component.

The thermal model of the fuel rods is based on a user-defined axial and radial discretization of the fuel pellets. In addition, energy balances on the pellet-cladding are implemented. As for the axial fission power distribution in the fuel pellets, two options can be selected by the user: either a uniform power distribution or a cosinusoidal distribution. The fuel zone is discretized radially and axially in control volumes of equal volume. The time-dependent Fourier equation, accounting for the heat source term due to fission and radial heat transfer through conduction, is adopted to model the thermal behaviour of the pellets. The fuel material properties and, similarly, the cladding and gap properties are available in dedicated models accounting for temperature dependencies within the *MaterialProperties* subpackage. The boundary conditions of the models are imposed through dedicated connectors, including the aforementioned *Fission* connector and ThermoPower's DHTVolumes component, which is used to exchange thermal power and temperature at the cladding outer surface with the coolant flow.

Pressurizer

The pressurizer model *PressEq* is based on the assumption of thermal equilibrium between liquid and vapour phases, i.e., considering a homogeneous fluid mixture within the pressurizer OD volume.

Compact Steam Generator

The *CompactSG* component relies exclusively on components of the ThermoPower library. In particular, the *Flow1DV* and the *Flow1DV2ph* represent the primary and secondary sides, respectively. The *MetalWallFV* component is adopted to account for the thermal resistance and inertia of the metal structure, whereas the *CounterCurrentFV* component allows considering counter-current flow directions.

The parameters required by these ThermoPower components can be computed, accounting for the steam generator configuration of interest. In the case of the E-SMR reactor, a printed circuit heat exchanger design, characterised by microchannels with a rectangular cross-section, is considered as a reference. As a result, the hydraulic diameter, flow area, and other parameters required by the *Flow1DV* component can be computed starting from the channel size and other geometric parameters.

Control strategy

The *Control* package includes examples of controllers to be coupled to the NSSS model to limit fluctuations in pressure and average core temperature. The package includes a controller for each variable, merged into the *NSSSctrl_ex1* and *NSSSctrl_ex2* components. These rely on the *Control_interface* model, available in the Interfaces package, used to connect the process and controlled variables to the signal buses of the NSSS model.

Pressure controller

Regarding the pressure control strategy, implemented through the regulation of actuators encompassed in the pressurizer model (i.e., sprayers, heaters, and relief valve), two examples of controllers are available in the *PressureControl* subpackage. In the *PressCtrl_OnOff* model, the measured pressure signal goes through the Hysteresis component of the Modelica Standard Library. This component allows for the comparison of the input signal with a lower and upper threshold value, switching the Boolean output whenever the input crosses one of the two limits. The Boolean output is then converted to a real value (0 or 1) that is multiplied with the nominal value of the actuators, e.g., sprayer flow rate, proportional and backup heater power, and is then transmitted to the pressurizer model. On the other hand, the *PressCtrl_linear* controller adopts a different approach for proportional heater and sprayer control, whereas the backup heater and relief valve opening are regulated according to the same philosophy as the previous controller. For the former, the value of the actuator signal is proportional to the deviation of the measured pressure from its setpoint. In the test case showcasing the dynamics of the NSSS models, the *PressCtrl_linear* has been considered as a reference.

Average core temperature controller

In the proposed average temperature control program, the average core temperature is controlled at its setpoint value through the insertion of external reactivity (e.g., through control rods) in the core. The normalised error between the measured average core temperature and its setpoint is used in the Modelica Standard Library's *LimPID* component to determine the required reactivity insertion. This approach is adopted in the *TavgCtrl_simple* model, whereas the *TavgCtrl_deadZone* version includes a controller's dead zone regarding the error on the average temperature. The latter controller is included in the *NSSSctrl_ex2* model, which has been considered in the test cases available in the *NSSS_ThermoPower* package.

Provided examples

This package provides a test case for each NSSS model version to analyse the dynamic response of the system following perturbations on the secondary side, either in terms of feedwater flow or exchanged thermal power. In each case, a ramp-wise power or feedwater decrease is simulated. In the test cases, the NSSS model is connected to an illustrative controller, encompassing pressure and average core temperature control by regulating the pressurizer's actuators and the reactivity insertion, respectively.

The following test cases are proposed:

- The *Test_NSSSsimple_fluid* demo showcases the dynamic behaviour of the simplified NSSS model with a fluid exchange interface. The model is tested by imposing boundary conditions for the fluid's state on the secondary side, namely the feedwater conditions entering the steam generator (in terms of mass flow rate and enthalpy through the ThermoPower *SourceMassFlow* component) and the pressure (through the SinkPressure component) at the steam generator's outlet.
- An analogous transient simulation is proposed in the *Test_NSSSbypass_fluid* model. In this case, the aim is to test the detailed NSSS model, which also features core and steam generator bypass flows.
- In the *Test_NSSSsimple_thermal* demo, the transient response of the simplified NSSS model to a reduction in thermal power removal at the steam generator is investigated. The boundary condition of the model, i.e., the thermal power exchanged at the steam generator's wall, is imposed through ThermoPower's *HeatSource1DFV* component.
- As for the fluid interface version, the detailed NSSS model with thermal interface is tested in the *Test_NSSSbypass_thermal* model.



The simulation outcomes obtained with the thermal interface are presented in the next section, together with a comparison with the results obtained with the ThermoSysPro model.

NSSS model benchmark

The NSSS package includes also a Benchmark subpackage that contains transient simulations for the ThermoPower (both the simplified and the complete version) and ThermoSysPro models. There is also a subpackage that contains the validation models on the Pressurizer module in both libraries. The results obtained with both NSSS models can be compared and thus the best model for the specific application and context can be selected.

Pressurizer

Recalling that the pressurizer components are based on different modelling approaches in the two models, namely assuming the liquid and vapour phases to be in equilibrium in the ThermoPower model and accounting for phase separation in ThermoPower, a dedicated comparison limited to the perimeter of the pressurizer model is performed. In particular, the two pressurizer models are tested with the same boundary conditions, imposed as mass flow sources at the inlet fluid connectors, to test the dynamic response of the components. Moreover, the simulation outcomes are compared to the experimental data collected for the pressurizer of the Shippingport reactor, available in literature (Pini, 2013).

For this validation, the pressurizers dimensions, operating parameters and control parameters were adapted to the one used in the Shippingport's reactor pressurizer, as the experimental data used for the benchmark are taken from two loss-of-load test performed on this pressurizer. Two transients were considered: the first one consisted of a load reduction that started from the steady state condition of 74 MWe, to 10 MWe and then, after about 6 minutes, the load is reduced to 0. The second one started from 105 MWe, then the load is reduced to 35 MWe, then 10 MWe and then 0 (Pini, 2013). The response of the two models in terms of pressure in the pressurizer's volume is compared to the results obtained on the Shippingport pressurizer in the plots below.

The simulation was run for 720 seconds in both cases.

Figure 4 and Figure 5 show that the intensity of the first pressure peak and the following decrease is correctly represented by both models, despite a significant delay, for both transients. The second peak is more smoothed in the computational results compared to the experimental data, which is consistent with the more "inertia" that seems to affect the models. However, the pressure trends for both codes are consistent among them and with the experimental data. For a deeper analysis of the results, more experimental data would be required.

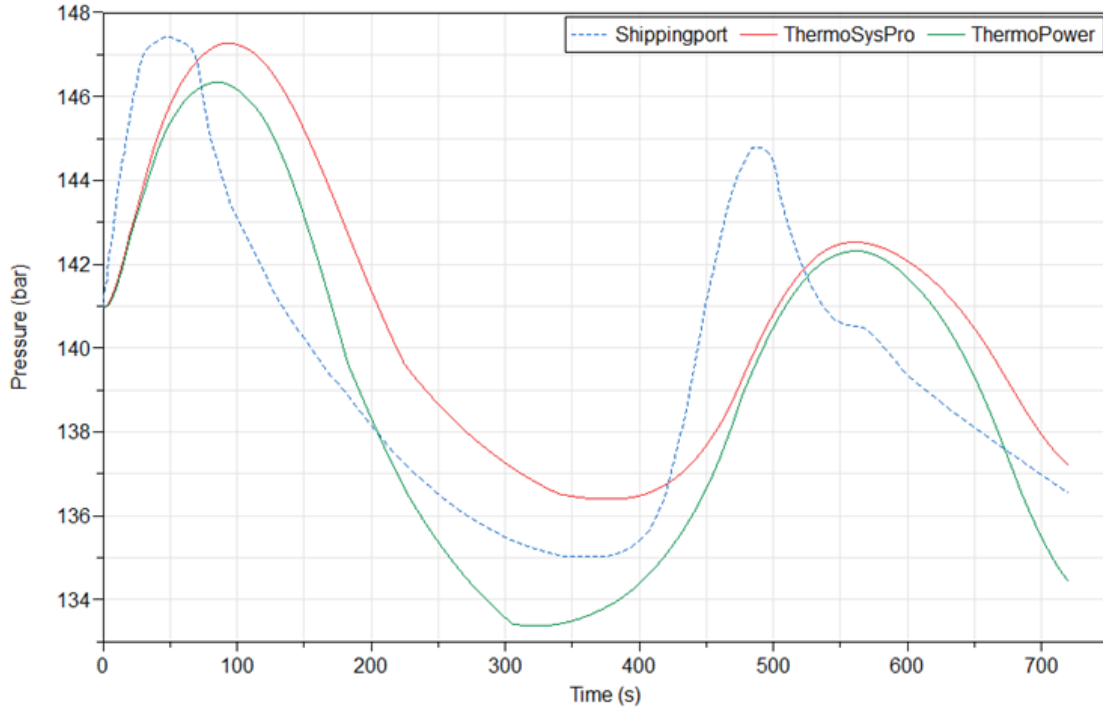


Figure 4. Pressure trend for the 74 MW transient results in ThermoSysPro and ThermoPower.

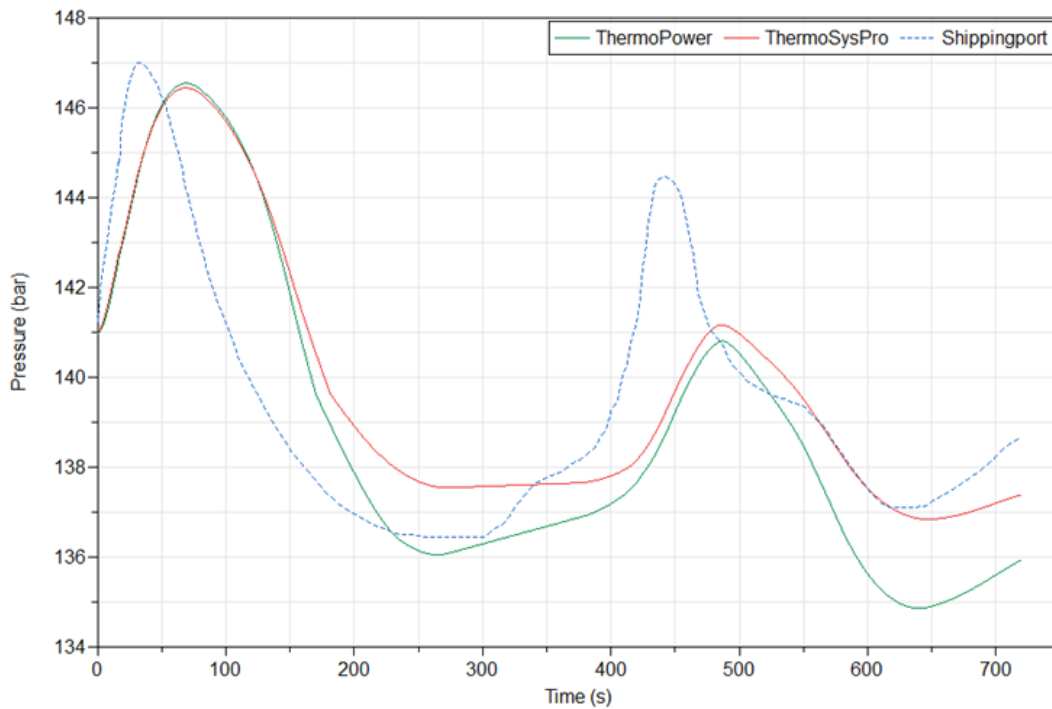


Figure 5. Pressure trend for the 105 MW transient results in ThermoSysPro and ThermoPower.



NSSS

The model was tested varying the power extracted from the secondary side of the steam generators, and in particular three different power transients were considered: one step power reduction of 10% and a ramp reduction to 50% of the nominal power (corresponding to 5%/minute). For the ThermoSysPro model, it was decided to set a variation of extracted power by varying the temperature on the secondary side: that was done using a PI controller. The ThermoSysPro model does not consider the dilatation and compression effects of the fluid, as the model turned out to be too computationally expensive otherwise, and employs a simplified set of balance equations in the primary side, in which the inflows and outflows are balanced in the *Volume* components and in the *DynamicOnePhaseFlowPipe* components. On the other hand, the ThermoPower model considers the expansion and compression of the fluid. This difference is particularly evident in the pressure trend during the transients (see Figure 15), while it does not affect notably the other variables considered. Another main difference is in the reactivity insertion and can be traced back to the different average temperature control systems of the two models: the ThermoPower model acts directly on the temperature by injecting reactivity in the core, while the ThermoSysPro model acts on the velocity of the control bars. Finally, we can see a different trend in the temperature evolutions during the 5%/min ramp (see Figure 11): this is related to the Xenon modelling in the ThermoPower model; the antireactivity injection due to the increase of its concentration leads to a temperature decrease within the deadband.

The results of the benchmark for the step power reduction and the 5% ramp reduction are reported below for the average temperature of the coolant, the inlet and outlet temperatures, the pressure, the reactivity and the thermal power.

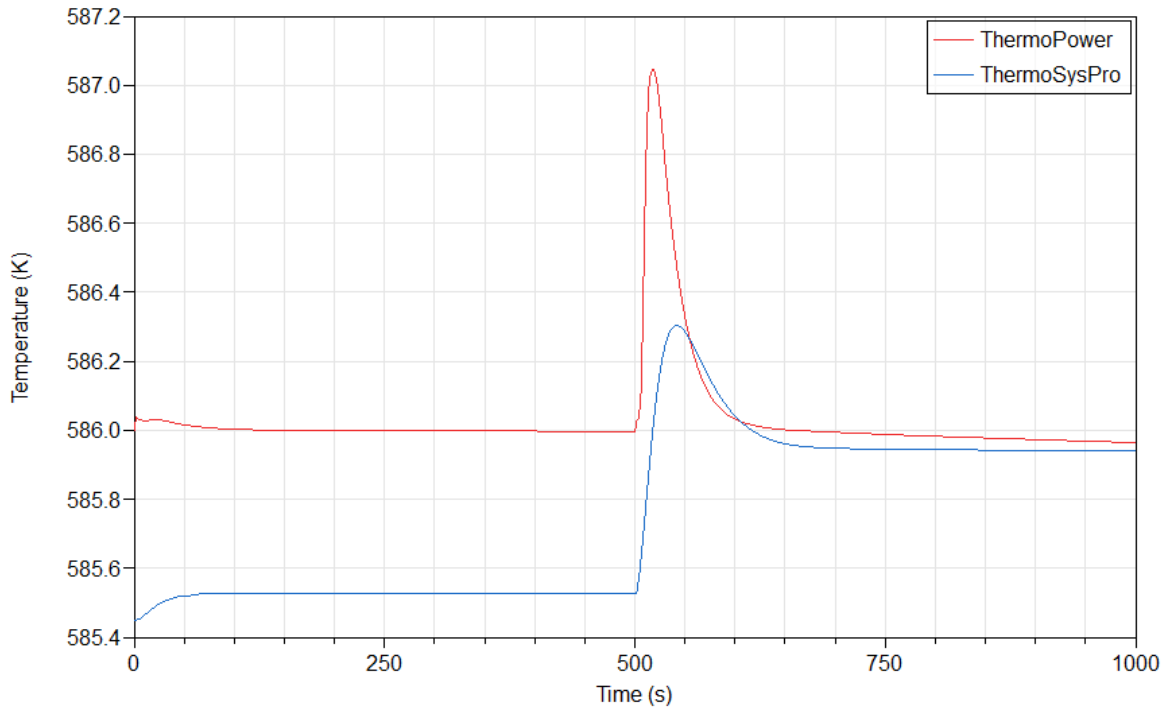


Figure 6. Average temperature of the coolant in the step power reduction.

Both average temperature control systems include a deadband of 0.5 K, nonetheless the ThermoPower model computes the steady state starting temperature each time, while the ThermoSysPro model starts from a fixed average temperature of 585.45 K.

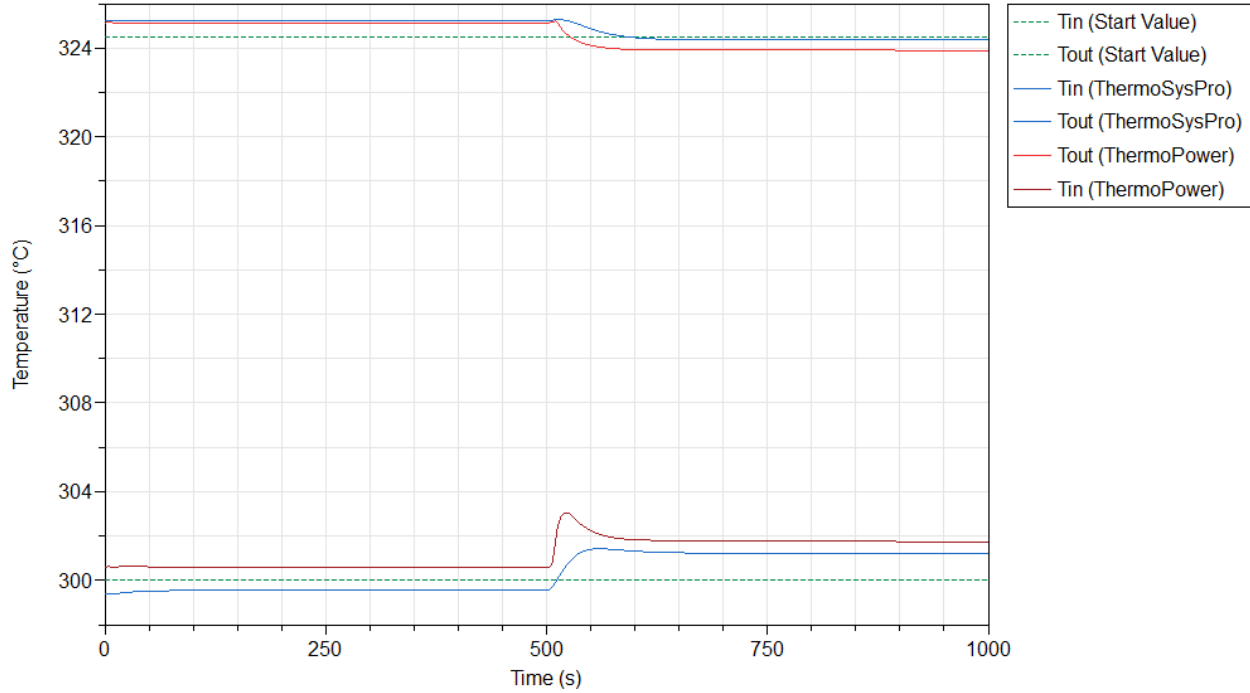


Figure 7. Inlet and outlet temperature of the coolant in the step power reduction.

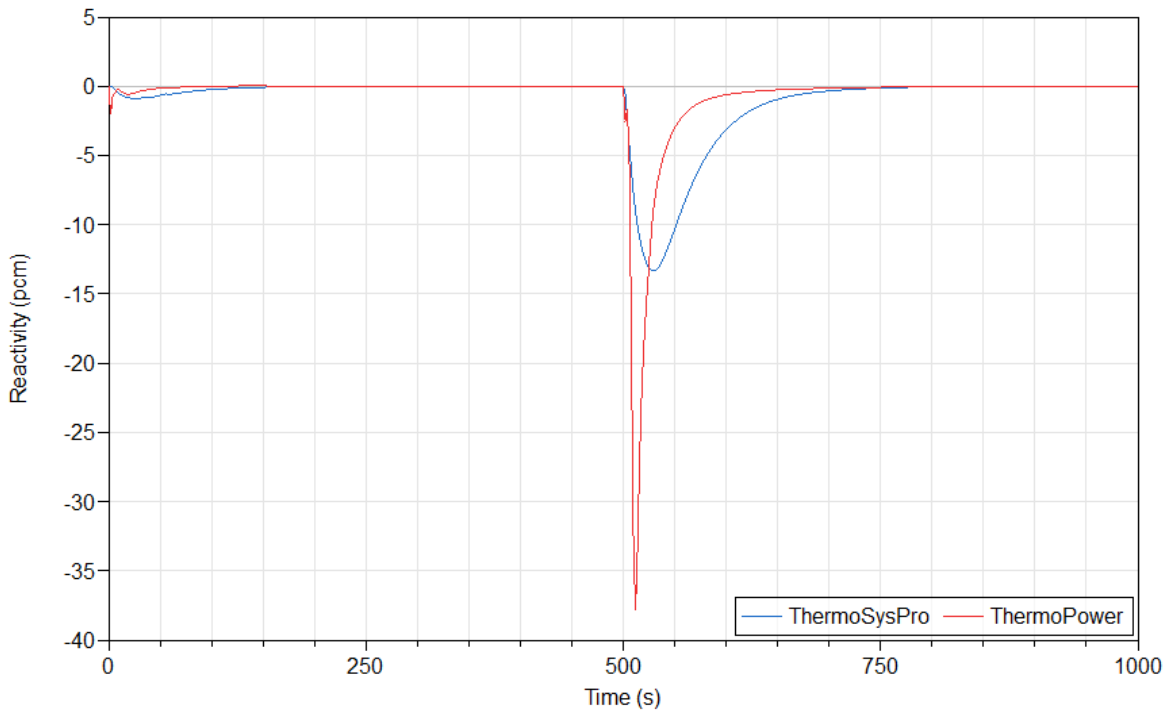


Figure 8. Total reactivity insertion in the step power reduction.



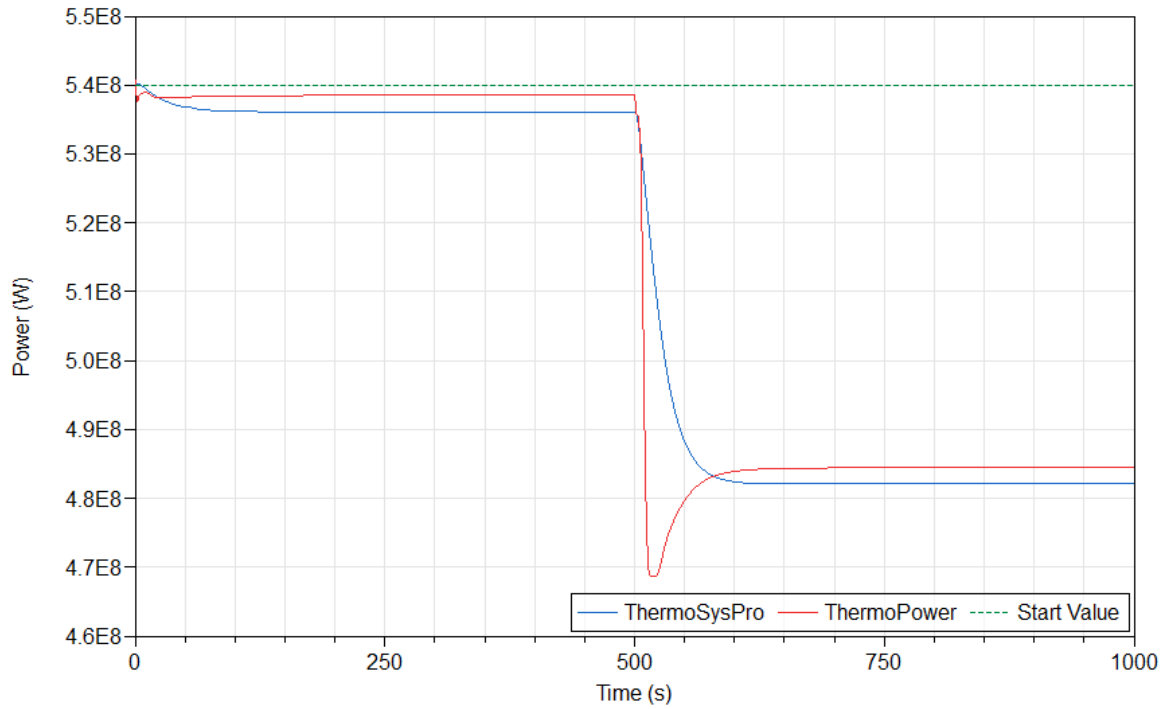


Figure 9. Thermal power in the step power reduction.

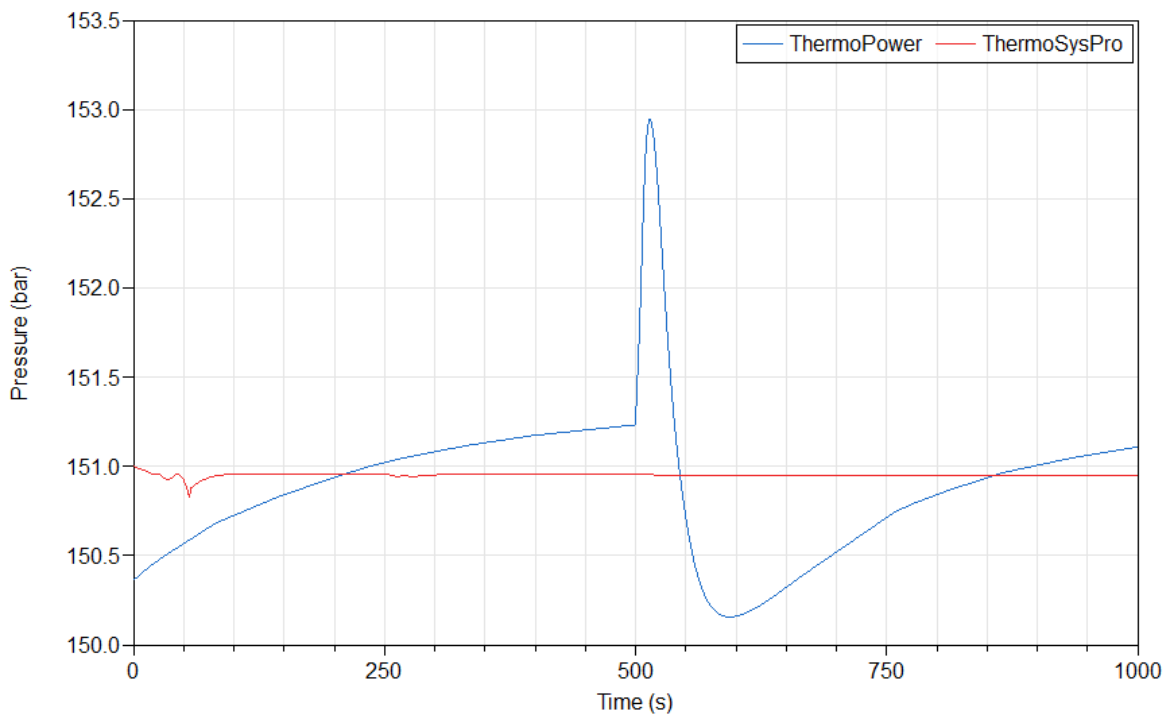


Figure 10. Pressure variation in the step power reduction.

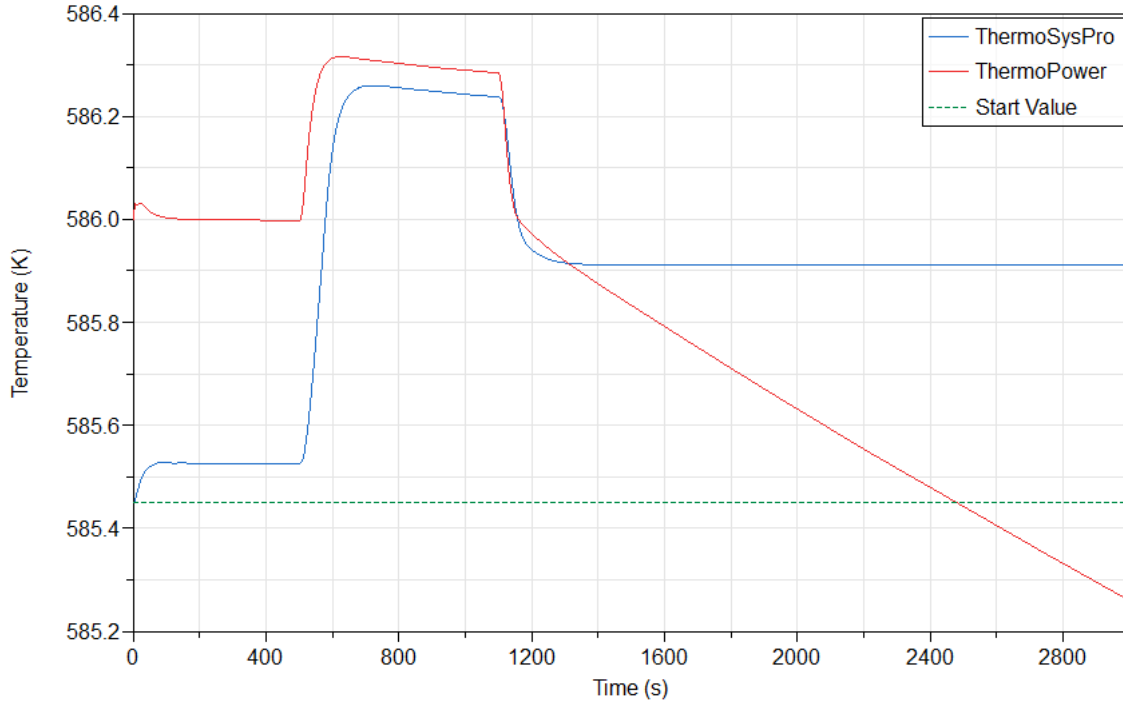


Figure 11. Average coolant temperature in the 5%/min ramp reduction.

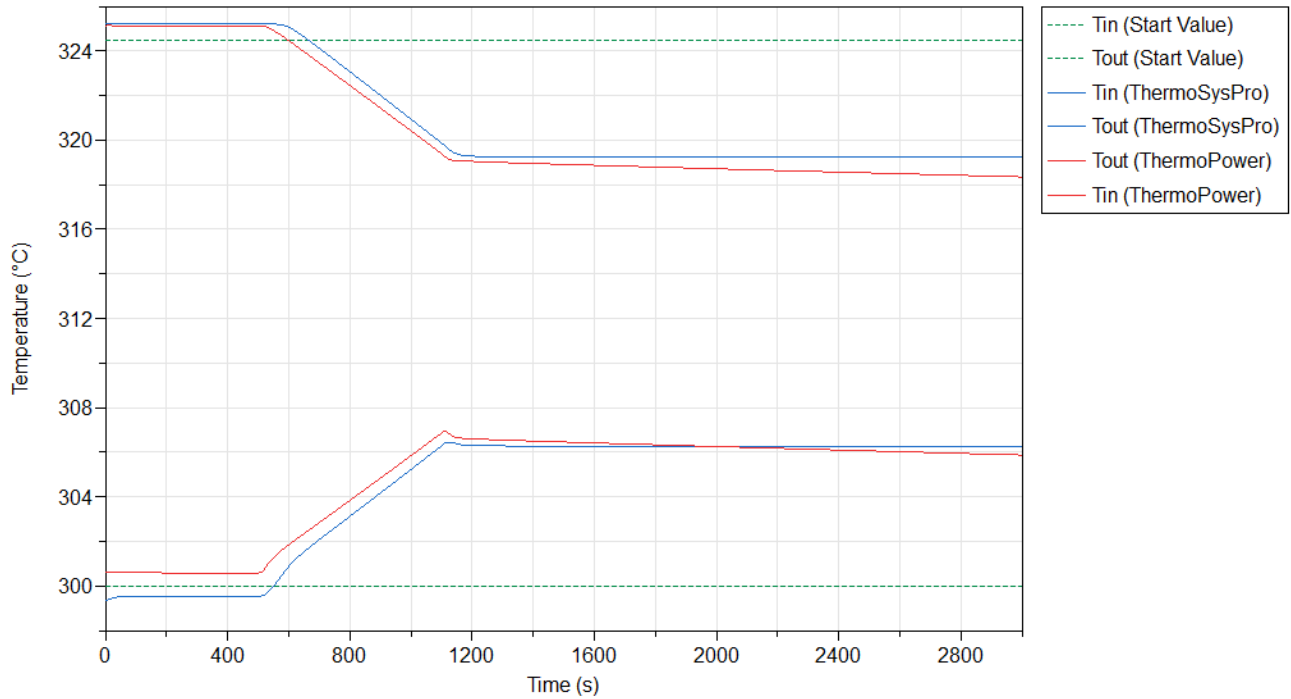


Figure 12. Inlet and outlet coolant temperature in the 5%/min ramp reduction.



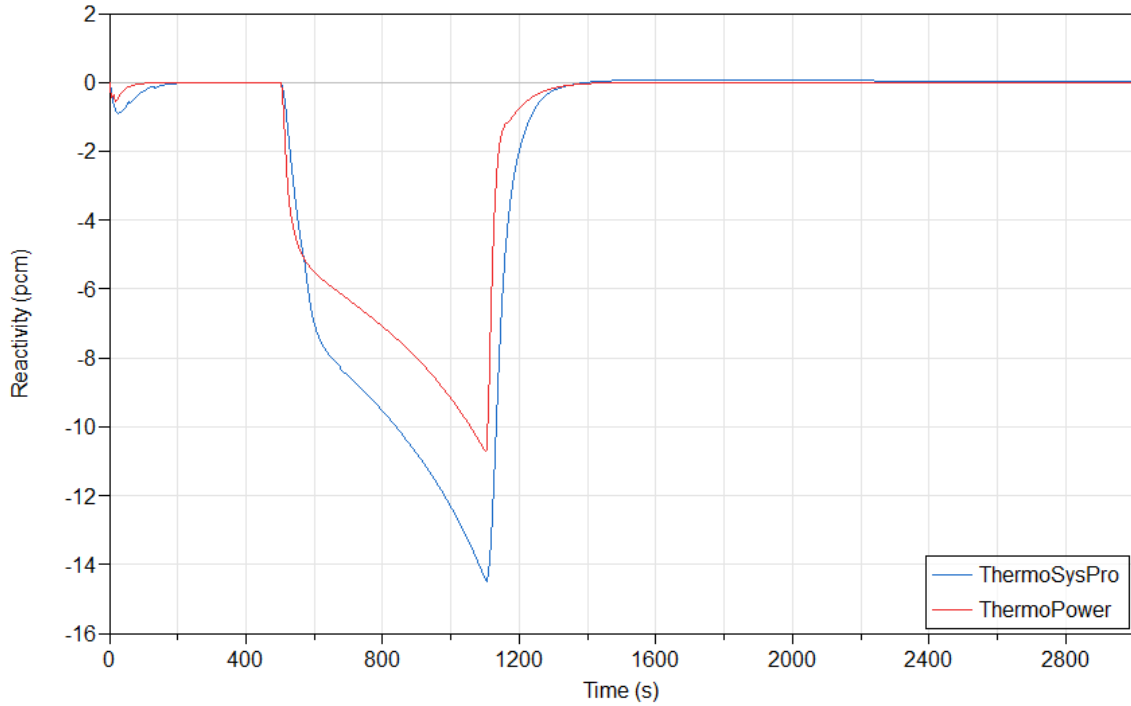


Figure 13. Total reactivity variation in the 5%/min ramp reduction.

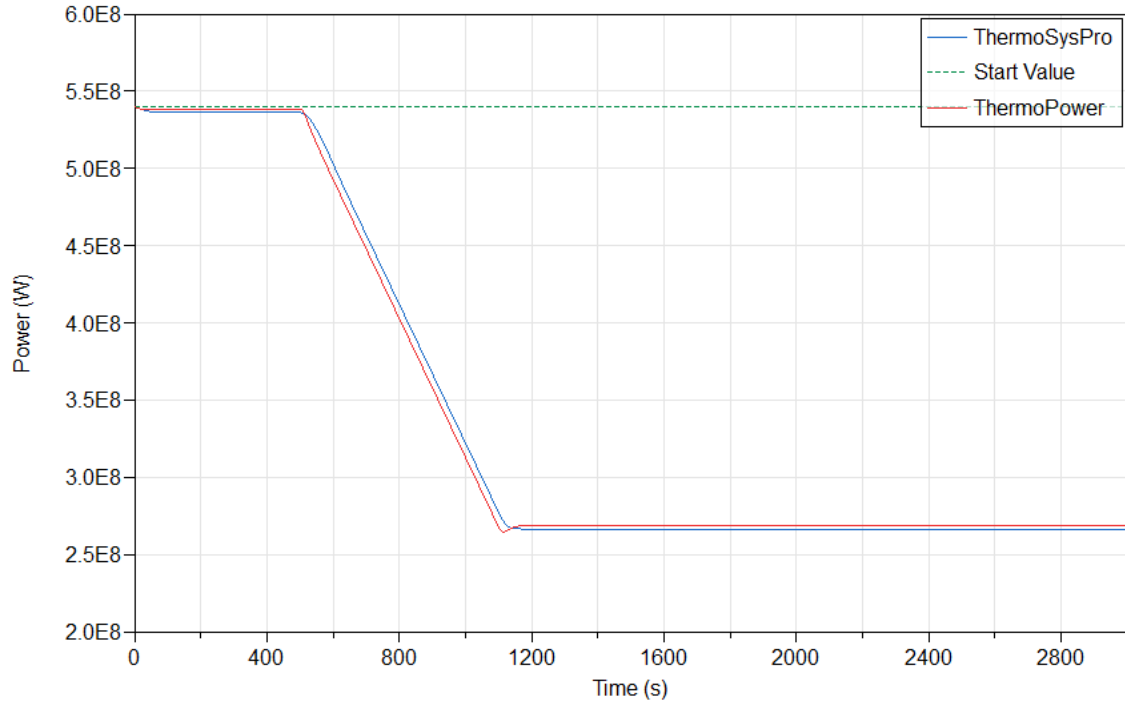


Figure 14. Thermal Power in the 5% ramp/min reduction.



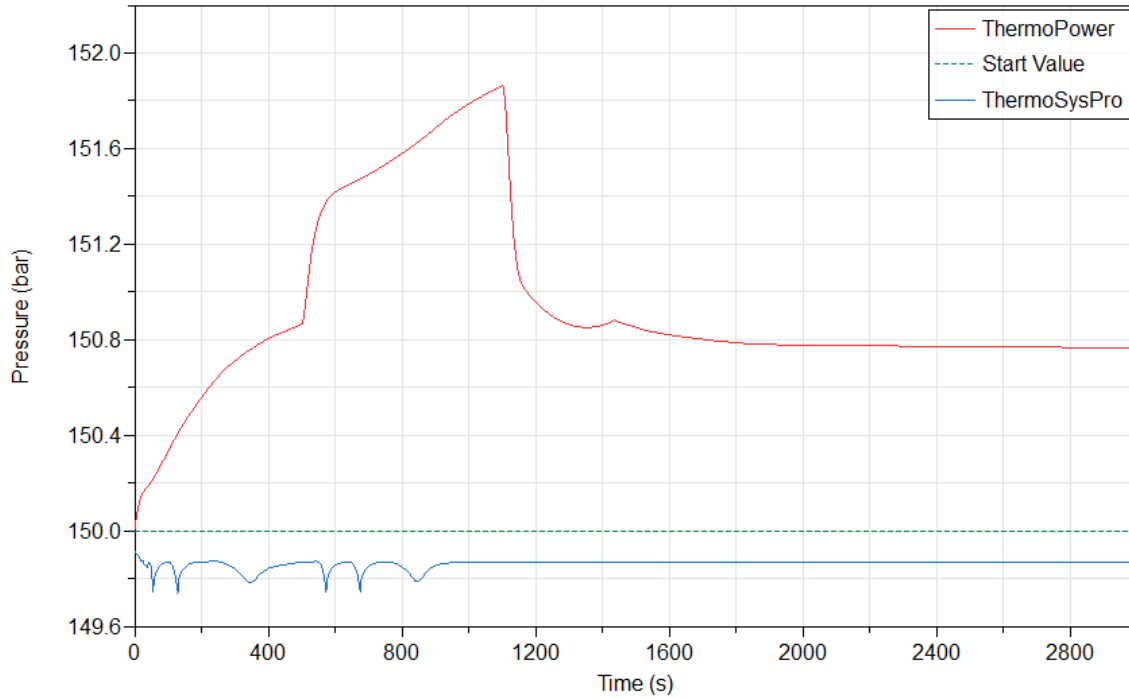


Figure 15. Pressure variation in the 5%/min ramp reduction.

3. Balance Of Plant

Three models of the balance of plant (BOP) are available in the TANDEM library, two of them based on the ThermoPower library and one on the ThermoSysPro library. These BOP models are employed to simulate a Rankine steam cycle, optimized using the CYCLOP tool (Haubensack et al., 2005). This tool provided the optimal thermodynamic points of the steam cycle, assuming the steam generator operating parameters as boundary conditions, to maximise the electrical power output³.

The following table outlines the main distinguishing features of each BOP model. The multi-development of BOP models that was carried out, is justified by the need to validate coupling connectors from one library to another: indeed the BOP plays a pivotal role in power distribution and TANDEM library effective versatility is strongly depending on the point. Another key reason for the parallel and coordinated developments, is the need to provide different possibilities to explore the challenging coupling between TANDEM library and system codes (CATHARE or ATHLET): consistently, the table below reports that different choices were made regarding

³ (Nguyen et al., 2020) have discussed the value and limitation of such a cycle design approach for hybridation, depending on the temperature grade and thermal power amount used for cogeneration

thermal or fluid ports. Finally, the possibility of benchmarking and measuring the effect of inertia according to the type of transient could also be seen as two aspects of prime interest. As such, the user may be more interested in having a calculation that is fast in terms of CPU (and therefore easily integrated into a global optimisation process of an energetic system) but quasi-static to address energetic performance, or on the contrary, with the possibility of fine representation of the dynamics to carefully analyse heat and electric networks service capacities.

Features	ThermoSysPro	ThermoPower (1)	ThermoPower (2)
<i>Cycle control</i>	ST sliding pressure, Feedwater valve, Variable speed pump , MSR control valve	Feedwater valve	ST sliding pressure, Feedwater valve, Variable speed pumps, MSR control valve
<i>Heat interfaces</i>	HP, MP & LP heat extractions	HP, MP & LP heat extractions	HP, MP & LP heat extractions
<i>SG interface modelling</i>	Fluid port	Thermal port	Thermal port
<i>Heat extraction interface modelling</i>	Fluid port	Thermal port	Fluid port
<i>Interface control</i>	External by-pass valve	Internal by-pass valves controlled on condensate subcooling	External by-pass valve
<i>Inertia modelling</i>	Quasi-static	Reheaters	All heat exchangers and drums
<i>Main limitations</i>	Control parameters are sub-optimal (but consistent with a QS approach)	MSR reheater and condenser inertia omitted	

Table 3: Comparison between the BOP models.

ThermoSysPro model

The ThermoSysPro BOP models a Rankine steam cycle with cogeneration possibilities:

- As mentioned above, the design of the cycle follows a preliminary CYCLOP calculation that was carried out to define the optimal cycle coordinate (P, H) optimised for electricity production, as well as the architecture of the cycle to be implemented (compromise between simplification and representativeness). Therefore a high and low pressure reheaters are employed, rather than a larger (more optimized) cascade of these components;
- Cogeneration capabilities are provided by controllable steam extraction lines at high pressure - HP (45bar, 300C), intermediate pressure - IP (7.5bar, saturated) and low pressure - LP (0.8bar, saturated).

Circuit Description

The Rankine cycle mainly features:

- An expansion line with 3 turbine groups that produce mechanical work and then electrical power through a generator;
- HP, IP and LP steam line tapplings that are connected to (ideal) heat exchangers;
- A dryer and a super-heater;
- A cooler that is the heat sink;
- Two pumps (LP and HP);
- Two reheaters;
- A heat source that is mimicked through fluid flow boundary conditions : this component is either in the TANDEM/N3S scope, either part of the system code - CATHARE or ATHLET - modeling;
- A liquid extraction line at the outlet of the BP pump is installed to add heat to the cycle and inject the steam produced upstream of the IP turbine.

The heat exchangers that condense the steam from the extraction lines are modelled in separate loops, plugged to the BOP model: the intention is to allow these loops to be replaced by more sophisticated models, possibly with a different secondary fluid (such as thermal oil). Hence, modularity was key target feature for the BOP development.

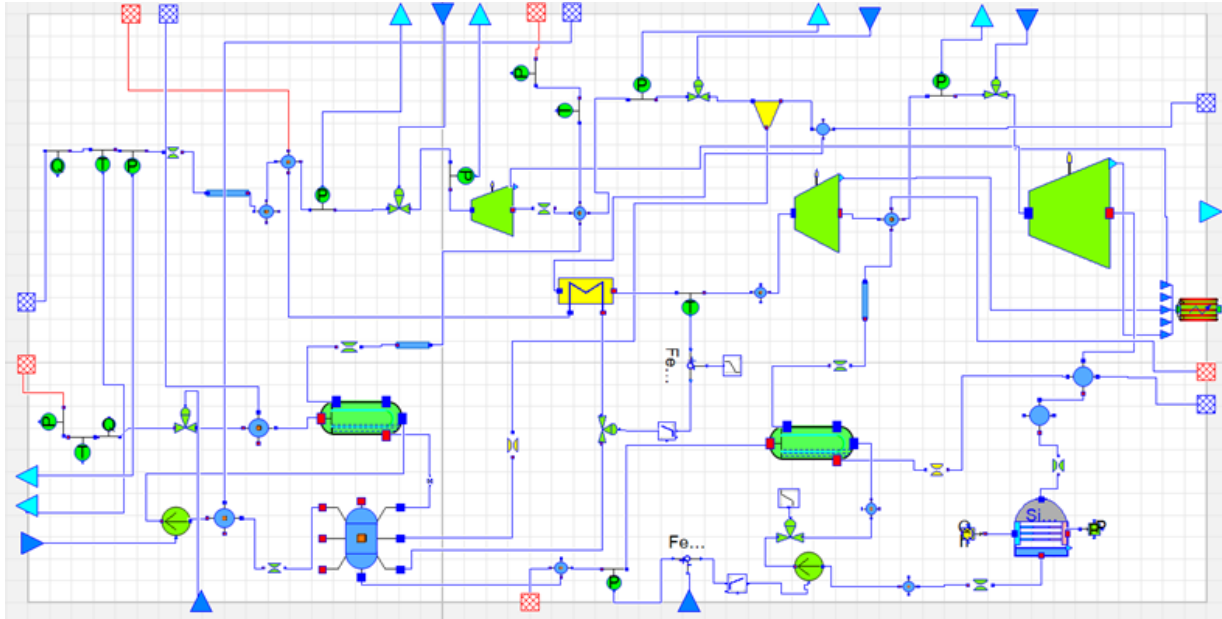


Figure 16. ThermoSysPro BOP model.

Modeling and Assumption

ThermoSysPro 4.0 is used, with Modelica 4.0 (which is the standard for the TANDEM project). *WaterSteam* is the only fluid used in the circuit, according to IAPWS-IF97 standard.

The modelling assumptions for each component, which are static (the same approach was followed by (Nguyen et al., 2020) for cogeneration study with a French PWR1300), are briefly introduced here; further details can be found in the ThermoSysPro Book, to which careful reference is therefore recommended (El Hefni & Bouskela, 2019). Some important points are summarized below:

- Turbine groups are modeled according to :
 - Stodola ellipse law that connects pressure ratio to inlet flow mach number;
 - An efficiency law which correlates steam flow wetness to entropy increase (also known as Baumann's rule);
- Reheaters are NTU heat exchanger models, featuring three geometrical sections, only two being actually engaged in our case: two-phase-flow and liquid single-phase-flow thermal exchange areas;
- Pumps follow classical quadratic flow maps, with speed as a parameter;
- Condensers that transfer heat from the steam line tapplings, are ideal: they fully condensate any steam flow.

To be consistent with these hypotheses, the scope of the use of the model should primarily address the thermodynamic aspects linked to cogeneration flexibility, in the framework of

conceptual R&D study. Thus, an example of use in an appropriate context is presented in (Masotti, Haubensack, et al., 2024).

Main Parameters

The main parameters of the cycle design are shown in Table 1.

Cycle parameters	Values
Heat source power	540 MW
Boiler inlet ; outlet temperature	163C ; 300C
Boiler inlet ; outlet pressure	45.4 ; 45 bar
Condenser pressure	70 mbar
IP tapping line	7.56 bar
LP tapping line	0.815 bar
SG feedwater mass flow rate	240 kg/s

Table 4. Main cycle design parameters.

These parameters are used to size the different components (calibration step), as reported in Table 2 for the main ones.

Main Components design data	Values
Stodola constant – HP	688136
Stodola constant – IP	24244
Stodola constant – LP	659
Reheater - HP: condensing and cooling zones "UA"	2.38e6 W/K ; 4.8e3 W/K
Reheater - LP: condensing and cooling zones "UA"	1.758e6 W/K ; 27.9e3 W/K
Pump - HP: a1 ; a2 ; a3 (normalized coefficients)	-2551 ; 0 ; 594
Pump - HP: b1 ; b2 ; b3 (normalized coefficients)	-16.5 ; 7.65 ; -7.5E-3
Pump - LP: a1 ; a2 ; a3 (normalized coefficients)	-477.7 ; 0 ; 72.8
Pump - LP: b1 ; b2 ; b3 (normalized coefficients)	-25.2 ; 9.47 ; -7.5E-3
Valve, CvMax : HP turbine inlet	90000 m ⁴ /(sN ⁵)
Valve, CvMax : IP turbine inlet	700000 m ⁴ /(sN ⁵)
Valve, CvMax : LP turbine inlet	2.8E7 m ⁴ /(sN ⁵)
Valve, CvMax : Steam generator inlet	1200 m ⁴ /(sN ⁵)

Table 5. Main calibration data of sized components.

Control Strategy

Various control strategies are proposed, as this is in fact a topic for research and development:

1. Control of the steam generator and turbine:

- The water flow at the inlet of the steam generator can be modified by the speed of the HP pump or by the opening of an inlet valve.
 - This inlet flow rate can be modified to control either the pressure ("P" approach) or the temperature ("T" approach) at the steam generator outlet:
 - In the first case, the turbine inlet pressure (admission) is defined as an auxiliary control parameter and is controlled by the opening of the inlet valve.
 - In the second case, the steam generator pressure is defined as an auxiliary control parameter and is controlled by the opening of the turbine inlet valve. Demo cases have been carried out for each approach (see below).
2. Steam flow from the extraction lines can be pressure controlled (e.g. to guaranty a given (saturated) temperature to the process cogeneration customer) or left free (pressure sliding mode).

It should be emphasized that the PI controller parameters must be adapted to each coupling and are therefore the responsibility of the user depending on his application and the associated couplings of modules.

Provided Examples

In the **Demo_BOP_Plugged** subpackage some usage examples can be found:

- **StaticBoP3_T_Plugged_BC**. This demonstration case connects the BoP3 model to a 0D heat source (boundary conditions). Control is performed by using the "T" approach, together with HP pump speed control. Along a 1000s (quasi-static) transient, the BOP switches from a pure power generation mode (100s) to a cogeneration mode. Cogeneration is achieved by simultaneous extraction of steam flows at HP, IP and LP, while pressure of the tappings are controlled and maintained to their nominal values. Cycle electrical efficiency, defined as the mechanical power of the turbine over the thermal power at the steam generator, falls from about 32.9% to 25.4% while cogeneration thermal powers reach 36.5 MWth, 54.2 MWth and 56.4 MWth, respectively at HP, IP and LP (i.e. a total of ~27% of boiler output). Conjointly, temperature at steam generator inlet rises from 163 to 172.3 °C. Figure 2 reports effective operability of the test-case along the 1000s transient.

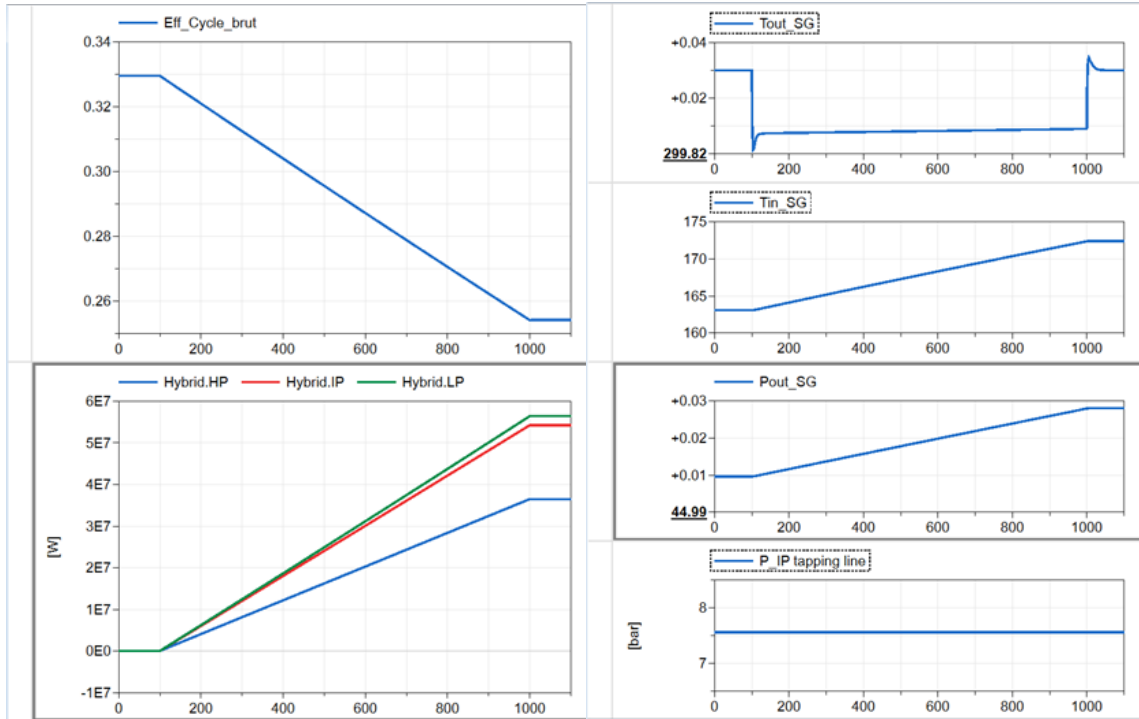


Figure 17. Electrical efficiency of the cycle and cogeneration powers (left); Control parameters and inlet SG temperature (right).

- **StaticBoP3_P_Plugged_BC.** This demonstration case connects again the BoP3 model to a OD heat source as boundary conditions, but by using the "P" control approach.
- **StaticBoP3_T_Plugged_N3S_TMPower.** This demonstration case connects the BoP3 model to CIRTEN-POLIMI's N3S TANDEM model, which can be seen as a challenge since both have been recently developed. In operational terms, this case shows that library connections via the fluid connectors, developed as part of the TANDEM project, are relevant. The "T" control approach is used, together with speed control of the HP pump. Over a transient of 1000s, the BOP switches from a pure electricity production mode (100s) to a cogeneration mode: cogeneration is achieved by simultaneous extraction of steam flows at HP, IP and LP. This demonstration case, obtained directly by coupling with the N3S model from the corresponding TANDEM directory, was then optimized in terms of numerical convergence and technical specifications (such as core power).
- This led to the demonstration case **StaticBoP3_T_Plugged_N3Sbypass_TMPower_Tail.** By differentiating it with **StaticBoP3_T_Plugged_N3S_TMPower**, it shows the (expert) user how to perform this type of tailored optimization. It is worth pointing out that, on a standard computing station, the 1100s transient requires only 90s of CPU, which illustrates the performance and versatility of the TANDEM library as an R&D engineering tool (e.g. its CPU consistency with additional uncertainty studies). Figure 3 reports

effective operability of the (non-optimized) **StaticBoP3_T_Plugged_N3S_TMPower** test-case for the first 100s.

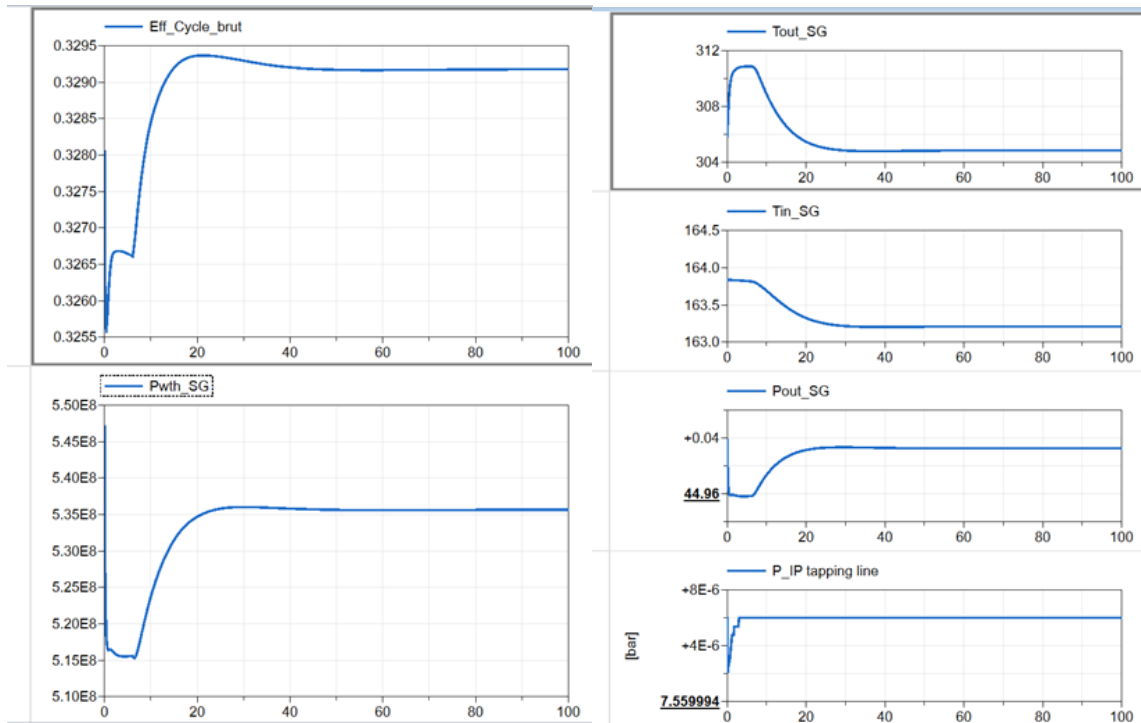


Figure 18. Establishment of the coupling steady state. Electrical efficiency of the cycle and boiler thermal power (left); Control parameters and inlet SG temperature (right).

- **StaticBoP3_P_Plugged_N3S_TMPower.** This demonstration case connects again the BoP3 model to CIRTEN-POLIMIS N3S TANDEM model, but by using the "P" control approach.

Thermopower model

The balance of plant component models a nuclear steam cycle converting the heat provided by the reactor coolant system (RCS) into electrical power and steam that can be supplied to various assets (HTSE, thermal storage, water desalination, etc.).

The steam cycle architecture considered includes a HP and a LP steam turbines (ST) with an intermediate extraction in the LP ST casing. Three pressure levels (HP, MP and LP) are then available. A moisture separator reheater (MSR) is installed at the outlet of the HP turbine (MP). Two reheaters (MP and LP) offer a small performance gain over the basic Rankine cycle.

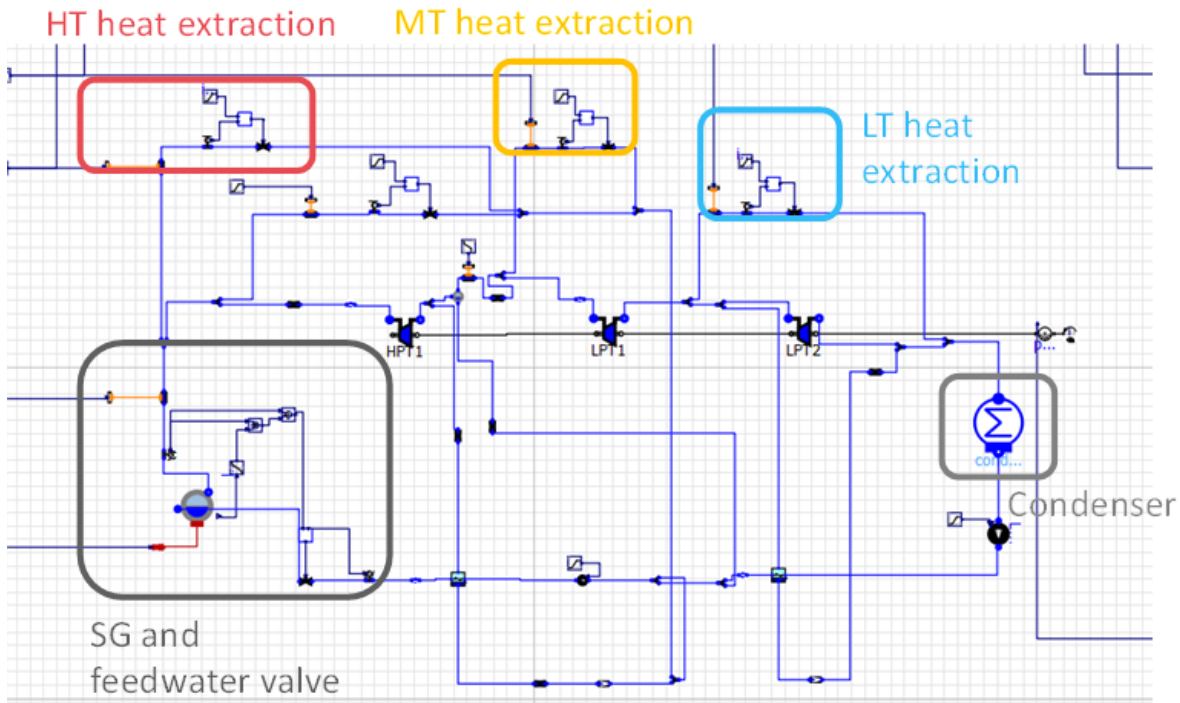


Figure 19 : ThermoPower BOP model.

Circuit Description

The BOP is supplied in heat from the RCS model, produces an overheated steam flow in the steam generator (SG), converts it in mechanical power in the steam turbines (ST) and converts it in electrical power in the generator. Main equipment models of the BOP are based on ThermoPower 3.2 library :

- A steam generator (SG) : drum simplified component ;
- A HP and two LP ST : Stodola steam turbines ;
- A moisture separator : built-in moisture separation component ;
- A condenser : prescribed pressure condenser ;
- Two reheaters : built-in reheater drum component ;
- Valves, pressure drop piping and single-tube heat exchangers (HX).

Modeling and Assumption

The BOP model nominal operating point is based on the CEA CYCLOP optimization of the cycle. Working parameters of BOP components are retrofitted on CEA's results. The moisture separator of the MSR is modelled but its heat exchanger is only virtually implemented (imposed cooling heat fluxes on both cold and hot streams). Performance prediction of this component is then only

realistic for near-to-nominal operation. Thermal inertia of main components (condenser and reheaters) is modelled based on a state-of-the-art sizing.

Heat extraction

The 3 heat extraction interfaces follow the same modelling principle:

- A perfect heat transfer is considered through a one-tube HX which includes a hydraulic capacity but no hydraulic resistance.
- A flowrate control of steam extracted from the BOP through a valve which is operated by a PID controller to keep a subcooling degree constant at the outlet of the HX.

The PID controller has been fine tuned to reach the targeted subcooling temperature with a latency of 10-15 min. These targeted subcooling temperature are:

- 240°C for the HP steam interface ;
- 150°C for the MP steam interface ;
- 80°C for the LP steam interface.

These temperatures correspond to a subcooling of 15°C relative to the saturated steam temperature under nominal operating conditions. Since the pressure gap between the steam extraction and the condensate reinjection from and to the BOP can be high, a condensate flash can happen in HP and LP control valves. Choked valves models are thus considered for these 2 interfaces.

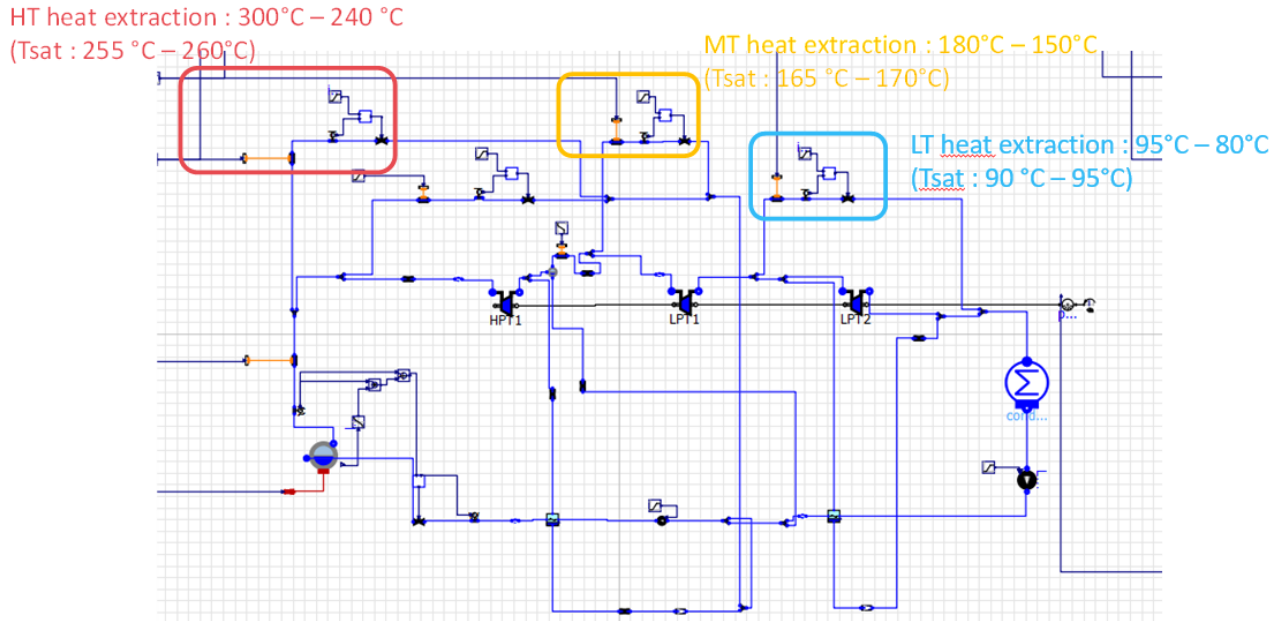


Figure 20 : BOP heat extraction interfaces.

Remark: Due to the hydraulic capacitance of the modeled one-tube HX, singularities can be observed during sharp transients (and the mathematical transient at the beginning of the simulation), that is why a first order derivative with a time constant of 4 s is added to smooth the heat inputs.

Remarks and limitations

- The MSR heat exchanger modelling does not allow to give a realistic prediction of steam reheating performance far from the nominal operating point.
- The fine tuning of the PID controllers implemented to keep a constant subcooling/overheating temperature at the outlet of each heat interface of the BOP has been performed to reach the targeted temperature after +/- 10 to 15 min. **Within this time latency of 10-15 min, the ideal heat exchange can be quite unrealistic** since targeted temperature profiles in the HX have not reached a steady state (risk of cross temperature).
- Interface heat fluxes limiters are set to 20 MW
- The BOP pump maps are linear instead of quadratic for real turbomachinery. Indeed, the model initialization is using a Newton solver combined with homotopy (mathematical tool used to make the initialization problem continuous). This OpenModelica solver is submitted to mathematical instabilities with a real quadratic pump curve. Therefore the pump behavior prediction of the model is only realistic for small flowrate variations (small heat demand < 10-15 MW from high and low temperature end-users).

- The pressure gap between the inlet and the outlet of the MP steam extraction control valve is narrow. Under certain limit operating conditions, the pressure gradient across this valve could reverse. The model check valve then makes null the flowrate across the valve but the hydraulic capacity of the HX discharge in upstream. This behavior leads to a crash of the model which remains unavoidable until now.
- Mathematical transient gives unphysical values: a too small timestep (< 1-2 sec) during this mathematical transient can lead to fail at the beginning of the simulation (< 20 - 50 s for OpenModelica solver).

Prerequisites

The model uses the Buildings 10.0.0 Modelica library, the Thermopower 3.2 Modelica library and some built-in components from the Thermopower_TBL revised library, which must be opened to compile the code.

Main Parameters

The BOP is interfaced with the RCS, the electrical grid but also to several heat users that can be connected.

The inputs interfaces of the BOP are:

- Heat flux from the RCS (real inputs):
 1. *SG_evaporator*: Heat provided for steam production;
 2. *SG_superheating*: Heat provided for steam superheating;
- Heat fluxes requested from end-users (real inputs):
 1. *Int_HP*: End-user demand for heat extraction from HP steam at 240 °C, 45 bar;
 2. *Int_MP*: End-user demand for heat extraction from MP steam at 150 °C, 7.5 bar;
 3. *Int_LP*: End-user demand for heat extraction from LP steam at 80 °C, 0.8 bar.

The outputs interfaces of the BOP are:

- Electrical power to the grid (real output):

1. *Power*: Power produced at the electrical generator;
- Heat fluxes really available for end-users:
 1. *heat_HP*: Model heat extraction from HP steam;
 2. *heat_MP*: Model heat extraction from MP steam;
 3. *heat_LP*: Model heat extraction from LP steam.

Control strategy

The BOP control takes into account a variable heat load on the SG. A feedwater valve with control logic based on inlet/outlet flowrate as well as drum level is implemented. This control logic prevents instabilities from the swelling/shrinking phenomenon in the drum. However, no HP ST inlet control valve is implemented. Finally, the feedwater pumps are modelled with a constant rotational speed and a linear characteristic curve.

Provided examples

An example of the model usage is provided in the Test subpackage.

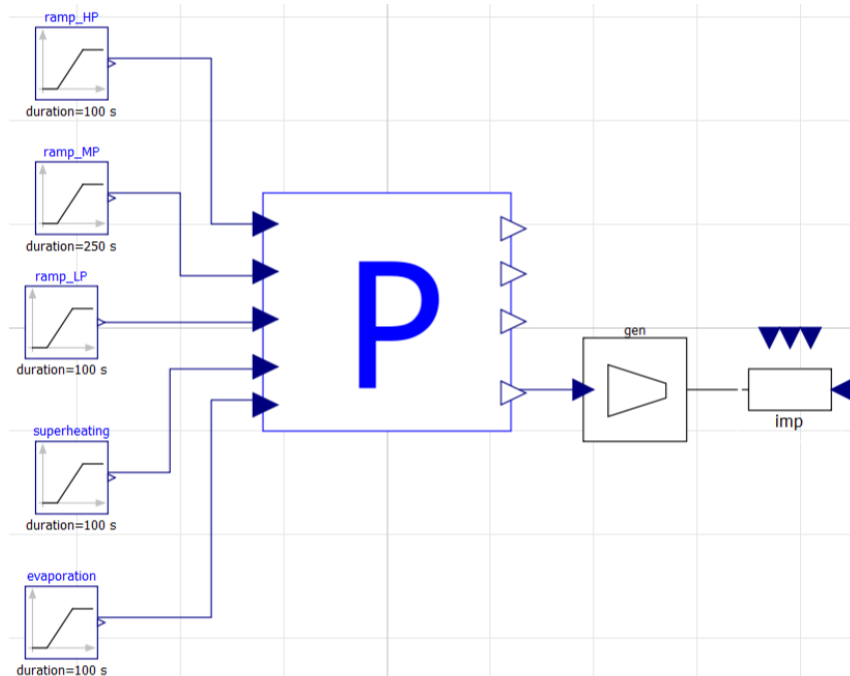


Figure 21 : Schematics of the test performed.

	CYCLOP	TBL	Error
SG, mass flow [kg/s]	239.64	240.7	0.44%
SG, Tin-Tout [degC]	163-300	160.2-307	1.47%
HP Turbine ,Pin - Pout [bar]	44-7.547	44.8-7.27	1.7-2.3 %
LP2 Turbine, Pin Pout [bar]	0.801-0.070	0.810-0.070	1.25%
LP2 Turbine, Tin [degC]	93.5	90.3	3.36%
Dryer, Liquid mass flow [kg/s]	11.64	12.24	5.15%
HP-LP1-LP2- Turbine [MW]	180.6	182.0	0.78%
HP Reheater [MW]	47.52	48.36	1.17%
LP Reheater [MW]	37.72	35.9	4.80%

Figure 22 : Main results for the test performed and comparison with CYCLOP results.

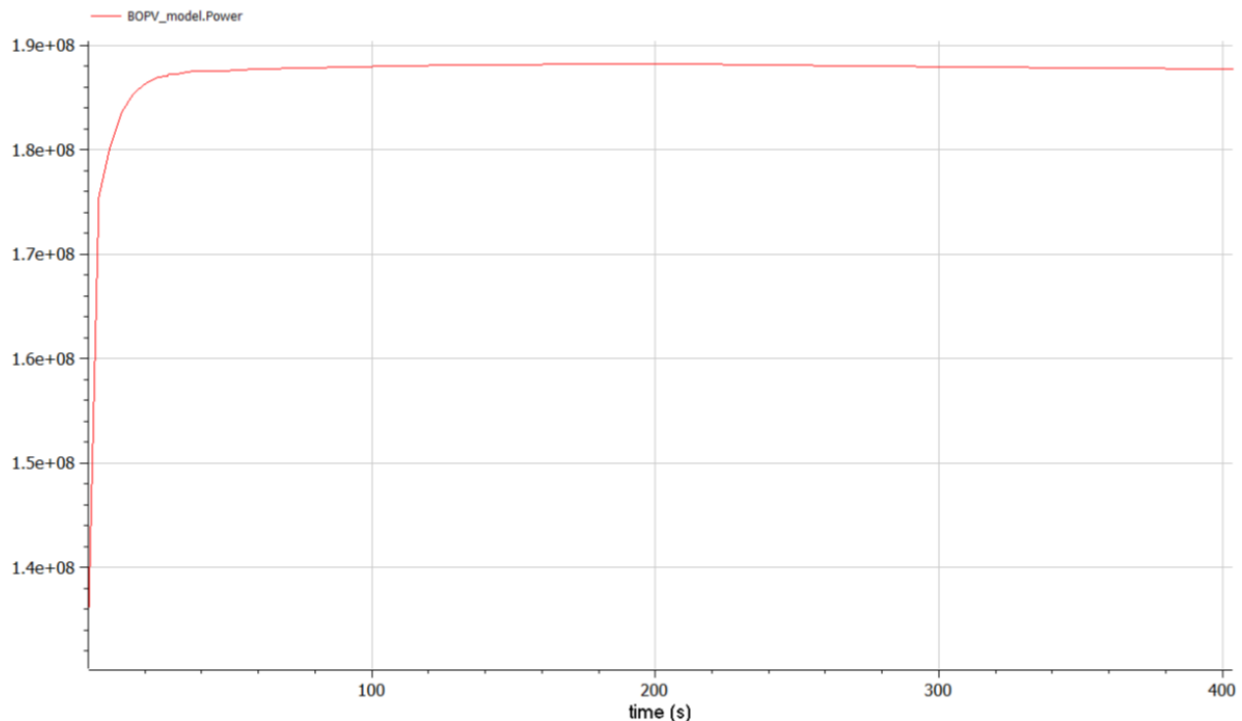


Figure 23 : Total mechanical power produced by turbine [W].

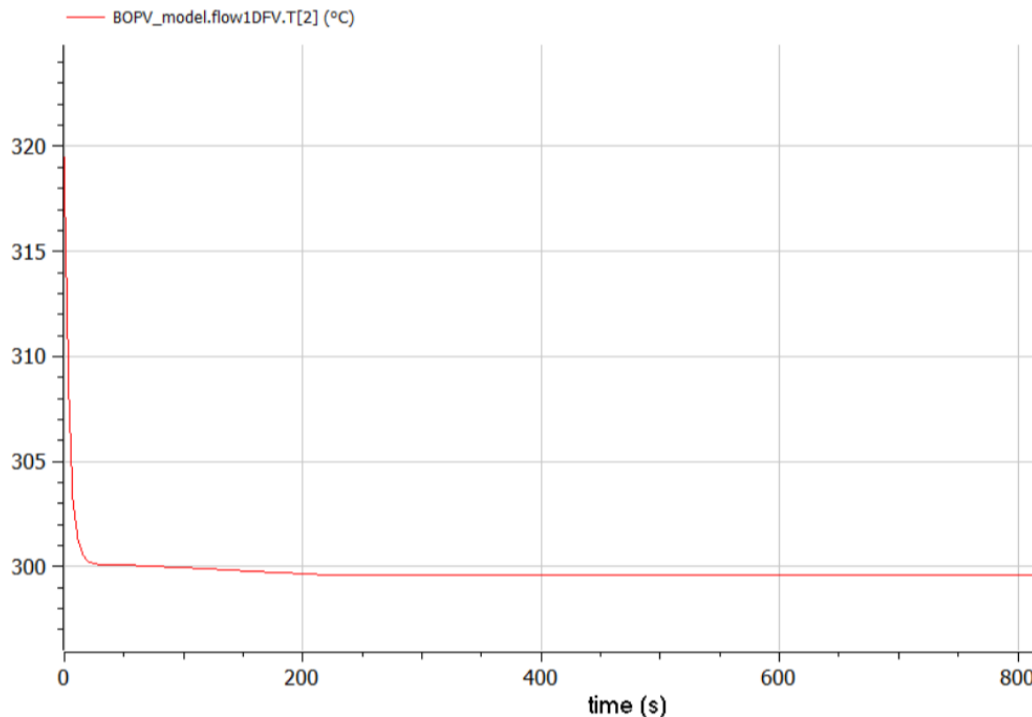


Figure 24 : Temperature [°C] at the inlet of the turbine.

ThermoPower (fluid exchange version)

A third dynamic model of the BOP has been developed in the ThermoPower library. The same architecture and operating conditions obtained from the CYCLOP optimisation have been implemented, despite some differences in terms of pressure levels due to different pressure drops in the heat exchanger components.

The BOP model features several steam extraction and return points. The following extraction points are included:

- High temperature steam extraction at the NSSS-SG outlet (45 bar, 300°C)
- Intermediate temperature steam extraction at the HP turbine outlet (7.547 bar, 168°C)
- Low temperature steam extraction at the LP-turbine (0.8 bar, 92°C)
- Liquid water extraction from the feedwater tank (7.147 bar, 108°C)

Return points:

- High temperature return point at the LP turbine inlet
- High pressure return point at the SG inlet
- Intermediate temperature return to the feedwater tank
- Low temperature return to the condenser



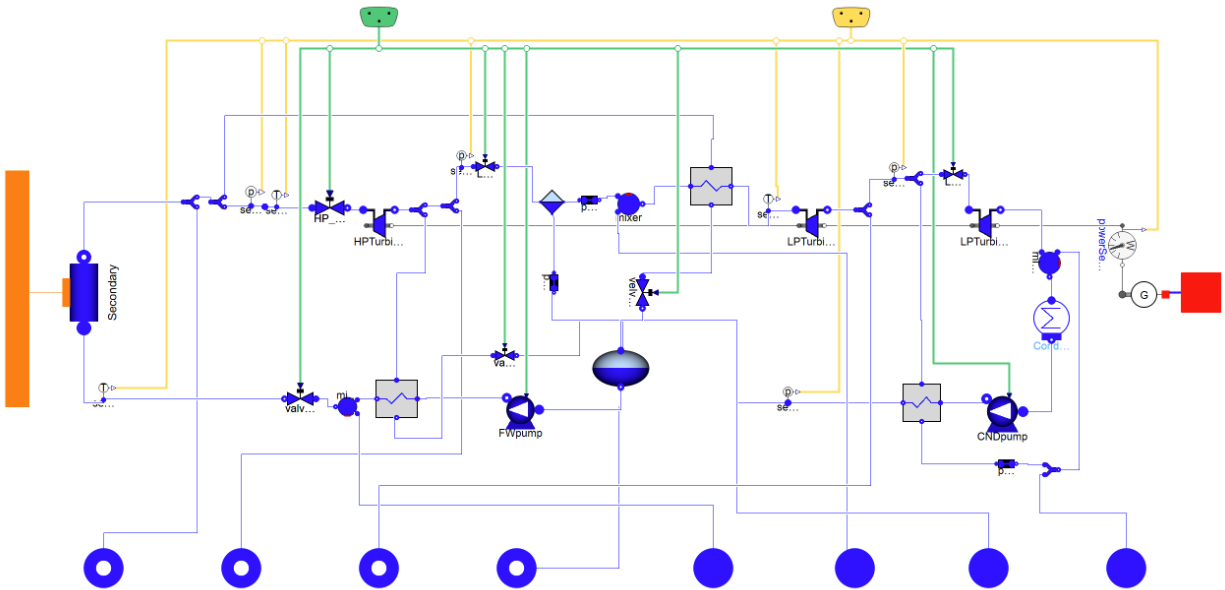


Figure 25. Dynamic BOP model with thermal interface.

Package description

- The Test subpackage provides several demonstration cases devoted to showing possible utilisation of the BOP models
- Two versions of the BOP are available, the first featuring only one heat extraction point and a fluid exchange interface with the NSSS and the second, more detailed, with several extraction and return points and relying on thermal power as exchange variable with the NSSS.
- The main components developed for the BOP, such as the heat exchanger and the moisture separator, are gathered in the Components package.
- Lastly, the Control encompasses some illustrative control systems to regulate the BOP operation according to user requirements.

Component description

The component described in this section will be the *BOPdyn_thermal* component, which results from advancing the developments started with the *BOPdyn_fluid* model.

Most of the subcomponents on which the model is built stem from the ThermoPower library and are based on the following assumptions:

- *ValveVap* and *ValveLiq* components to model the valves in the system
- Turbine stage models based on *SteamTurbineStodola*, extended to be able to include wettness losses (through Baumann's rule) and flow losses

- HP and LP pumps modelled adopting ThermoPower's *Pump*, implementing a quadratic characteristic curve
- Ideal condenser, characterised by a fixed condensation pressure, based on the *PrescribedPressureCondenser* component
- Ideal moisture separator draining the liquid fraction of the two-phase mixture with unitary efficiency
- Concentrated pressure losses are proportional to the square of the fluid velocity
- Feedwater tank model based on dynamic mass and energy balance equations, encompass a user-defined number of inlets and outlets to be able to flexibly accommodate multiple fluid extractions and returns
- Generator modelled with the ThermoPower *Generator* component, used to convert the mechanical power into active power generation, accounting for the inertia of the turbo-generator group.
- Dynamic, one-dimensional shell and tube heat exchangers are used to model the HP and LP preheaters as well as the reheater. They have been sized according to the nominal conditions proposed by the CYCLOP optimization tool. The shell and tube sides are modelled through a finite volume discretization approach, using the *Flow1DFV2ph* and the *Flow1DFV* components, respectively. The heat transfer model relies on the Dittus-Boelter correlation in the case of single-phase fluid conditions, whereas a constant heat transfer coefficient is assumed during phase transition. The shell and tube side flow components are thermally connected through a component accounting for the counterflow disposition and the *MetalTubeFV*, used to simulate the thermal resistance and inertia of the heat exchanger solid structure.

Control strategy

In addition to illustrative controllers developed to showcase potential applications of the model, the Control package encompasses an actuator and sensor signal bus used to collect the main control signals of the BOP. In this way, it is easier for the user to develop its own external control system and couple it to the BOP model to test the dynamic response of the system.

At this stage, the following actuator (green in Figure 25) and sensor (yellow) signals are included in the model:

Sensor signals	Actuator signals
<ul style="list-style-type: none"> • Steam generator inlet temperature • Steam generator outlet temperature • Steam generator pressure • HP-turbine outlet extraction pressure • LP-turbine inlet temperature • LP-turbine outlet extraction pressure • Feedwater tank pressure • BOP power output 	<ul style="list-style-type: none"> • Steam generator admission valve • HP-turbine admission valve • HP-turbine outlet control valve • Reheater hot side flow control valve • LP-turbine extraction valve • HP-pump rotational speed • LP-pump rotational speed • HP-preheater control valve

Table 6. Examples of actuator and sensor signal included in the model.

The user is free to choose the process and control variable pairs that best suit his/her application and design the corresponding controller.

Provided examples

Test cases to showcase the behaviour of the BOP models in different scenarios are available in the Test package. In particular, the models are tested with different heat sources (ideal heat source, steam generator, or NSSS) and different cogeneration requirements. For the latter, the thermal power extractions in *Test_BOPth_ODsource* and *Test_BOPth_NSSS* correspond to those considered in the *BOP_TSPro* package. The simulation outcomes obtained with *Test_BOPth_ODsource* are reported in Figure 26.

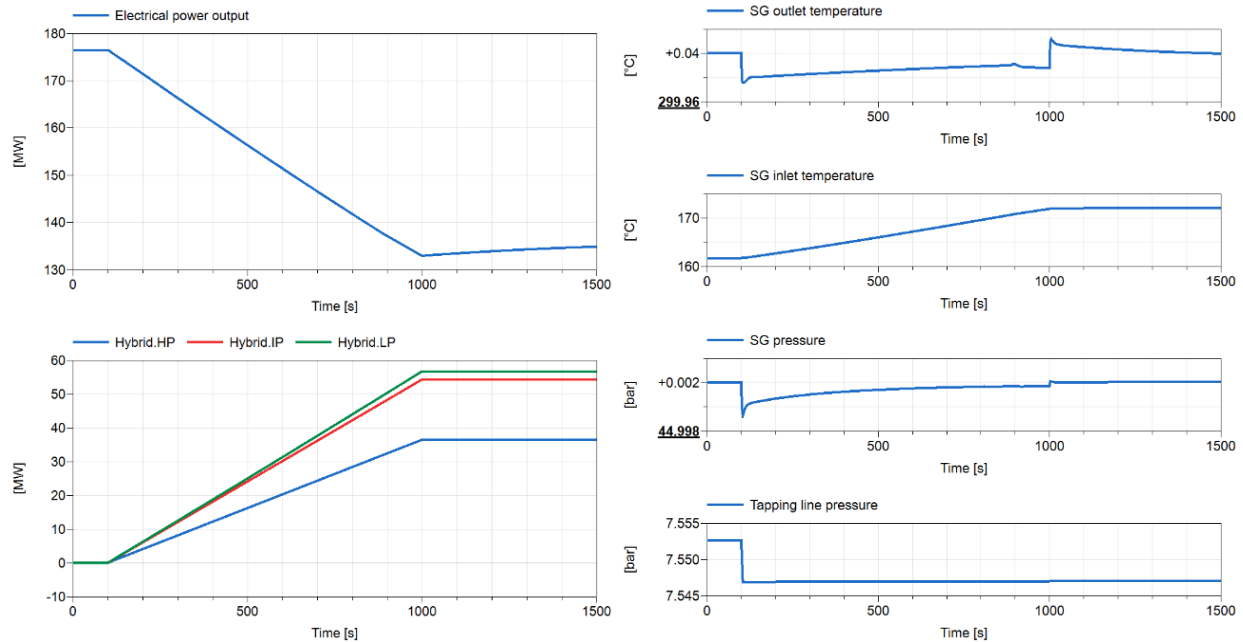


Figure 26: Test case with the dynamic BOP model.

4. Electrical grid

The electrical grid component serves as a connection between electrical ports of various electrical producers and consumers such as the BOP, HTSE, etc.

The grid component is divided in 2 sub-components:

- The grid node, a base element including electrical line impedance, compensation devices and transformers. Several nodes can be put in series or parallel in order to produce various grid architectures.
- The "node array" which consists of a serialization of identical nodes with the same loads connected along the line. This allows for a faster configuration of a large grid with homogeneous load repartition.

There is no fixed grid architecture: it is left to the user to create his own architecture from the 2 sub-components available depending on the simulation needs.

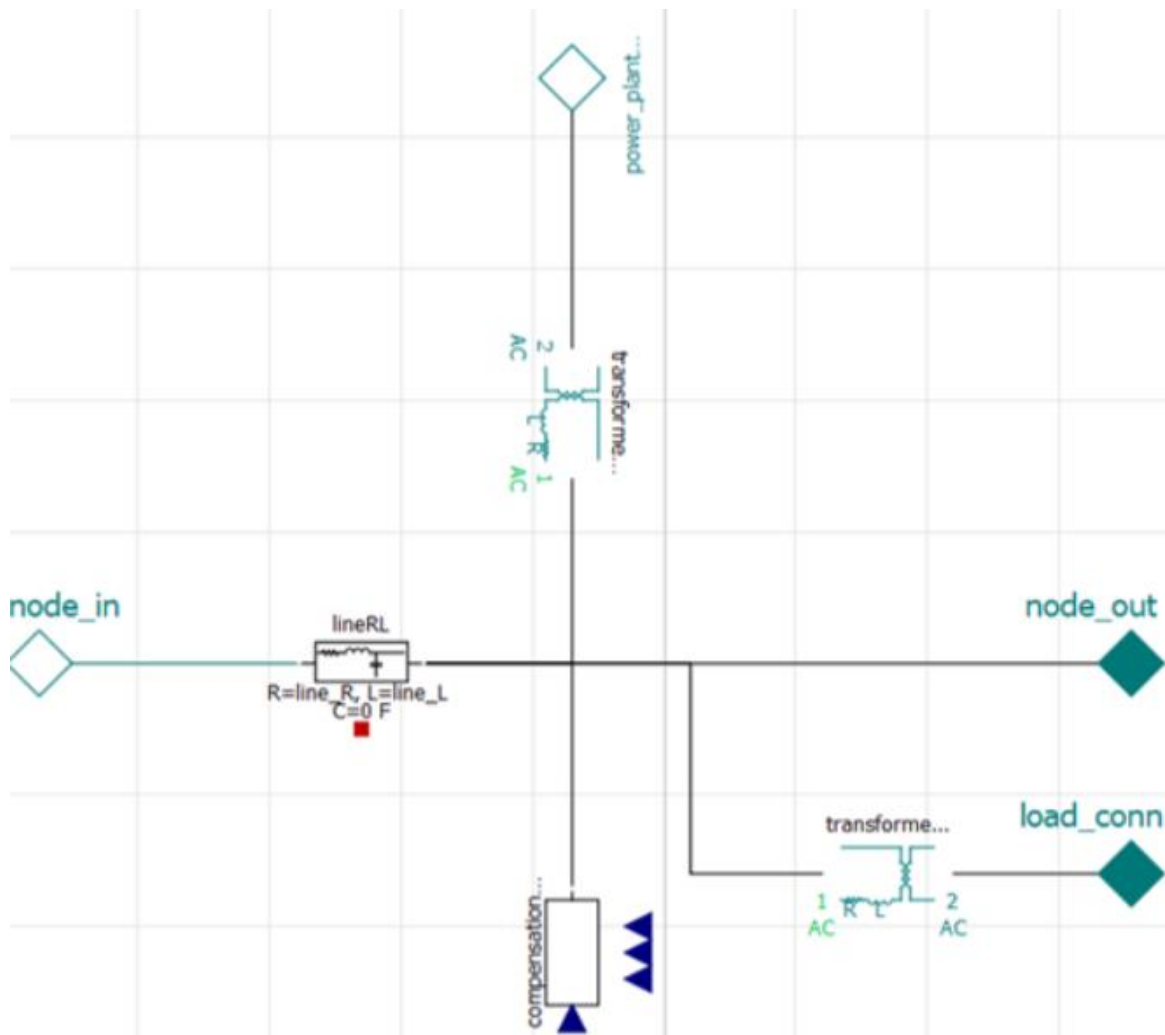


Figure 27. Grid node schematic with line RL, compensation, and transformers.

Circuit Description

The node input and output are directly connected to the line impedance. The compensation device, supply transformer and load transformer are all connected in parallel to the output, after this impedance. The transformers can be left floating, i.e. it is not mandatory to connect a power supply or a load.

Modeling and Assumption

- The electrical line is modeled as a RLC impedance, characterized by a linear impedance value. The linear capacity of the line is neglected by default, which is realistic for lines shorter than 150 km.
- The linear impedance value is typical value for 380 kV overhead lines.

- Transformers characteristics (X/R, Zcc and power) are interpolated from typical values found in the literature based on the voltage operating point (Birchfield et al., 2017; Janssen et al., 2012; *Power Transformers. Part 5, Ability to Withstand Short Circuit (IEC 60076-5, Ed. 3.0 (2006) MOD)*, 2012).

Prerequisites

The model uses the Buildings 10.0 Modelica library, which must be opened in order to compile the code.

Main Parameters

The nodes parameters are:

- Line length (km): used to compute line impedance.
- Plant voltage (kV) in: source nominal voltage used to calculate transformer characteristics.
- Load voltage out (kV): load nominal voltage used to calculate transformer characteristics.
- C compensation (F): capacity value of the compensation device. Default is set to 1 μ F.
- L Compensation (H): inductance value of the compensation device. Default is set to 0 H.

The following parameters are present in component settings but should be left blank:

- XoR
- apower_transfo
- Zp

These parameters are computed by the "getTransfoParams" function based on the plant/load voltage value and therefore can be left blank.

Provided examples

In the Tests subpackage some usage examples can be found:

- UT_node_behavior: test single node behavior with fixed and ideal voltage source, and load.
- UT_node_serialization: test 2 nodes in series with fixed grid voltage, an extra ideal voltage source and loads.
- UT_sizable_grid (Figure 28 and Figure 29): test a "random" grid architecture with several nodes, nodes arrays, ideal voltage sources and loads.

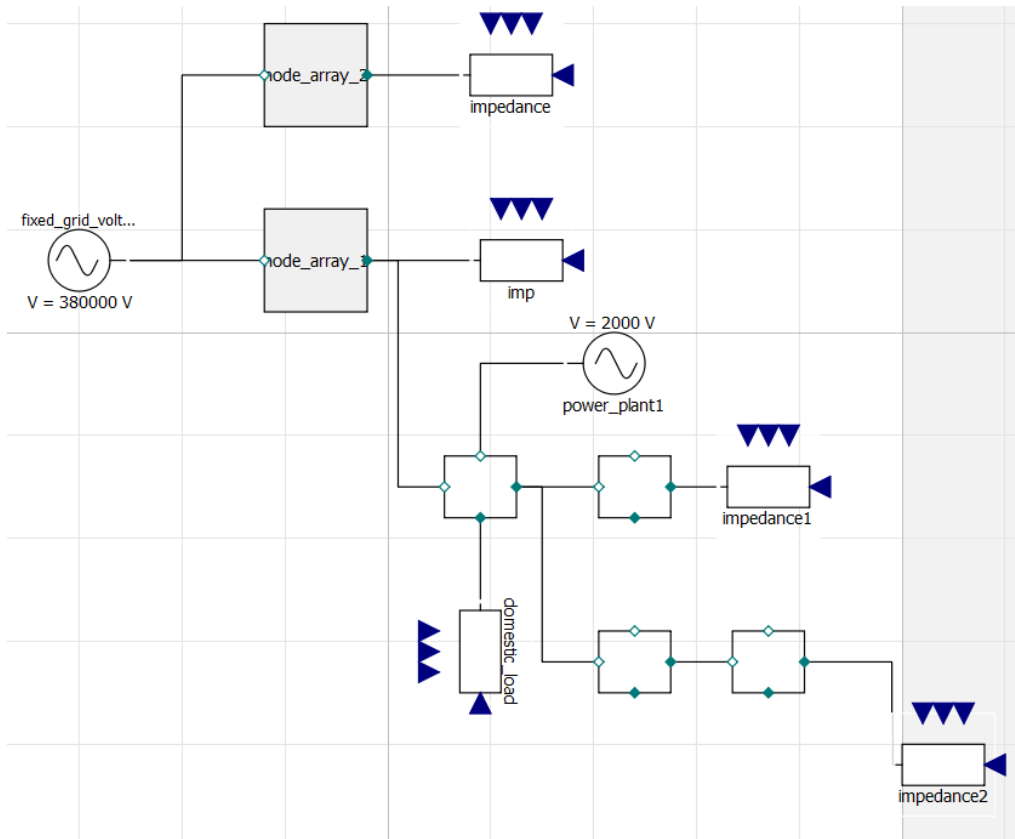


Figure 28. Grid architecture for the test "UT_sizable_grid".

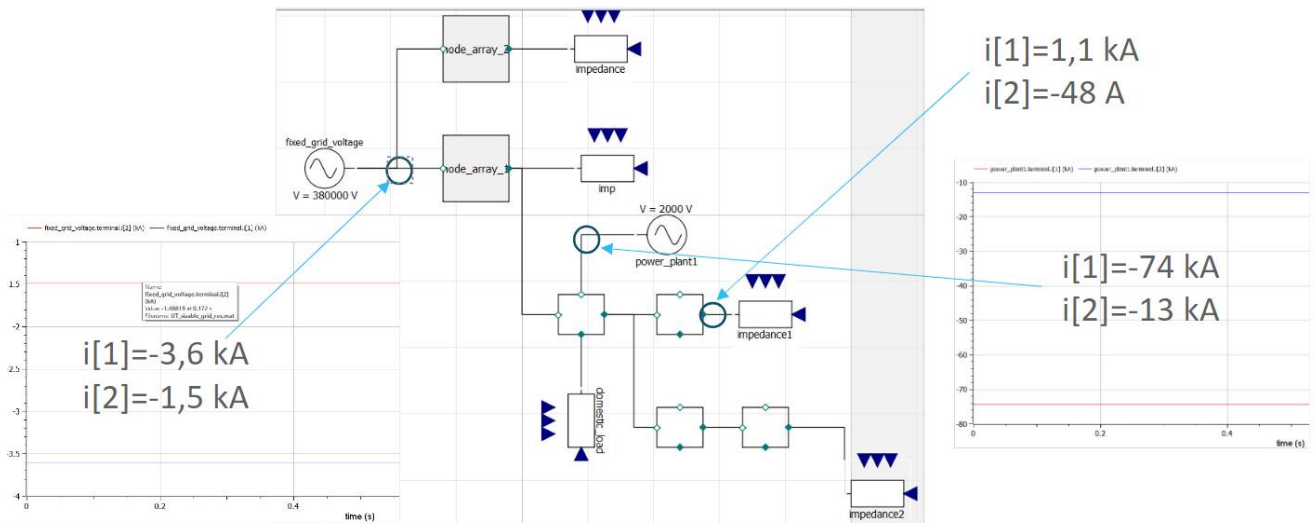


Figure 29. Active and reactive current amplitude given at different nodes for the test performed.

5. High Temperature Steam Electrolyser

Component description

The HTSE component produces H₂ in a *Solid Oxide Electrolyser Cell*, operating at high temperature (about 750 °C). To do so, the steam is produced and pre-heated by using thermal power coming from an external source, i.e. a SMR plant.

The HTSE component may be divided in two sub-components:

- The **Stack**, where the electrolysis of the steam takes place.
- The **HTSE-BOP**, which provide the *fuel* for the reaction, i.e. the high temperature steam, mixed with a fraction of recycled H₂. The BOP has also the role of recovering heat from the stack outlet gases to preheat the fuel.

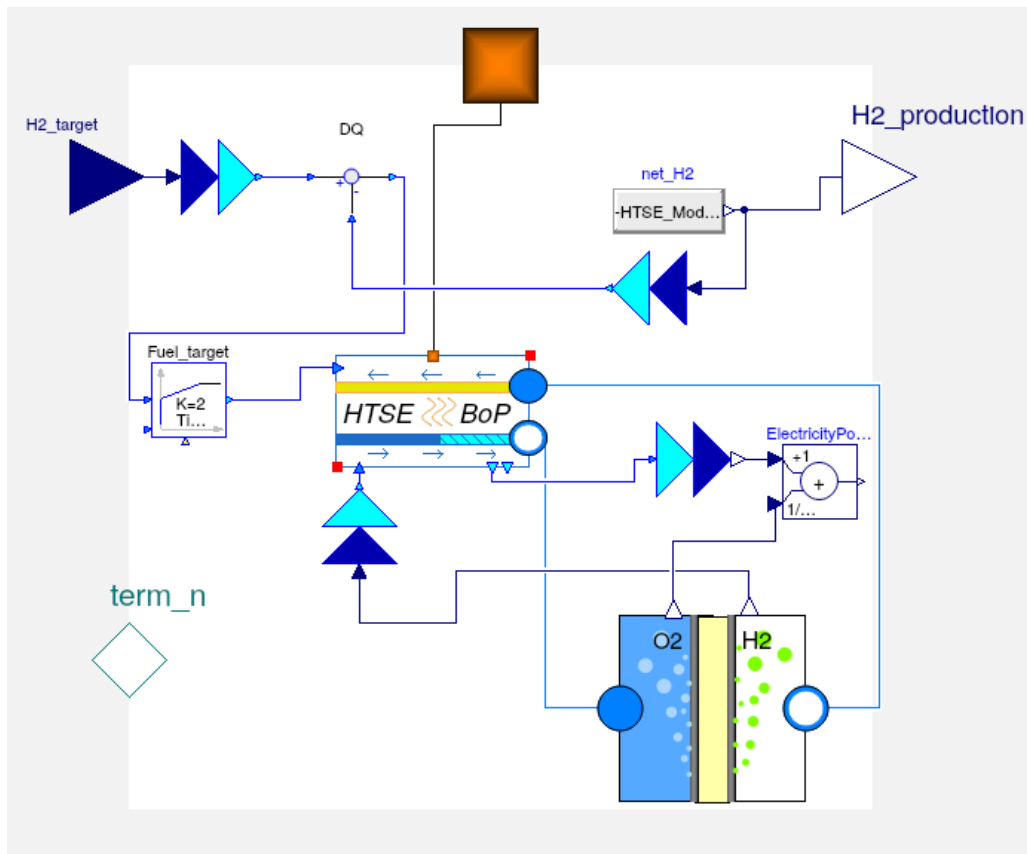


Figure 30. Diagram of the HTSE module.

Firstly, the fuel, i.e. the water, goes through several heat-exchangers to reach the target temperature:

1. A pre-heater, fed, in terms of thermal power, by the exhaust gases.
2. A boiler, fed by the external source.
3. A pre-heater, fed by the exhaust gases.
4. An electrical heater.

Between 2 and 3, the steam is mixed with some recycled hydrogen (10% of mass fraction).

The steam enters then the stack where part of it is converted to hydrogen. The produced gases flow back to the pre-heater 3 and the pre-heater 1. The hydrogen is then dehumidified and stored.

Model description

The HTSE model is composed by two separate sub-components: the stack and the BOP.

The stack model

The following is the description of the stack model as detailed in the Modelica code documentation.

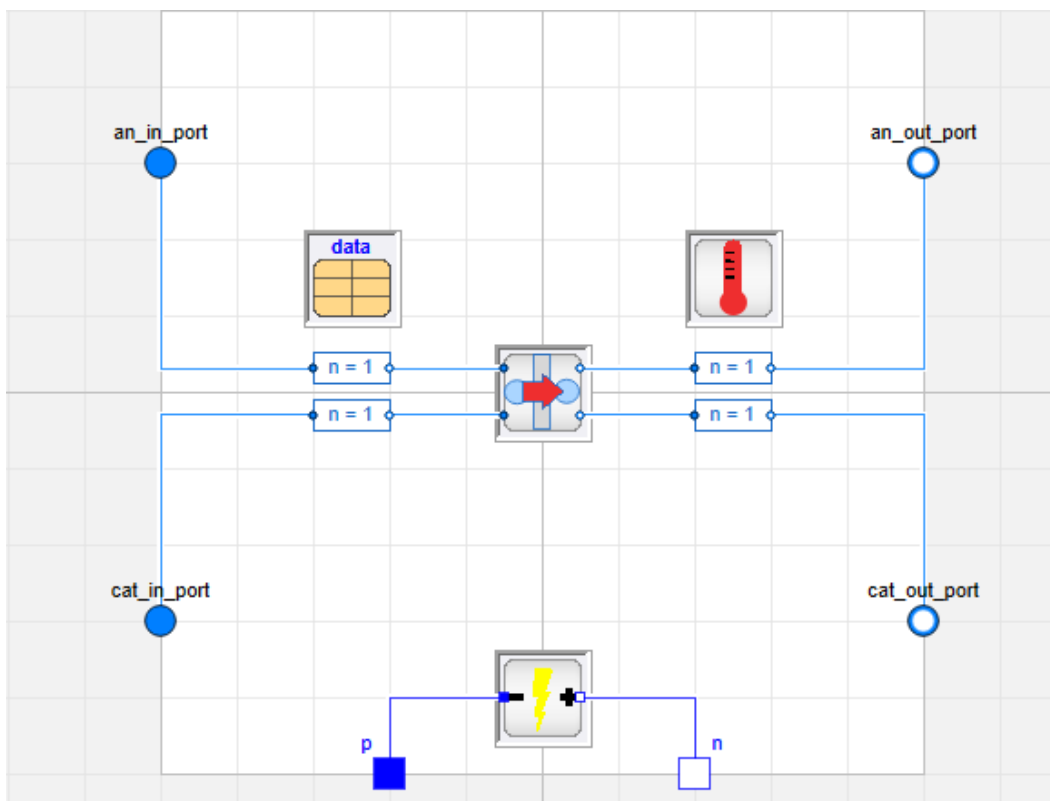


Figure 31. High temperature electrolyser stack model.

Description

This model allows for simulating the electrochemical, thermal, and fluidic behaviour of a Solid Oxide Electrolysis Cell (SOEC), composed of a stack of elementary cells connected in series current wise and in parallel fluid wise, subjected to a current source and supplied by two circuits: the air side at the anode, and a mixture of H₂O/H₂ called the fuel side at the cathode.

The model is interfaced with 4 fluid ports (in anode, out anode, in cathode, out cathode) and 2 electrical pins (p and n) to provide electrical power to the electrolyser. Both current or voltage sources can be used.

The model is discretized along the gas channel to better represent the current density repartition inside the cell. The model aggregates various sub-models and components that communicate with each other through outer variables:

- **The fluidic model:** transport equations and link to the fluid ports. The sub-model is mostly composed of equations that describe either co-current-flow, counter-current-flow or crossflow type of fluid movement and the interactions between molar fractions of gas components and current density. The electrolyte crossing of gas components is handled here.
- **The electro-chemical model:** equation between current density, molar fractions and voltages. The main outputs are the cell voltage and the current density repartition along the 1D/2D cell.
- **The thermic model:** computes the temperature along the electrolyser cell.
- **The pressure model:** computes the pressure drop along the cell for various fluid movements.
- **A data record:** provides material/cell information and other parameters separating the cell characteristics from the rest of the Model.

The sub-models are described in their own description sections. The choices made for the TANDEM library are:

- To represent the physics of the electrochemical component with equations from the literature.
- To have a co-flow fluid movement, which means that gases in the anode and cathode channel flow in parallel and in the same direction. It is the simplest way to transport gases in the cell.
- The temperature of the cell is computed to maintain the cell voltage to follow thermoneutral voltage using a basic PID.
- Pressure losses are linear and averaged in the cell.

Stack Model Assumptions

The stack model assumptions can be divided in two parts, the conversion assumptions which are linked to how much hydrogen is produced given an electrical and thermodynamic state, and the encapsulation assumptions, which dictates how the model behaves given steam mass flow rate.

The conversion assumptions

The model for the conversion of hydrogen is described in the scientific publication (Laurencin et al., 2011). The overall assumptions are:

- All cells in every stack are strictly identical.
- The description of the cell is one dimensional. We consider that all the channels providing gas to the cells are identical. We make no difference between the edge and the centre of the cell (where in reality some differences would appear especially thermally).
- The temperature of the cell is maintained uniformly throughout the cell and is regulated by a PID controller to follow to the thermoneutral voltage (ensuring the most efficient hydrogen conversion since no heat is produced or consumed by the electro-chemical reaction). We could summarize by saying the stack is perfectly controlled in temperature.
- The flow of gas is co-linear, the gases flows from the cathode and anode are parallel and in the same direction. Only this model is provided but other type of flow can be implemented in the structure.
- The cells data comes from (Laurencin et al., 2011). They can be easily replaced by the user's specific cells characteristics using the same format.
- The current is always computed to convert 70% of the steam provided in the steam entry connector. This steam conversion is quite standard for a standard working High Temperature Steam Electrolyser. A delay of 60s is introduced for the current to synchronise with the mass flow rate. (A valid hypothesis compared to reality, also allows for Dymola to simulate since both the current and the steam are not "provided" at the same time).

The encapsulation assumptions :

- A mass flow of pure hydrogen is provided in case no fuel is provided from the BOP. No current is used while the mass flow rate remains less than 10% of the nominal one. The main idea is to keep a reduced gas flow inside the electrolyser even when the hydrogen generation is shut-down.
- The anode gas is standard air, the mass flow rate is two times the fuel mass flow rate, as it is often seen in the literature.

- Electrical power is computed as the product of the current and voltage provided to the overall stack. A conversion efficiency of 0.9 is taken into account from the grid current.
- The current is computed at all times to convert 70% of the steam provided in the fuel_in connector. This steam conversion ratio is a typical value for SOEC. A delay of 60s is introduced for the current to synchronise with the mass flow rate. (A valid hypothesis compared to reality also making the numerical resolution easier temporally decoupling the current and the steam flow).

The HTSE-BOP

The Balance of Plant modelling is essentially a thermo-hydraulic modelling, based on the ThermoSysPro library. The detailed documentation of the library is available in the book of El Hefni and Bouskela and on the library website.

The BOP is modelled from the liquid water coming from the main pump (not included) to the separator of the exhaust gases (not included).

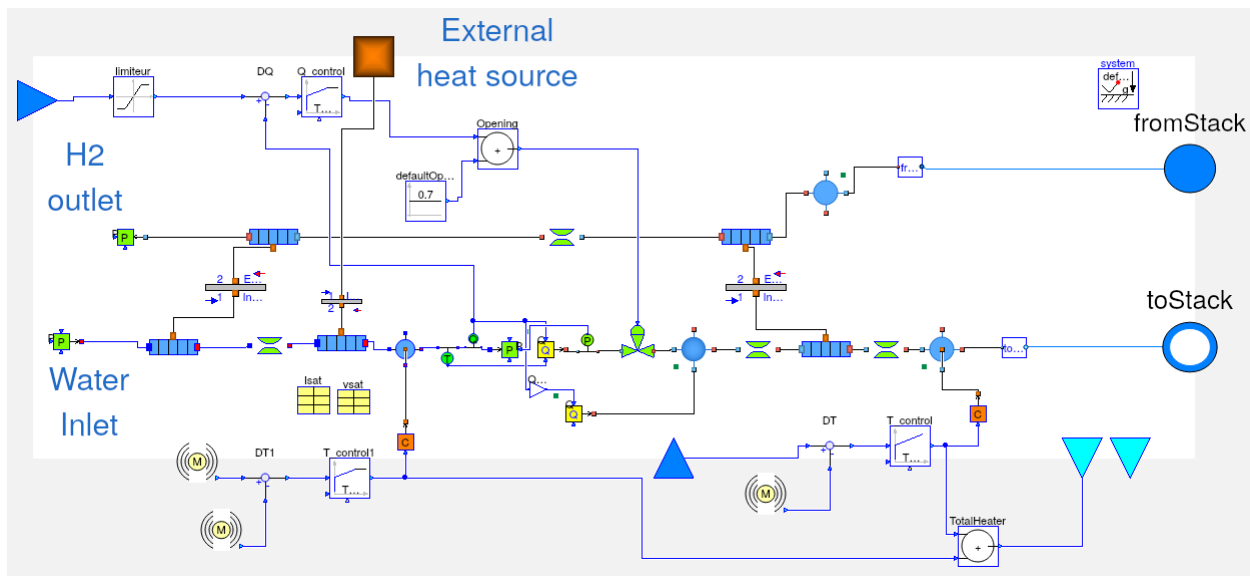


Figure 32. Diagram of the HTSE-BOP module.

The heat-exchangers, the pre-heaters and the boiler, are modelled as meshed 1D pipes with staggered mesh scheme: the ThermoSysPro component used is DynamicOnePhaseFlowPipe. Volumes are also used to model:

- the mixing of steam and hydrogen before the last pre-heater;
- the final and the auxiliary electrical heaters.

The main assumptions of the BOP model can be summarized as follows:

- Thermal inertia is taken into account. This is not the case for the mass flow inertia because of some incompatibilities with the stack modelling; mass flow inertia is supposed to have little impact on the results for the target studies.
- Correlations are used to evaluate the heat transfer coefficients and the pressure drops so that they depend on the mass flow rate (e.g. Dittus-Boelter for heat transfer; see El Hefni and Bouskela for further details).
- There is no mass accumulation in the model (e.g. thermal dilatation is neglected).
- A minimal value of mass flow rate of 0.05 kg/s is hardcoded for stability reason.
- For compatibility reasons, the pressure is decoupled at the inlet of the stack, as if there were a perfect valve controlling the pressure at the stack. This is supposed to have no significant impact on results, taking into account the low operating pressure of the stack.

Parameters

The model is designed for a nominal fuel mass flow rate of 1 kg/s. It is supposed to start with no hydrogen production (null stack current, 0.05 kg/s of mass flow rate in the circuit) and no external heat provided.

The BOP design is not optimized, since such optimization would depend on the application (e.g. the desired H₂ mass flow rate, the available external steam characteristics...). The model being essentially composed by heat exchangers, the main design parameters are Diameters, Length and Number of Pipes.

Fluids

Several fluids are used in the circuit:

- ThermoSysPro.WaterSteam (IAPWS-IF97) is used from the inlet to the boiler (included).
- ThermoSysPro.H2mixGases is used from the mixing between steam and recycled H₂ to the electrical heater.
- Adaptors are then used to connect the BOP to the Stack inlet and outlet, which use media defined as standard media of the Modelica Standard Library.
- ThermoSysPro.H2mixGases is then used from the stack outlet to the BOP outlet.

Control Strategy

The component is operated to achieve a requested production of H₂: this target is the main input for the I&C of the component.

The target H₂ production is compared to the actual H₂ production (measured @ the outlet of the BOP) and a PI controller is used to set the target fuel mass flow rate.

This information is processed in the BOP by a PI to properly open the steam admission valve. In the BOP, a second PI adjusts the power sent to the electrical heater to meet the target temperature at the stack inlet; this target is provided by the stack module to maximize the efficiency of the electrolysis.

At the stack level, the current is set to be proportional to the fuel mass flow rate, with a delay of 60 seconds.

This global control logic is illustrated by the following diagram.

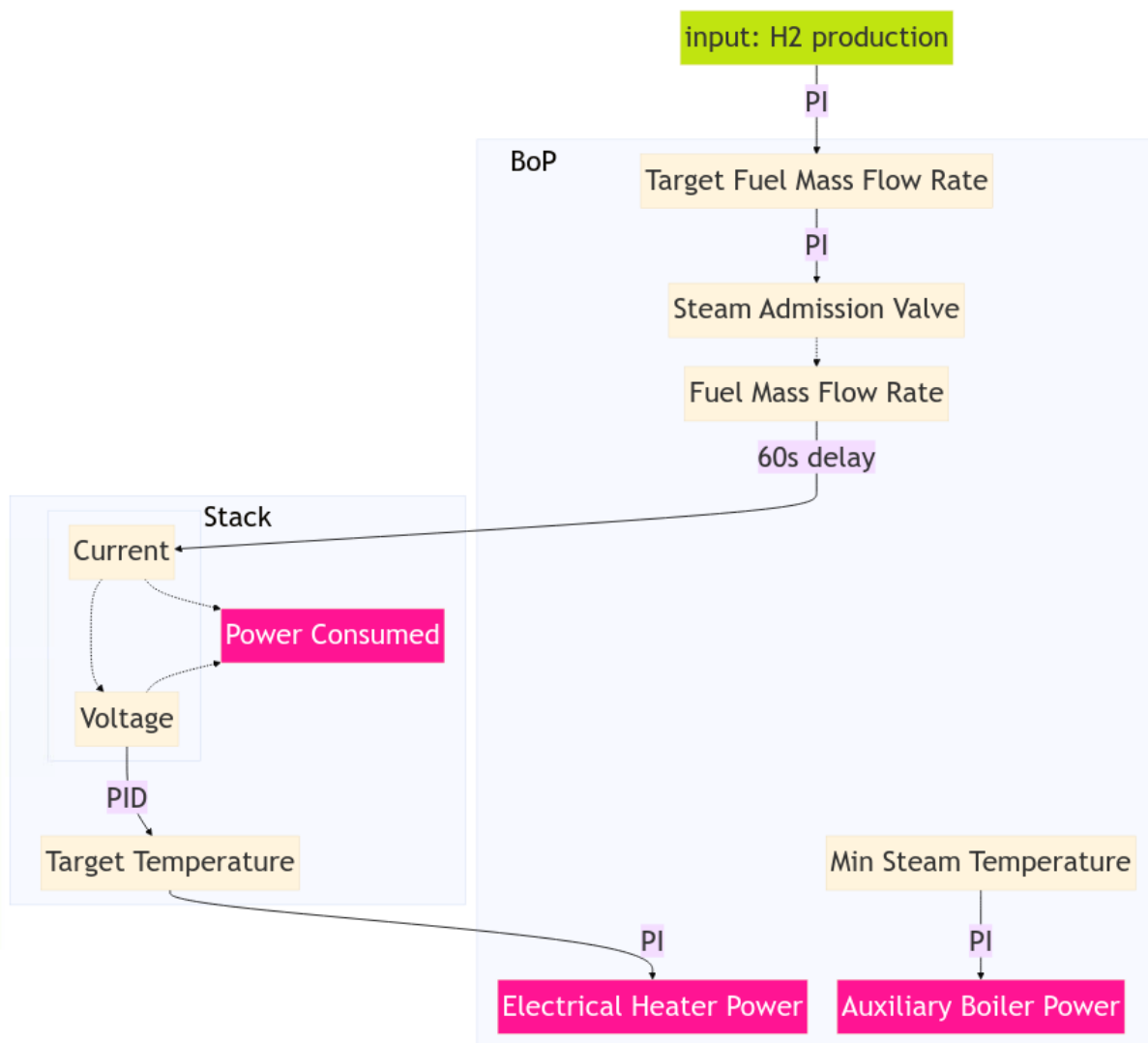


Figure 33. Control logic of the HTSE module.

Package Structure

The HTSE package is structured as follows:

- The HTSE_module_steam: the main model of the package, connected to the SMR.
- The Subcomponents package contains the submodules BoP_module_1Dboiler and Electrolyser_module.
- Validation package: a unit test of the electrolyser module and the BOP module.
- The Tools package contains some useful components, such as the adaptors to connect ThermoSysPro, with H2 gases, to the MSL blocks. The Tests package hosts some examples and checks of these tools.
- The Demo package presents some demonstrative uses of the HTSE_module:
 - In Test_HTSE_steam, the external heat source is represented by hot steam flowing through the external side of the HTSE-BOP boiler. The model is initialized, as requested, with null hydrogen production (resulting in the minimal mass flow rate in the HTSE-BOP, 0.05 kg/s) and negligible but non-null external steam mass flow rate (0.01 kg/s). Then a ramp of both H2 production request and external steam mass flow rate is realized.
 - In Test_HTSE_heat, the external heat source is modelled by its injected power. Starting from zero, it is ramped up as in the previous example.

Illustrative results

The following graphs show the simulation results of the Test_HTSE_steam results.

Figure 34 illustrates the increase of H2 demand (from 0 to 0.1 kg/s) and the consequent increase in steam production by the BOP and then in H2 production meeting the target. Figure 35 shows the evolution of electrical and power consumption. The low thermal power consumed by the BOP, compared to the electrical heaters power, confirms the need of optimization of the component design.

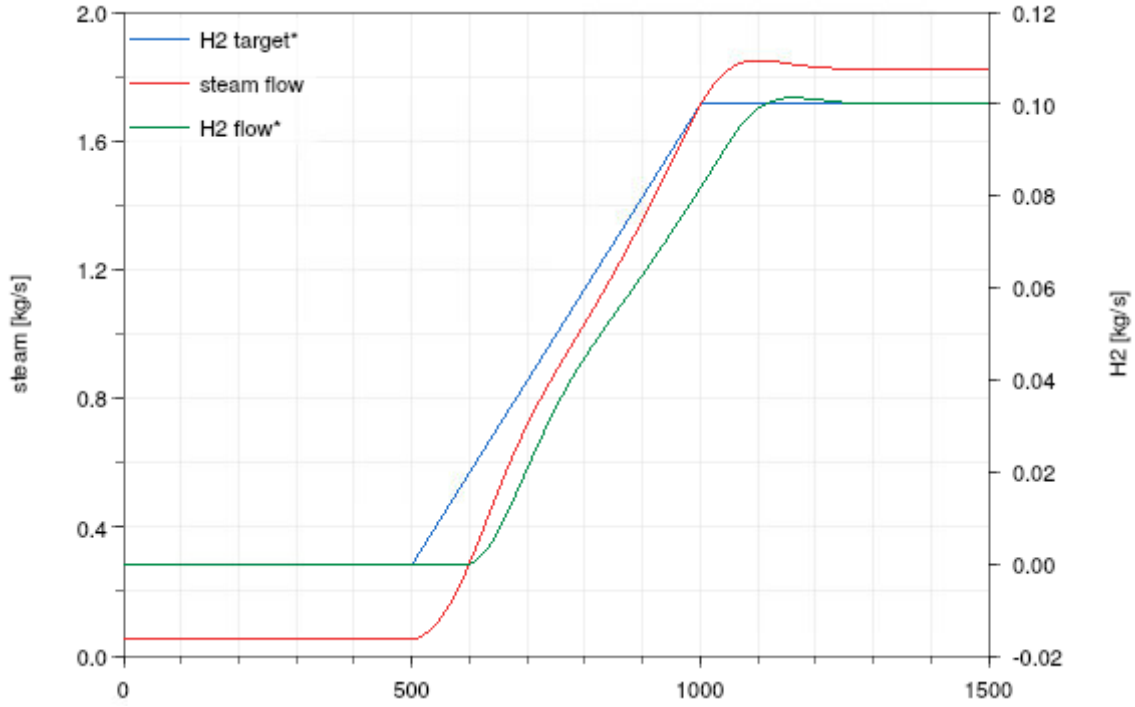


Figure 34. HTSE demo case: H2 and steam production.

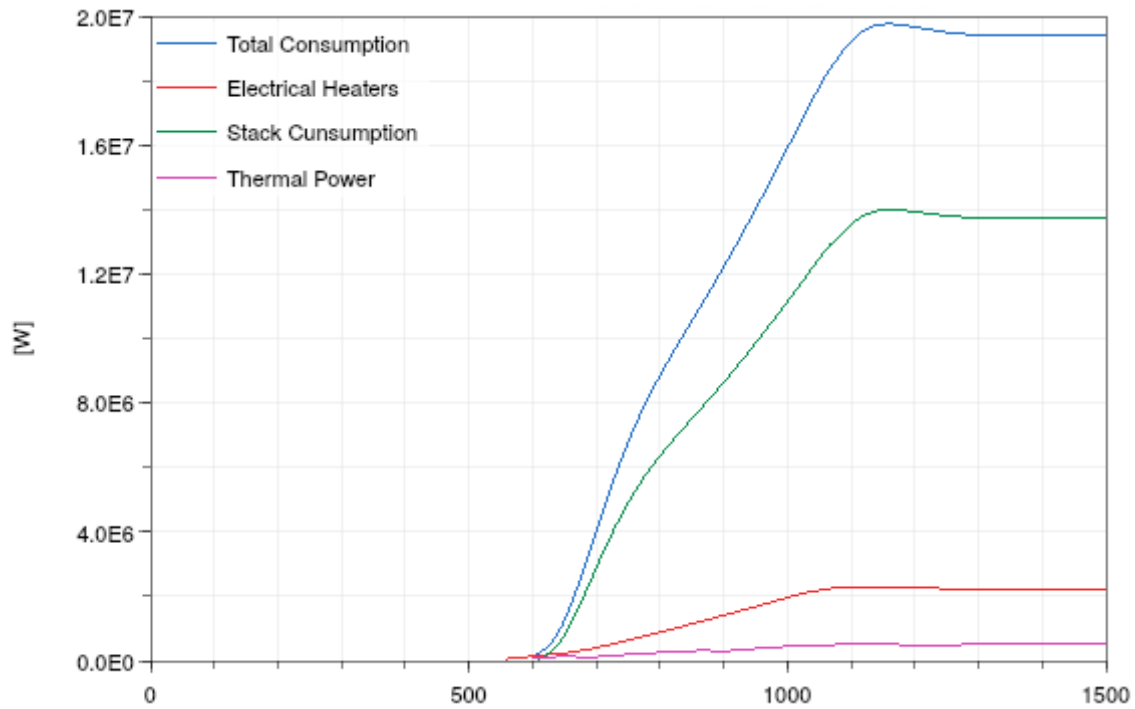


Figure 35. HTSE demo case: electrical and thermal consumptions.



6. Low Temperature Electrolyser

Component description

The present component (Figure 36) models a Low Temperature Electrolysis (LTE) Plant based on the Proton Exchange Membrane (PEM) technology.

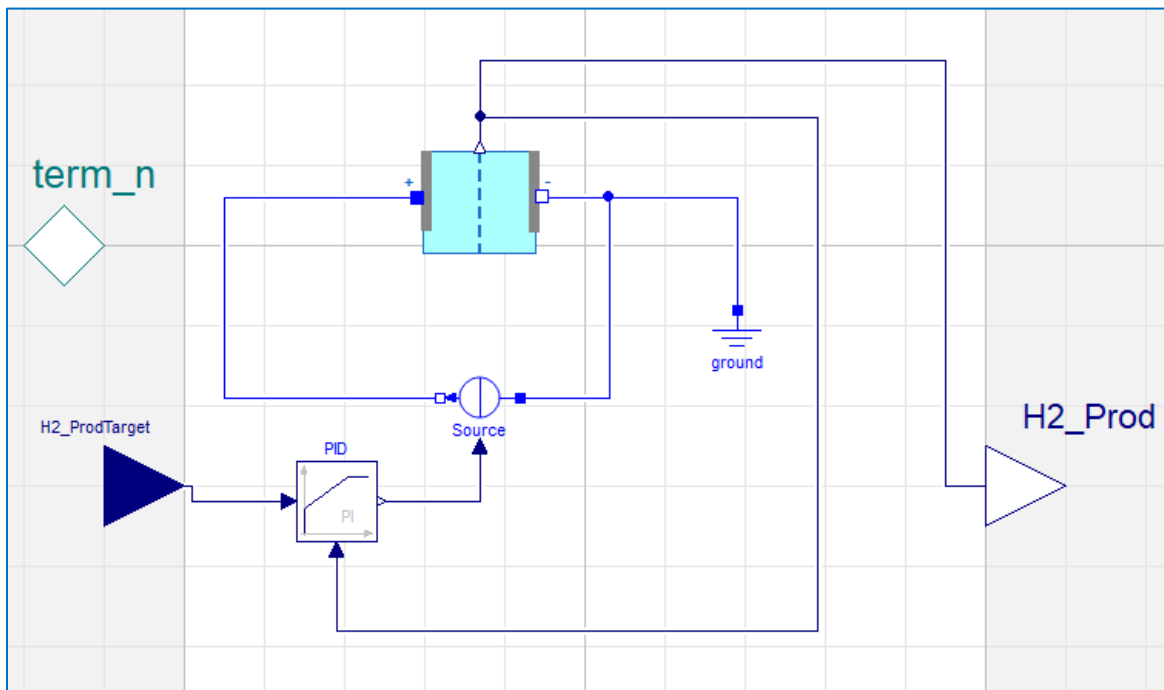


Figure 36. LTE Modelica Diagram.

This component is intended to be connected to the TANDEM Electrical Grid component through the "term_n" electrical port. To be able to run simulations, the LTE component also needs a real input signal giving the H2 production target. This target is given as an input to a PI controller block which adapt the current intensity applied to the stack module until reaching the H2 production target. As an output, the LTE component provides the real instantaneous H2 production of the plant.

The stack represents the heart of the LTE plant where the inlet water is converted to H2 and O2. The proposed stack Modelica module is based on four types of equations:

- The **electrical equations** that link the electrical consumptions of the stack (P_{elec}) to the stack current and voltage. The stack cells are assumed to be connected in series. We note that P_{elec} doesn't account for the electrical consumptions of the plant auxiliaries such as AC/DC converters, pumps, inlet water conditioning, de-ionized water production unit, gas

purification and compression units, and so on. Those previous auxiliaries electrical consumption are taken into account at the LTE component level through the “ElecEfficiency” factor parameter. Finally, the energy efficiency of the electro-chemical conversion is given by the “ne” variable.

- The **mass balance equations** which are based on the Faraday’s law. As in (M. Espinosa-Lopez et al., 2018), we assume that the faraday efficiency is equal to 1.
- The **thermal modeling equations** which can be used either in their static form (when the parameter UseDynamicModeling=false) or in their dynamic one (when UseDynamicModeling=true). When “static modeling” is chosen, the stack temperature is set to the operating temperature (Top). When “dynamic modeling” is chosen, the user needs to specify the response time characteristics “Tau”, the stack starting temperature “Tamb” (which is assumed to be equal to the ambient temperature) and the stack operating temperature “Top”. The stack temperature evolves then following the first order differential equation “Tau*der(T) + T = Top”. In both static and dynamic modeling approaches, the electrolysis heat loss (Qelectrolysis) and the heat loss to ambient (Qloss) are computed. To perform this last calculation, an equivalent thermal resistance (Rth) must be known.
- The **electro-chemical equations** which express (using some semi-empirical equations) the cell voltage as the sum of the cell reversible voltage, the ohmic overvoltage and the activation overvoltage. In order to compute the reversible voltage, we use the Nernst equation and the partial pressures Dalton’s law, while assuming that the absolute pressure is the same at anode and cathode outlets, and that the water vapor is saturated at both cathode and anode outlets.

Circuit description

The LTE component was developed as a simplified component. The Balance of Plant is not represented. We assume that the input water feeds the stack at the convenient mass flow rate (following the desired H2 production target), and that a water conditioning loop exists to regulate the feeding water temperature around the operating value.

Main Modeling Assumptions

- The gas-liquid separators, the demisters as well as the gas purification unit are not modeled. We assume that pure H2 is produced at the cathode outlet and pure O2 is produced at the anode outlet.
- The electrolysis cells are assumed to be series-connected.
- We assume that the absolute pressure is the same at anode and cathode outlets, and that the water vapor is saturated at both cathode and anode outlets.



- Faraday's efficiency is assumed to be equal to 1 (M. Espinosa-Lopez et al., 2018).
- The number of cells is computed based on the MYRTE platform characteristics using a simple rule of three once knowing the nominal H2 production rate of the LTE plant.

Main parameters

The LTE component parameters are:

Name	Description
ElecEfficiency	Electrical efficiency factor to take into account the conversion from AC to DC and the LTE auxiliaries consumption
PID_Ti	Time constant of the PID integrator block
PID_k	PID controller gain
QvolNormalNominal_H2_out	Nominal volume flow rate of produced H2 in standard conditions (p=1.01325 bar, T = 273.15K). This quantity is used to compute the number of electrolyser cells (series-connected)
P	Operating Pressure
Top	Targeted Operating Temperature
UseDynamicModeling	Choosing Dynamic or static modeling
Tamb	Ambient Temperature = stack starting temperature
Tau	Response time characteristic for a first order differential equation : $T(t=Tau)=0.63(Top-Tstart)$

Table 7: LTE parameters.

Control Strategy

The LTE component is controlled through a PI block which allows to adapt the current intensity applied to the stack module until reaching the H2 production target.

Prerequisites

The model uses the Buildings 10.0 and the ThermoSysPro 4.0 Modelica libraries.

Provided Examples

The "Stack_Validation" subpackage contains two examples that allowed to validate the "Stack" module:

- MYRTE_Platform : modeling the stack of the MYRTE platform at nominal conditions (M. Espinosa-Lopez et al., 2018). Some illustrative results are shown below:

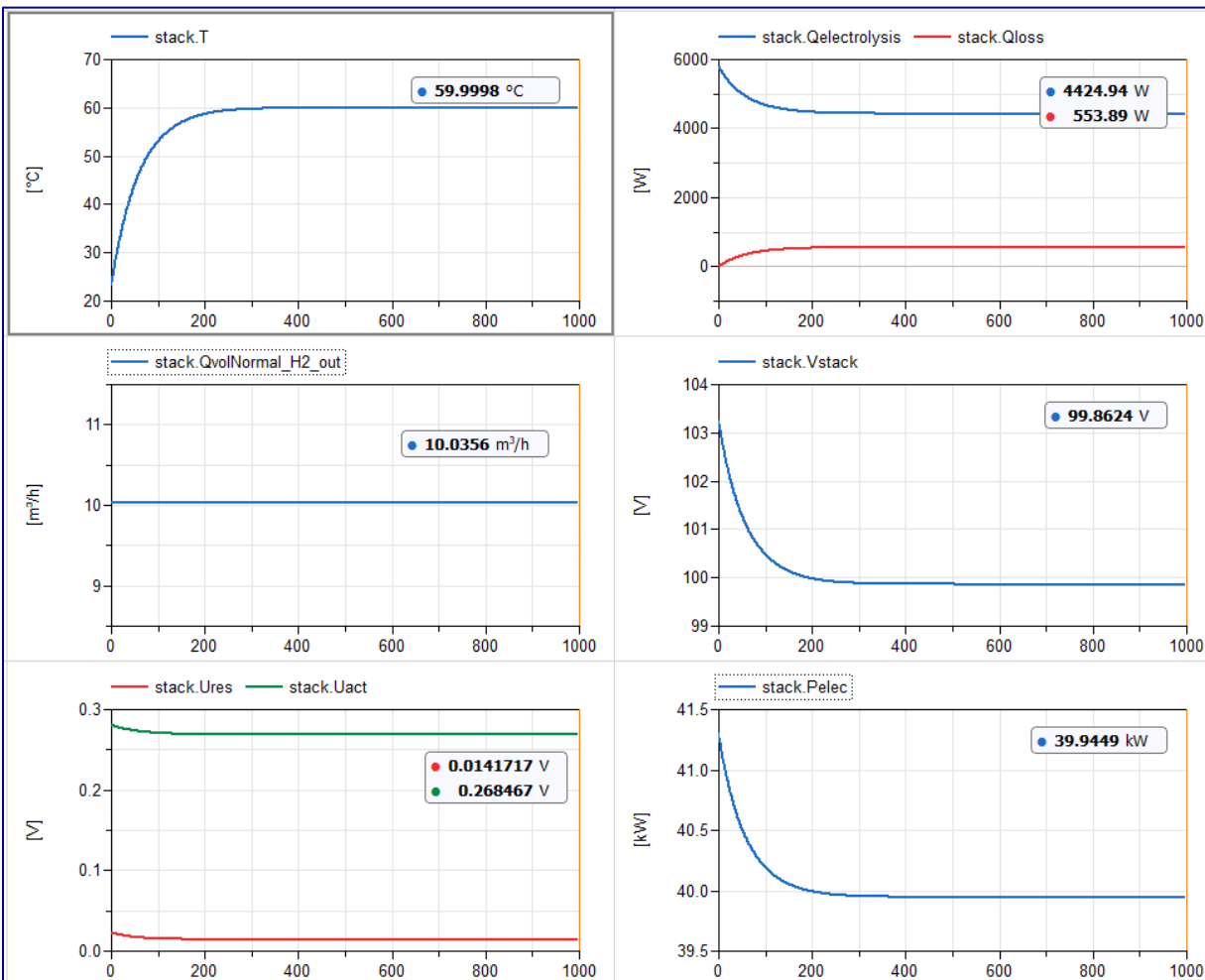


Figure 37. Some illustrative results of the MYRTE Platform modeling (1/2).



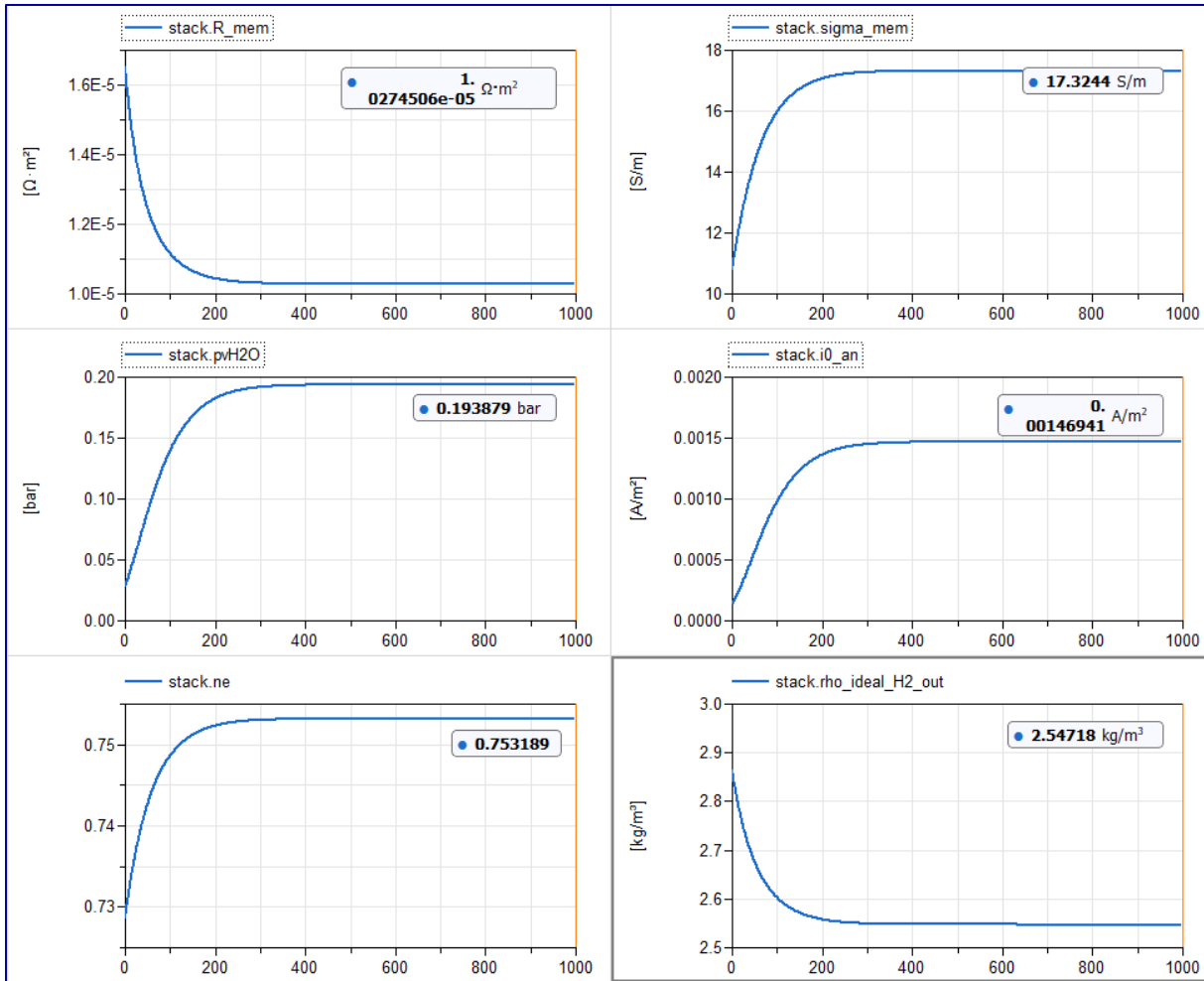


Figure 38. Some illustrative results of the MYRTE Platform modeling (2/2).

- MYRTE_Platform_PolarizationCurve : modeling the stack of the MYRTE platform at ($P = 35 \text{ bar}$, $T = 50^\circ\text{C}$) and variable current intensity in order to plot the numerical polarization curve (shown below) and compare it to the experimental one.

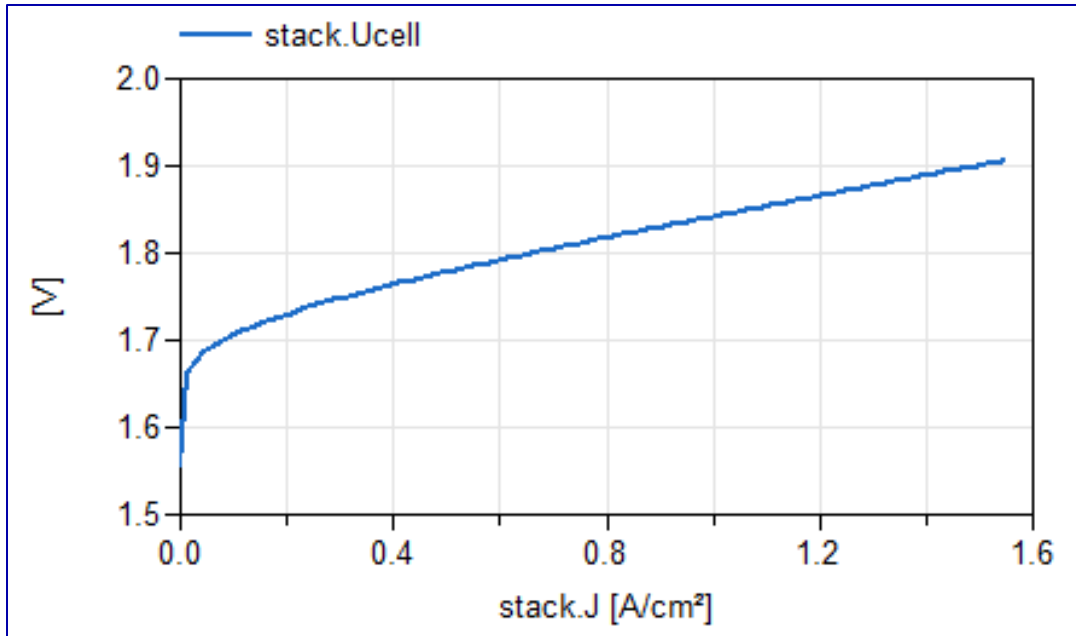


Figure 39. Numerical polarization curve at ($P = 35$ bars, $T = 50^{\circ}\text{C}$) for the MYRTE Platform.

The "LTE_Validation" subpackage contains an example that allowed to validate the LTE component:

- GridConnection: it enables for testing the connection of the LTE component to the electrical grid while targeting a dynamic H2 production rate objective. Some illustrative results are shown below.

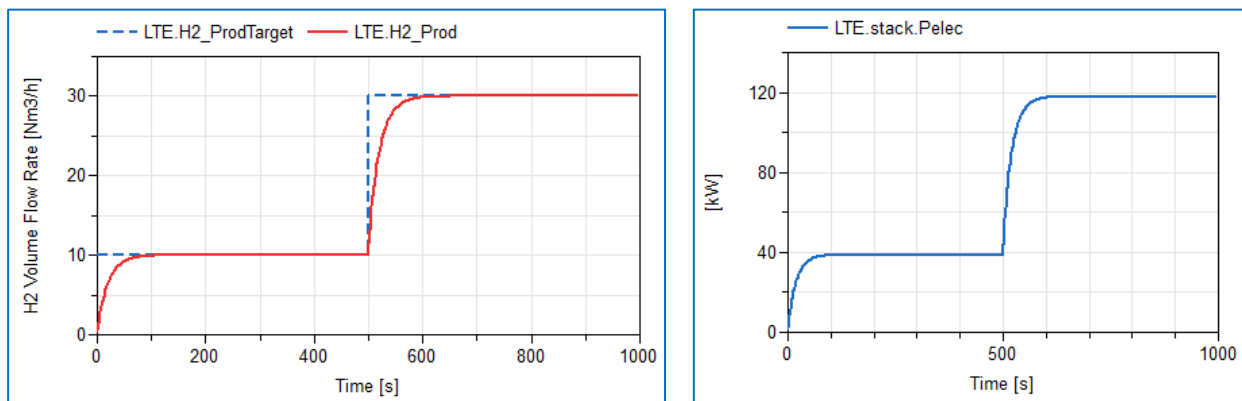


Figure 40. Some illustrative results from the "GridConnection" example.

7. Energy Storage

Two energy storage systems are available in the TANDEM library:

- In the *ThermalStorage* package, the components for a two-tank sensible heat storage system are available.
- A simplified battery model, treated as a black box, is included in the *ElectricalStorage* package together with a dedicated control system.

Thermal Energy Storage

The thermal energy storage (TES) technology included in the TANDEM library is a two-tank heat storage system. During the charging process, thermal power is transferred through a charging heat exchanger to the sensible loop. During this process, the heat transfer fluid (e.g., oil or molten salts) flows from the cold tank to the hot tank, increasing its temperature in the heat exchanger. The higher the charging power, the higher the flow rate pumped between the tanks. Similarly, the thermal energy storage system is discharged by releasing the thermal power of fluid flowing from the hot tank to the cold tank through a discharging heat exchanger.

Package description

The ThermalStorage package is structured as follows:

- Demonstration cases showcasing possible applications of several versions of the TES model are provided in the Test package.
- The Components package collects the components developed for the SensibleLoop model, i.e., the Tank and the charging and discharging heat exchanger components.
- Controller components, based on an illustrative control strategy for the TES, are provided in the Control package.
- The heat transfer models and correlations adopted in the heat exchanger models are provided in the HeatTransfer package.
- The thermal properties of the sensible fluid, which are required in the various SensibleLoop subcomponents, are proposed in the Media package.

Component description

The sensible loop model, shown in Figure 41, is based on two *Tank* components, storing the hot and cold fluid, two ThermoPower *Pump* components followed by a ValveLin model to regulate the flow from one tank to the other according to the charging and discharging requirements.

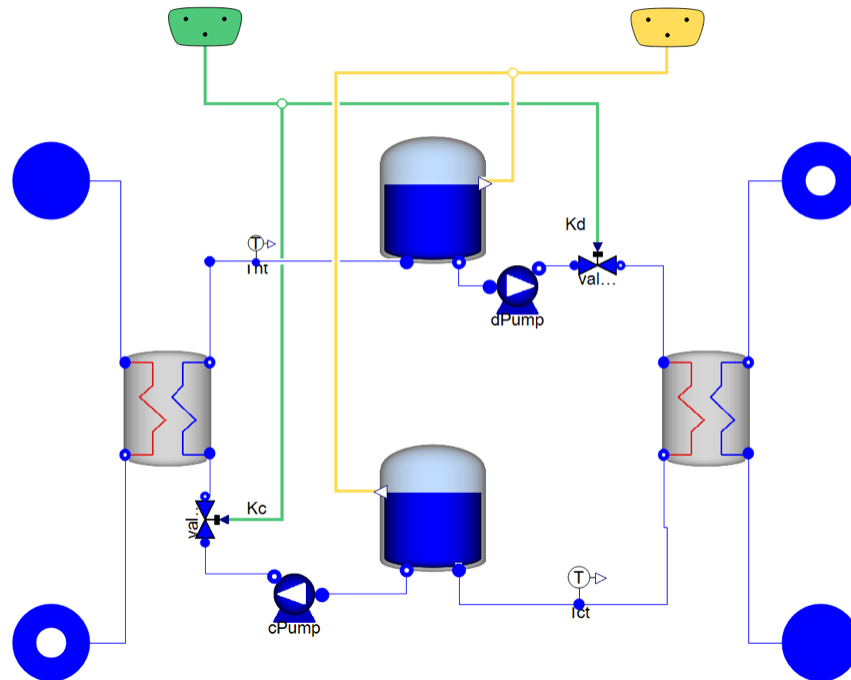


Figure 41. Sensible loop model.

The charging and discharging powers are governed by the heat transfer through two heat exchangers. Several sensible loop models are available in the *ThermalStorage* package, differing from each other exclusively in terms of the heat exchanger model:

- In the *SensibleLoop_HX0D* model, the ideal heat exchanger model does not account for dynamic aspects, *HX_0D* is used.
- *SensibleLoop_HX1D_WaterOil* encompasses 1D shell and tube heat exchangers. The fluid on the shell side of the heat exchanger is water, condensing on the charging side and evaporating to superheated steam conditions on the discharging side.
- Similarly, *SensibleLoop_HX1D_OilOil* is based on shell and tube heat exchangers, assuming a single-phase fluid flow on the shell side. As a result, this model is suited for thermal power exchange with an intermediate oil loop, for example.

The main subcomponents, i.e., the *Tank* and heat exchanger models, developed for the sensible loop models available in the TANDEM library are described in the following sections.

Tank

The *Tank* model is used to simulate the sensible fluid accumulation in the tanks. It is based on mass and energy balance equations. The liquid surface pressure is assumed to be at a fixed, user inputted, pressure (imposed by the presence of a cover gas), whereas the bulk pressure is given by Stevino's law. It is possible to account for heat losses to the environment, computed through

the convective heat transfer between the wall and both liquid in the tank and external environment and heat conduction through the wall material. This term can be deactivated through a dedicated flag, which allows the user to assume the tank to be perfectly insulated.

Shell and tube heat exchanger

The shell and tube heat exchangers are based on a 1D finite volume approach. They are built with models of the ThermoPower library, namely the *Flow1DV* (and, in case of applications with phase change on the shell side, the *Flow1DV2ph* component) to simulate the fluid flow. In addition, the *MetalWallFV* component is adopted to account for the thermal resistance and inertia of the metal structure, and the *CounterCurrentFV* component is used to account for the counter-current thermal power exchange. Two models are available in the package, the *ShellAndTube_WaterOil* and the *ShellAndTube_OilOil* component. The only difference between the two models is related to the shell side flow model. In the first case, it is assumed to have two-phase water on the shell side; thus, the *Flow1DV2ph* component is adopted. On the other hand, oil or other single phase fluids are acceptable in the shell side of the *ShellAndTube_OilOil* since it is based on the *Flow1DV* class.

Static heat exchanger

HX_0D is a simplified heat exchanger model that does not account for dynamic aspects. The heat transfer in the components is governed a global thermal conductance, UA ($W/^\circ C$), a parameter to be tuned according to the heat exchanger operating conditions.

Control strategy

This package provides two controller models, intended to provide the opening signal to the valves in the sensible loop model. The *TEScontroller_SST* imposes nominal conditions, assuming the valves to be fully open. On the other hand, PI controllers are used in the *TEScontroller_PID* component to regulate the valve opening according to the error of the measure of hot and cold tank temperatures with respect to their setpoints.

The control package also encompasses the *ActuatorBus* and the *SensorBus*, used to collect the control signals in the models and exchange them through single connectors.

Provided examples

Several demonstration cases are available in the Test package, showcasing the dynamic behaviour of the various SensibleLoop versions in response to the same transient scenarios. For instance, the results obtained by testing the *SensibleLoop_HX0D* and *SensibleLoop_HX1D_WaterOil* to a ramp-wise decrease of 50% charging and subsequent 50% discharging flow rate are presented in Figure 42. An application in a more complex energy system,



with the TES model directly coupled to the BOP model in ThermoSysPro and the NSSS model in ThermoPower, is available in the *TestCases* package and described in (Masotti, 2024).

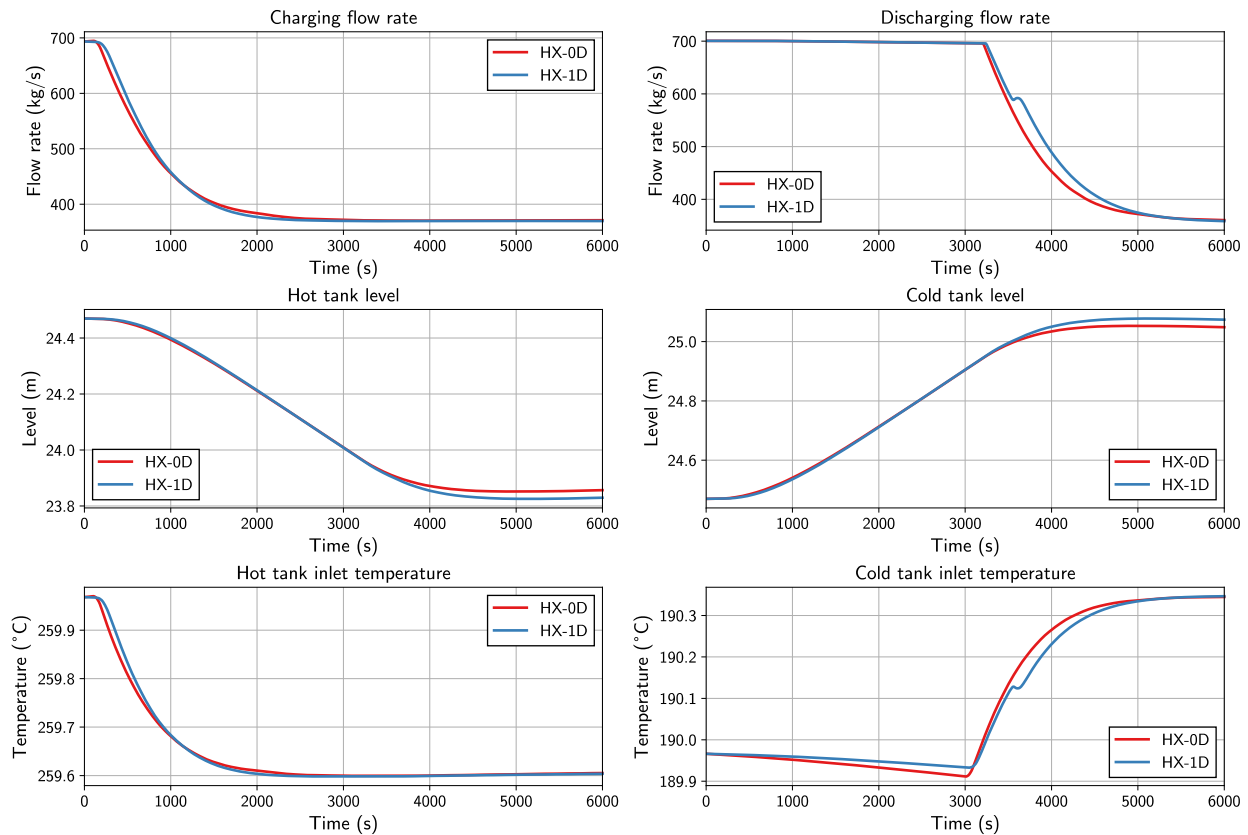


Figure 42. Illustrative transient simulation with two versions of the *SensibleLoop* model.

Electrical Energy Storage

The *ElectricalStorage* provides the black box model *SimpleBattery* to simulate the charging and discharging process of a battery exchanging electrical power.

Component description

The *SimpleBattery* model relies on components from the Modelica Standard Library and from the ThermoPower library and does not account for any dynamic features of the component. The Integrator component is used to integrate the input signal for the exchanged power, which corresponds to the state of charge of the battery. The latter variable is an output of the model, as it will be adopted in the controller to regulate the charging and discharging processes.

The input power signal is associated to the *PowerConnection* connector of the ThermoPower library to facilitate the coupling of *SimpleBattery* with other models.

Control strategy

An example of controller *BatteryControl*, meant to translate an input power signal from a supervisory control system into an acceptable exchanged power signal for the battery, is also included in this package. It is based solely on components from the Modelica Standard Library that are used to regulate the exchanged power accounting for the operational limits of the battery, i.e., maximal charging and discharging power and state of charge. For example, if the state of charge reaches the maximal capacity, the controller transmits only negative power signals, preventing further charging of the battery.

8. District heating

The *DistrictHeating* package provides the main components required to simulate the dynamics of a district heating network. These include the transmission line, which encompasses a feed and a return pipeline for the transmission of the heating water from the power plant to a distribution network or between different distribution networks, the model of the distribution network itself, as well as additional heat sources (i.e., conventional combined heat and power plants or heat pumps). In this package, the classes are all based on components from the ThermoPower library.

Package description

The package is further divided into the following subpackages:

- The *Test* package provides some test cases for the proposed components, namely for the transmission and distribution network (both in steady state conditions and with an illustrative control strategy) and for the heat sources.
- The aforementioned classes are collected in the *Components* package.
- The *Control* package provides examples of controllers to be coupled to the district heating network, as well as dedicated signal buses to facilitate the coupling.

Components description

Distribution network

The distribution network model *Distribution* is used to simulate the water inertia within the ramifications of pipelines in urban areas where heat consumers are located. Figure 43 shows the structure of the model. The *Inertia* component, available in the *BaseClasses* subpackage, is modelled as a closed water volume exchanging water with the transmission line through two *Flange* components from the ThermoPower library. Moreover, an additional flange allows for fluid exchange with the pressure sink, which ensures that the pressure within the distribution network remains at its nominal value. The volume exchanges thermal power through three different *HeatPort* connectors, available in the Modelica Standard Library. These are connected



to ideal heat sources *PrescribedHeatFlow* that convert the signal power profiles from a control system into exchanged power. In particular, the connectors represent three separate thermal power flows: the heat demand, the heat supplied directly to the distribution network, and the potential heat trade with other distribution networks. In a modified version of the model, *Distribution_externalSource*, one *HeatPort* connector is extended to be able to couple the ideal heat source model directly to the distribution network. Two signal buses, available in the *Control* package, are used to collect the actuator and sensor signals, such as the distribution network feed and return temperature, which could play an important role in the control of the district heating network.

Transmission network

The transmission line model *Transmission_bypass* is based on components from the ThermoPower library. In particular, the *Pump* component is used to model the pumping stations in the transmission line. Two pumps located at the inlet of the hot and cold legs, are included in the model. As for the pipelines, a 1D finite volume approach, implemented in ThermoPower *Flow1DFV*, is used to model the fluid flow in the tubes. The hot and cold legs are thermally coupled to the *MetalTubeFV* components, used to simulate the thermal inertia and resistance of the metal walls. The external wall connector is linked to a temperature source *TempSource1DFV* to account for the heat losses to the environment. Two *ValveLin* classes are added to the model to facilitate the control of thermal power delivered to the distribution network. For example, if thermal power to be delivered to the distribution network increases, the lower valve is opened and, at the same time, the valve connecting the hot leg to the cold leg (or, in other words, a bypass valve) is closed to increase the mass flow rate delivered to the distribution network.

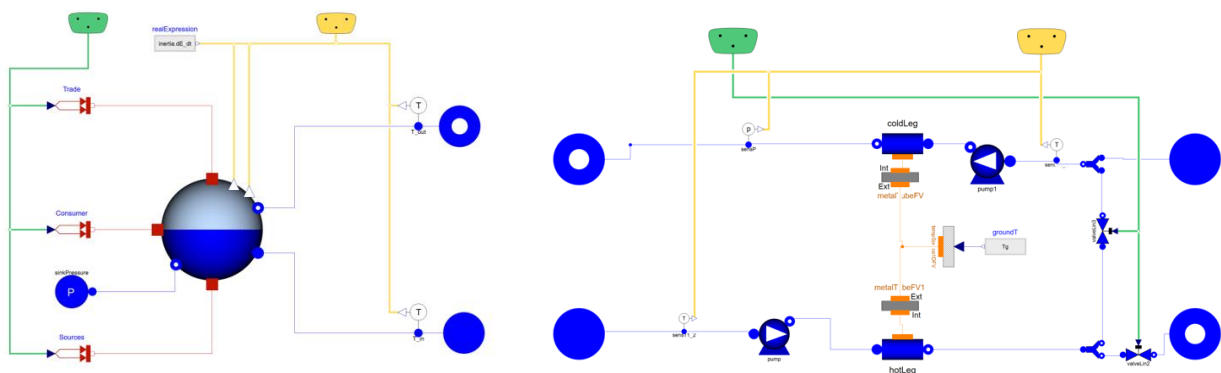


Figure 43. Models of the distribution network (left) and of the transmission network (right).

Control strategy

The *Control* package provides two examples of controllers for the regulation of the valving system in the transmission line and the sensor and actuator signal buses required to connect the controllers to the models.

The *DHNcontroller_SST* imposes the nominal value for the valve opening, i.e., with the bypass valve fully closed and the distribution line admission valve fully open. Moreover, it transfers the distribution network's input power profiles to the model.

The latter aspect is also present in the *DHNcontroller_PID* component. In addition, it provides an illustrative control strategy to be adopted in district heating networks: the bypass and admission valve opening is coordinated through a PI controller (see Modelica Standard Library's *LimPID* component) to ensure that the distribution network's return temperature meets a given input setpoint.

Provided examples

- In the steady-state demo *Test_simpleNetwork_SST*, the district heating network model is coupled to a controller that imposes the nominal value of the controlled variables, i.e., the valves in the transmission lines. The controller also delivers signals of heat demand and supply to the distribution network. Under steady state conditions, the difference between these signals reflects the thermal power supplied by the transmission line.
- In contrast to the previous demonstration, the *Test_simpleNetwork_ctrl* test case is used to showcase a possible control strategy using the *DHNcontroller_PID* controller component. In the test case, the heat demand is reduced, and the control system is activated to reduce the amount of thermal power supplied by the transmission network, thereby ensuring that the distribution network's return temperature meets the given setpoint.

A similar test case, *Test_simpleNetwork_ExternalSources_ctrl* is available to showcase the use of the distribution network model connected to ideal heat sources, in this case represented by the *SimpleCHP* and the *HeatPump* models (see § 9).

Moreover, a simplified simulator integrating the nuclear power plant with the district heating network is available in the *TestCases* package (Masotti et al., 2024b).

9. Additional Energy Sources

Combined heat and power plant

The combined heat and power plant (CHP) *SimpleCHP* model is treated as a black box component, assigning the values of two input signals for the thermal and electrical power output to the *HeatPort* connector of the Modelica Standard Library and to the *PowerConnection* of ThermoPower.

Heat pump

Similarly, the *HeatPump* model requires a signal for the thermal power output, which is assigned to the *HeatPort*. The required electrical power, exchanged through *PowerConnection*, to achieve the required thermal power output is computed through the definition of the coefficient of performance that characterises the heat pump, which is given by the ratio between thermal power output and electrical power input.

Provided examples

In the *Test_HeatSources* model, the simplified heat sources, namely the *SimpleCHP* and the *HeatPump* classes, have been tested. The goal is to showcase the required connections, such as those to a heat sink and to the electrical grid. In this test case, constant values are assigned to the power signals.

10. Desalination

Desalination is seen as a potential end-user segment to be coupled to a nuclear hybrid energy system. Within the scope of the TANDEM project, reverse osmosis stands out as the reference technology for this process. As a result, this industrial process solely relies on electrical power and is not thermally coupled to the integrated energy system.

The package contains the *ReverseOsmosis* model as well as a test case with a ramp in input power to showcase a possible utilisation of the model.

Component description

Having only an electrical interconnection, a simplified version of the model has been proposed within the framework of the TANDEM project. In particular, the desalination plant is treated as a black box, converting a given input power signal to the electrical power exchanged by ThermoPower's *PowerConnection* connector, facilitating its potential link to the electrical grid model.

The power signal is integrated to compute the electrical energy delivered to the desalination plant, which is then converted into the cumulative amount of produced fresh water through a proportionality constant given by the specific energy consumption (SEC) of the considered reverse osmosis desalination plant. The model also provides the volumetric water flow produced in each instant by computing the derivative of the cumulative water output.

11. Renewables

The dynamic model of the wind turbines will be used to compute the electric power output provided by this renewable energy source considering fluctuating environmental conditions, e.g., in terms of wind speed. Only the dynamic model of wind turbines will be considered in the TANDEM library, whereas the contribution of other renewable sources, such as solar PV, will be accounted for directly in the electrical load profile.

The open source library *WindPowerPlants* has been considered to account for the dynamic behaviour of this power source (Eberhart et al., 2015).

Provided examples

In addition to the test cases in *WindPowerPlants*, extended also in the TANDEM library to showcase how to use the wind turbine component, and additional test case demonstrating the coupling of the wind power plant, via the electrical grid, to the desalination plant is included. The latter relies on dedicated adaptors to translate the exchanged electrical power into the pin connector variables of the Buildings library, i.e., voltage and current.

12. Conclusion

The Modelica TANDEM library is one of the main deliverables of the Euratom TANDEM project. The TANDEM library provides the main bricks to build an easy customizable simulator of Hybrid Energy Systems. It constitutes a valuable tool to, for example, build a HES simulator of performance, perform techno-economical and safety investigations taking into account the complex interactions between the diverse components of the HES: SMR, CCGT, thermal storage, electrical grid, hydrogen production, district heating,

Despite the young age of the library (v1.0 published during the 2024 summer), some applications have already been developed and the related results published. For example, (Masotti, Haubensack, et al., 2024) shows the building of a first version of the DH simulator, connecting the SMR (ThermoPower N3S and ThermoSysPro CI-BOP) to the DH component. (Masotti, Lorenzi, et al., 2024) also used the library to explore the potential of heat storage implementation in HES to improve the flexibility performance of a SMR. Both these applications are provided to the public within the library itself, in the *TestCases* subpackage.

In the next future, more complex applications, i.e. the whole representation of the two TANDEM HES configurations will be performed. To widen its application domain, new components will potentially be developed in the future to include, for example, Advanced Modular Reactors.

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