Thermo hydraulic library for power systems applications

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Abstract

The thermo hydraulic library presented here has a long history starting in the 70's with dynamic simulations of servo systems and power plants at ASEA (ABB), then with parallel efforts in the 80's at Sydkraft, to finally in the 90's move into the ENERGY library of the Sydkraft group. The library was initially implemented in the Dymola language of Dynasim, and in recent years transformed gradually into Modelica. This paper presents the basic rules and structures of the library, and provides examples of the dynamic modeling ordered by the power industry from Carl Bro Energikonsult AB[1] in Sweden. The examples show both the suitability of the rules of the ENERGY library, and give important feedback of 'lessons learned' for further library development and for identification of missing features of Modelica and generally of dynamic simulation capabilities today.

1 Introduction

The history of modeling energy systems at Carl Bro Energikonsult AB traces back to the application of MMS[2] by Sydkraft and development of the Dymola-based ENERGY library in the 90's. The library was originally developed to model the complex thermo hydraulic processes of thermal power plants, but it proved applicable to energy systems in general where various fluid media transport energy throughout processes. Such a general "non-intended" application of the library is modeling of the ventilation system of complex buildings. Various rules to model media transportation were developed, and cover today different cases of heat transfer, mixing media, chemical reactions etc.

The structure and rules of the library establish a base for easy use and consistent applications. The rules were defined at the initial establishment of the library and developed further based on practical experience of the library use. We also found out that when people used the library they found it difficult and wanted to take short cuts, e.g. "I can do it simply for this application only", " I have no time to study handbooks...", etc. We are now convinced that this individual approach is the way to trouble – missed quality, reuse not possible, poor documentation, etc.

This paper will firstly present structures, rules and components of the library, and then go through a number of typical models delivered to Carl Bro Energikonsult AB's customers. The examples cover model descriptions, results and 'lessons learned'. Conclusions of our applications address missing features of the Modelica as experienced by us, and general needs for complementary tools required for efficient and cost effective modeling of the energy systems.

2 Energy Lib

2.1 Model structure

The Energy library is a component archive for the basic simulation tool Dymola / Modelica. The foundation of the library is the classic concept of a network of interconnected nodes, or finite thermo dynamical control volumes.

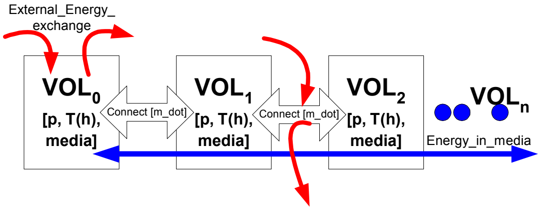

***Figure 1** Basic network*

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[1] Carl Bro Energikonsult was formerly Sycon Energikonsult AB - technical consultants of Sydkraft utility.

[2] Modular Modeling System, EPRI, Babcock

The state of the media transported through the network, is calculated mainly in nodes, while node-connecting elements calculate mass and energy exchanged between the nodes. The main objective of the modeling is then to simulate energy flows carried in the media and energy flows passed between the media containments and the environment (energy sources and sinks)

The model structure builds then on a number of basic rules / assumptions, where those most important are the following:

- The state of the media (liquid, gas or both) is presented in a state vector of dynamically calculated primary elements: pressure [p], enthalpy/temperature [h/T], and media composition [X].
- Media properties are derived from media 'tables' identified by X and [p, T] / [p, h] states. The media property vector and state vector will accordingly provide complete description of the node behavior.
- Each node is identified by the node pointer (node identifier) available through node ports for any component in the network. In the other words, any component of the model can read both node state and node media properties by knowing node identifier only.
- Connecting elements transfer basically media mass flow [w (m_dot)], and media energy content [h] on the outlet.
- Outlet energy content depends naturally on the inlet energy and on the energy transfer between the connecting element and the environment, and can follow one of the basic "iso-transformations". Note that all energy content of the media is expressed in the static enthalpy [h]; it is assumed that the media transform all their kinetic energy ($v^2/2$) into 'h'.
- Connecting elements will normally not change media composition, and accordingly outlet media is assumed the same as on the inlet. This assumption has implications for the simulation of reversible flows.
- Each node (VOL) can change its media through mixing of incoming media and through the chemical reactions between the same
- Simplified nodes are allowed by inheriting selected components of the node state vector of the other nodes. E.g. Pressure calculated dynamically in VOL$_0$ (figure 1) could be inherited by VOL$_1$ and VOL$_2$
- In the same way the connecting element can inherit mass flow from other element, reducing calculations to energy content only

2.2 Structure of the Energy library

The library is composed basically of four library levels.
Level 0: ModelComponent
Level 1: SubUnit
Level 2: Unit
Level 3: System,
Shown in figure 2

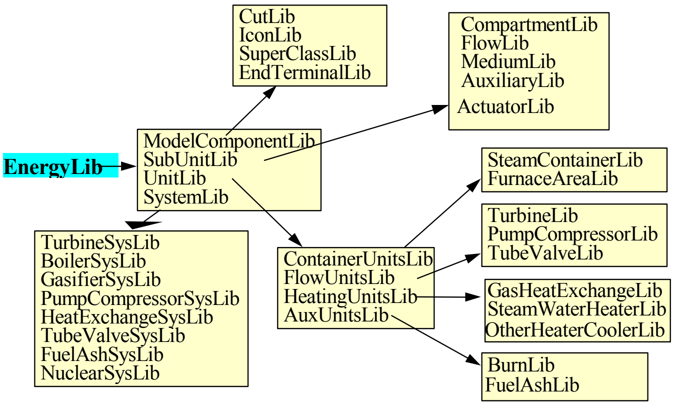

Figure 2 *Structure of the Energy Lib*

The components level 0 includes various basic sub-components specific for energy models. The original formulation, which builds on the object inheriting features, is now redone to Modelica formulations.

The sub-unit level 1 includes all basic thermo-dynamical concepts of the basic structure introduced above. The library is divided into four groups: CompartmentLib, FlowLib, MediumLib, ActuatorLib and AuxiliaryLib. Some details concerning compartments (i.e. VOL of figure 1) and flows (connecting elements) are discussed below.

MediumLib covers 'tables', or modules describing media properties. Initially the tables could be read directly or indirectly. The direct method means high resolution read-up by direct use of the media properties tables of the external programs. Indirect methods build on the polynomial or splines matching of the selected working area of the media table. The purpose of using polynomials instead of table interpolation is to speed up calculations, especially in calculations of derivatives, as C_p (dh/dT) or the coefficients α_h ($d\rho/dh$) and α_p ($d\rho/dp$). As media calculations recently generally have improved and the modern algorithms address derivability efficiently, we are going to reformulate our original concepts accordingly.

ActuatorLib, and *AuxiliaryLib* cover various types of valve actuators and e.g. auxiliary calculations of heat transfer between different media and materials. Here the heat transfer dynamics of the walls is represented. Other modules of this group represent chemical calculation (e.g. balance coefficients for different groups of chemical reactions) and calculations of special phenomena as (e.g. gas/steam moisture removal, fast particle separators etc.)

The unit level 2 includes models of machinery and equipment used at power plants (energy processes). The library is structured basically in four groups: ContainerUnitsLib, FlowUnitsLib, HeatingUnitsLib and AuxUnitsLib.

The system level 3 covers mainly complex machinery or whole plants. The library is filled up gradually with models of the actual simulations and only to a lesser extent as a result of library development effort. It should be noted that the specific solutions taken in plant simulation cases are usually the supplier's properties and general availability of those for the Energy library must be negotiated.

Levels 2 and 3 are introduced below through the presentation of the actual simulation cases

2.3 Selected features of the basic components

Basically all models of the Energy library are derived of the local conservation equations (mass, energy and momentum) converted to ordinary differential equations valid for the distinct, separable control volumes of the library modules. This approach can be exemplified on the basic components of VOL and the connecting element.

Node /Volume/

The basic structure of the VOL module is the following:

1. Calculate media property [MP] vector according to the node state vector [p, h, X]. This is basically a call to media 'tables' of the media identified by X. The MP-vector is composed of the normally required property data as e.g. density, entropy, viscosity, and saturation data for steam (x – steam content in water, p_s, T_s, etc). Our tables calculate as well a number of derivate properties, e.g. C_p=dh/dT. The derivates used for pressure and enthalpy calculations are elasticity coefficients dρ/dp and dρ/dT (ρ – density)
2. Two basic calculations characterizing the particular node can now be expressed in,
   - The sum of all mass flows (Σw_i) connected to the node
   - The sum of all energy flows (Σe_i) passing through the node[3]
3. As the media in the node is assumed to be in rest (which is actually not necessarily true) mass and energy conservation equations are used here, but in an extensive form valid for the whole volume. Those equations describing dM/dt (M-total media mass in the node), and dU/dt (total internal energy of the node), are converted to state equations of, dp/dt and dh/dt, functions of (Σw_i, Σe_i, X_properties)[4]

Using Σw_i and Σe_i as the inputs to the state calculating equations allows easy adaptation of the basic node model to the particular kind of the sought after module.

$$\sum w_i = \sum_{i=1}^{n} w_i + \rho \cdot \frac{dV}{dt}$$

and

$$\sum e_i = \sum_{i=1}^{n} w_i \cdot h_i + Q - W - (h \cdot \rho - p) \cdot \frac{dV}{dt}$$

where:

n	*number of ports connected*
w_i	*mass flow from (-) / to (+) the port*
V	*node volume*
Q	*heat energy flow in (+), out (-) of the node*
W	*work energy flow in (-), out (+) of the node*

Please note now that for simple, constant volume nodes dV/dt = 0, and no additional heat transfer is expected, = 0. On the other hand nodes with moving pistons (as in compressors) can be modeled by adding the term dV/dt, and Q can be given by simple heat transfer through the walls (A*α*ΔT), or by the heat of the chemical reactions (combustion).

Adapting node dynamics to model frequency

It is quite well known that the models should be adapted to the frequency range actual for the

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[3] Both Σw_i and Σe_i should be treated as 'auxiliary variables' and not strict physical meaning implied by 'mass' and 'energy'

[4] For single phase media we use states of [p, T]; derivative of dh/dt is then replaced then by dT/dt

particular application. The approach used in the Energy library is through switching off dynamics of nodes of frequencies out of the range simulated. That switching off was done originally by replacing derivatives by residua, e.g. residue(p) = Σw_i; and residue(h) = Σe_i. In the modern Modelica version the same effect will be reached by simple zero setting of both Σw_i and Σe_i.

Elementary 'Connecting Module'

Connecting element in its elementary form transports media from the inlet to the outlet and behaves according to the equation of the momentum conservation,

$$\frac{d(M\cdot v)}{dt} = w_{in}\cdot v_{in} - w_{out}\cdot v_{out} + (A_{in}p_{in} - A_{out}p_{out} - F_f)$$

For normal frequency ranges d(Mv)/dt can be assumed = 0, and all pressure drop accounted to F_f; loss on friction. Assuming $F_f = K_{loss}*w^2$, the basic form for calculation of pipes and valves will get into the form of w= K*sqrt(Δp). Calculation of K is based on the common knowledge of pipe and valve characteristics.

In case media inertia should be considered, the basic momentum equation can be rewritten into a differential equation of dw/dt,

$$\frac{dw}{dt} = \frac{1}{L}\cdot(A_{in}\cdot p_{in} - A_{out}\cdot p_{out} - F_f)$$

where L is the length of the pipe.

Note that having 'w' as a state variable of the connection will actually simplify calculation of F_f , which requires knowledge of the Reynolds number and depends accordingly on the mass flow in the first place.

Special cases of the connecting module

Pretty straight forward calculations of connecting elements get complicated if,

- Compressible media transported at the over-critical pressure drops over the element. This case is solved by introducing in w-form factor Φ allowing similar structure to the one given above; w = K*Φ*sqrt(p_{in}). Note that for p-ratios higher than critical the Φ-factor will be constant and 'w' will depend on p_{in} only. The form for 'w' is not reversible, as the known 'w' will not allow calculation of p_{out}. Furthermore the form is strongly non-linear close to pressure ratios 1.
- Junctions, or direct coupling of pipes and valves.
  The junction problem can be described as forcing calculations into non-relevant stiff nodes where several pipes meet. Introducing a non-dynamical node described above can solve the problem, which means that we solve algebraic equations instead of integrating state vector derivatives. The library approaches junctions through simple methods of finding resultant C coefficient of the above forms, or by special handling of pipe-valve-pipe group approximating pressure drop over the valve
- Changing energy content of the media along the connection.
  For simple connectors we assume that no heat exchange is taking place and accordingly $h_{out} = h_{in}$. This is of course not true in case of a change of energy content in the media. The special modules are provided to calculate outlet energy content at the isentropic (turbine exhaust), isenthalpic or isothermal transitions. The module is strongly coupled to the media table modules
- A heat exchanger is a case of connector where heat of the media is exchanged with the environment. The basic heat flow is simple to calculate as Q = C*(T_{inside}- $T_{outside}$), the problem is anyhow serious as both temperatures are varying along the connector, and lumped parameter approach is not longer valid. Two solutions are applied;
  1. By assuming logarithmic temperature profile along the connector
  2. By dividing the whole length of the connector in segments, each segment composed of a node and single connector. The nodes of this solution will calculate dh/dt only inheriting average pressure of the boundary nodes. In a similar way, connectors will inherit common 'w' and transport changing energy along all segments.
- Examples of our models presented below show the second solution most often applied. The first method takes no consideration of time aspects of stabilizing the logarithmic temperature profile, and can therefore not model the rapid transients we have simulated.
- Chemistry is actually a case of changing media composition when media components are reacting with each other in the node. Typical examples are in burner chambers of gas turbines, or in gasifiers. The problem is addressed through the following:

1. The (dominating) chemical reactions are identified
2. Reaction equilibrium form is defined, with equilibrium coefficient expressed as an empirical function of media state (normally [p,T])
3. Mass balance equation is now expressed in mole form, ΣN_i.

3 Experience and Lessons Learned

3.1 Short overview

All modeling examples introduced here originate from our assignments from conventional and nuclear power plants, from local utilities, or from using simulation models as a validation tool during research of the new concepts of energy systems.

All modeling was done on commercial basis, where costs of the modeling were critically evaluated against potential advantages. The following were the main reasons cited by our customers:

- Tool for designing control systems
- As above, for the control system evaluation including formal validation of concepts proposed
- Preparation of commissioning. Evaluation of tests proposed, selection of controller parameters, etc.
- Training and education

The examples below address those purposes and give the experience feedback of the lessons learned.

3.2 Controller Design

Customer: Barsebäck Kraft AB.
The customer required a model of the process for design and testing of the reactor water level controller for the auxiliary feed-water system. There was no access to the real process during controller development. Controller design through predefined load cases on models using pre-validated equations. The controller parameters where then used on the real process with good result.

At the start of the project it did not include a modeling phase. Parameters from Oskarshamn Nuclear Power Plant should be used with slight adjustments.

The controller strategy is fairly simple, it contains a reactor level controller connected in cascade with a flow controller that acts on a valve. The flow controller can be tested on a cool reactor with a good result. The dynamics of the level control loop changes with the reactor temperature and pressure. This could not be tested on a cool reactor. A heated reactor is expensive and should be in operation.

A model is built to tune the level controller. The controller is tuned to be able to handle predefined load cases in particular ways. To achieve this the model is changed several times as the load cases get more and more complicated. In figure 3 the final model is shown.

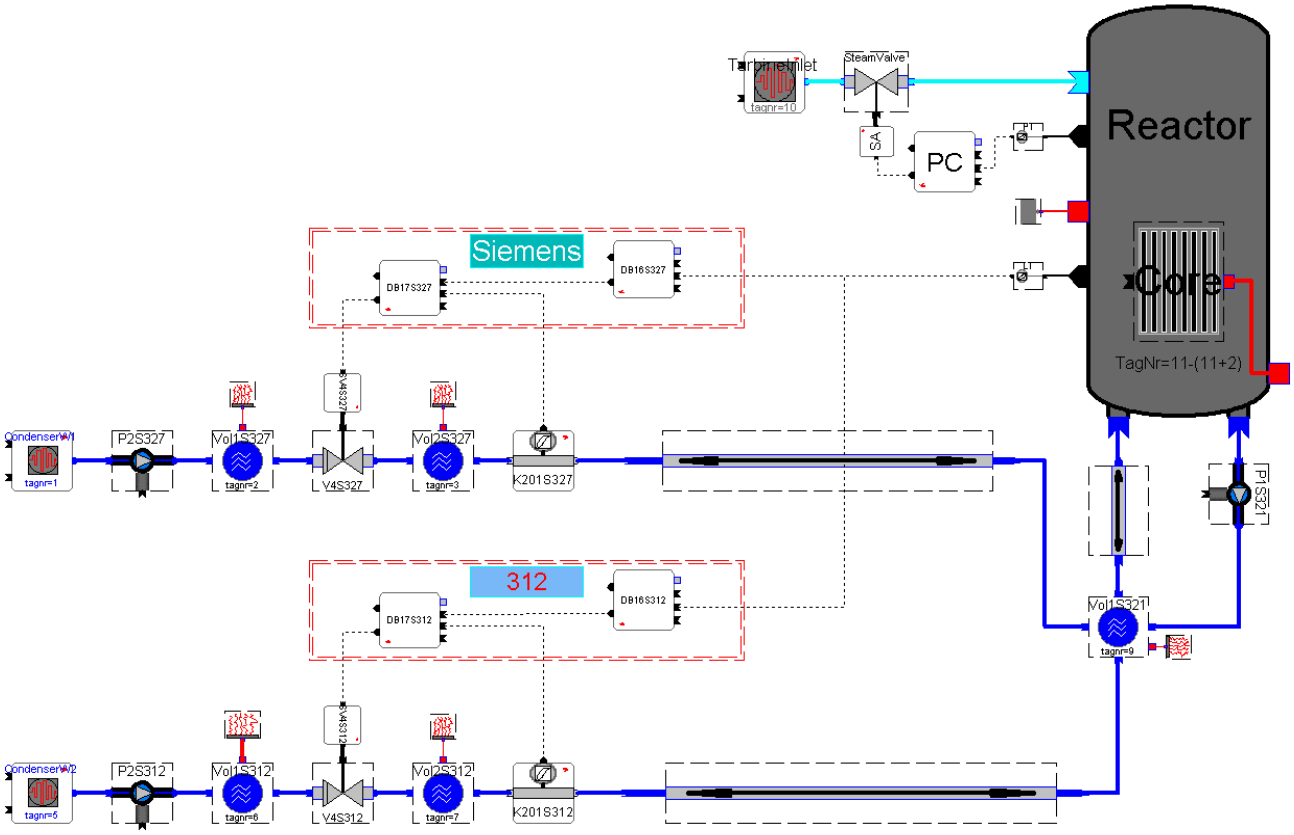

Figure 3. *The model of the reactor and the main- and auxiliary feed water systems, (312) and (327).*

The reactor model started as a model of an expansion vessel. The model was then upgraded in several stages to accommodate the increased demands on the result.

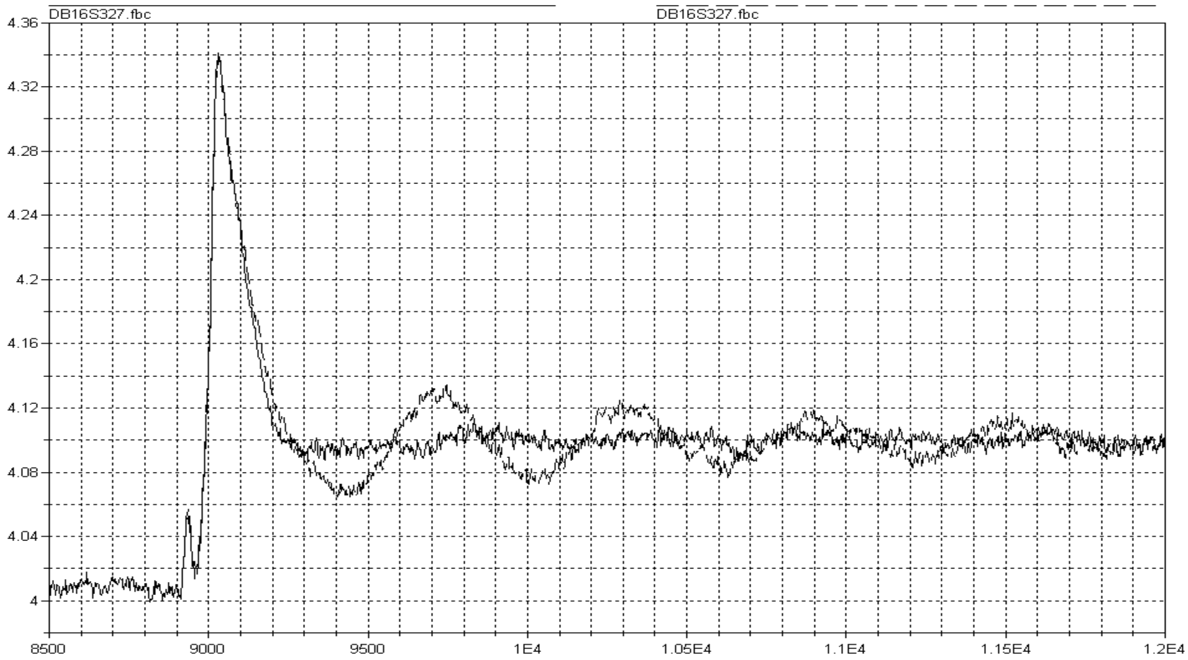

Figure 4. *The plot shows the simulated reactor level with two sets of controller parameters. The transient originates from the start of the auxiliary feed-water pumps.*

The solid line is the filtered reactor level from the simulated controller. The line is from a simulation with the controller parameters designed through simulation.

The dashed line is the reactor level from a simulation with the implemented controller parameters. The derivative part was decreased in the implemented controller since it was thought to be too aggressive.

The controller implemented today is faster and more robust than the controller used before the start of the project.

Lessons Learned: Pre-validated models can be used in other, not directly related, projects with good result.

3.3 Validation of the new concept

Customer: Elforsk AB and Sydkraft AB, Miljö och Utveckling.
Development and validation of models used to comprise an Evaporative Gas Turbine process (EvGT) model. The plant is a research plant, with extensive instrumentation, located at Lund Institute of Technology. This model includes non-linear processes, e.g. evaporation and condensation into a gas mixture with a fully dynamic gas composition.

The model was developed over a period of several years and started within a licentiate thesis. The plant model is composed of several, separately validated, component models, which consists of several sub models.

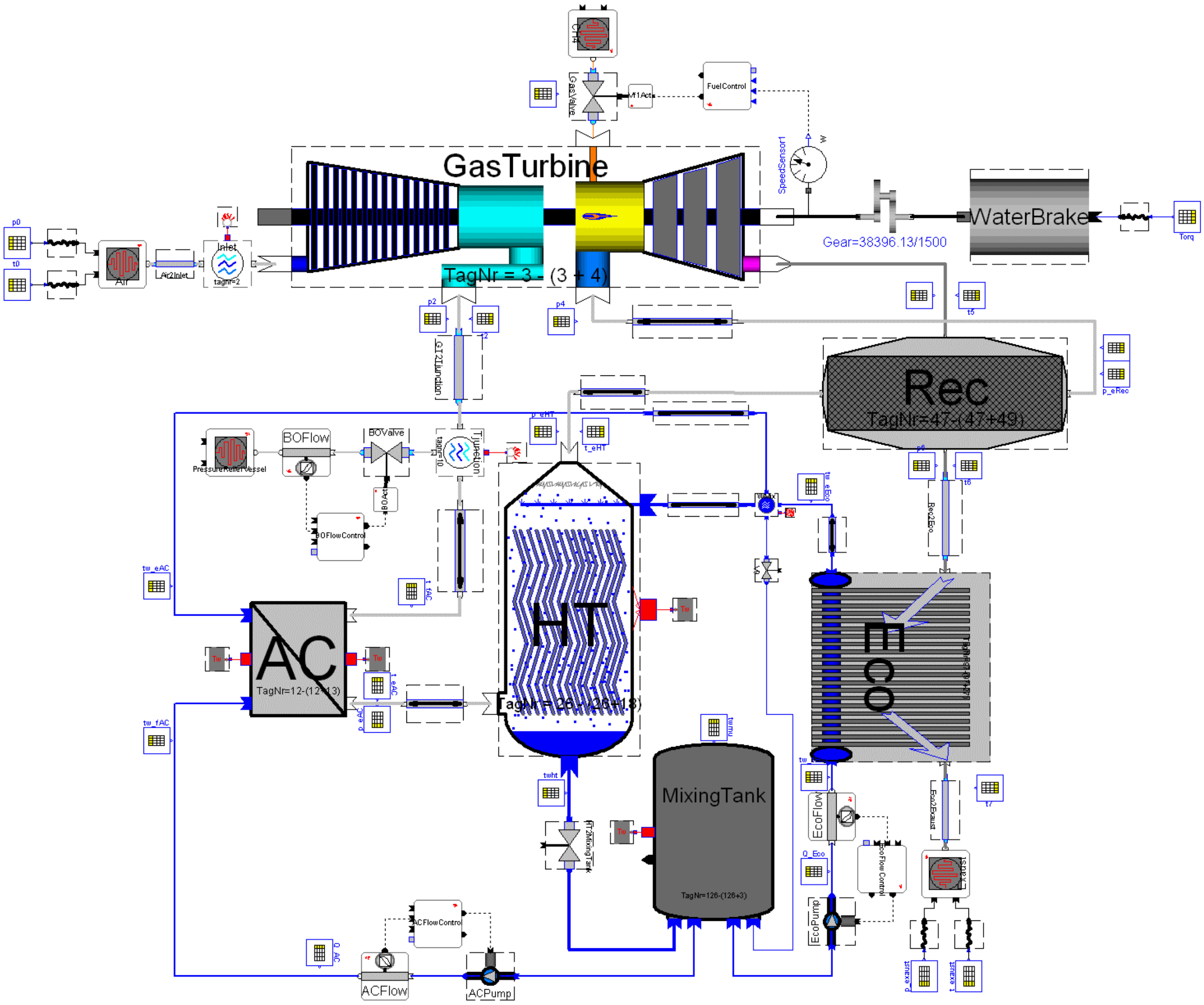

Figure 5 The model of the pilot plant at LTH.

The validation of component models was carried out through test benches. These test benches were fed with series of measurements for flow, pressure, temperature, composition and so on. The result was then compared with the measurements.

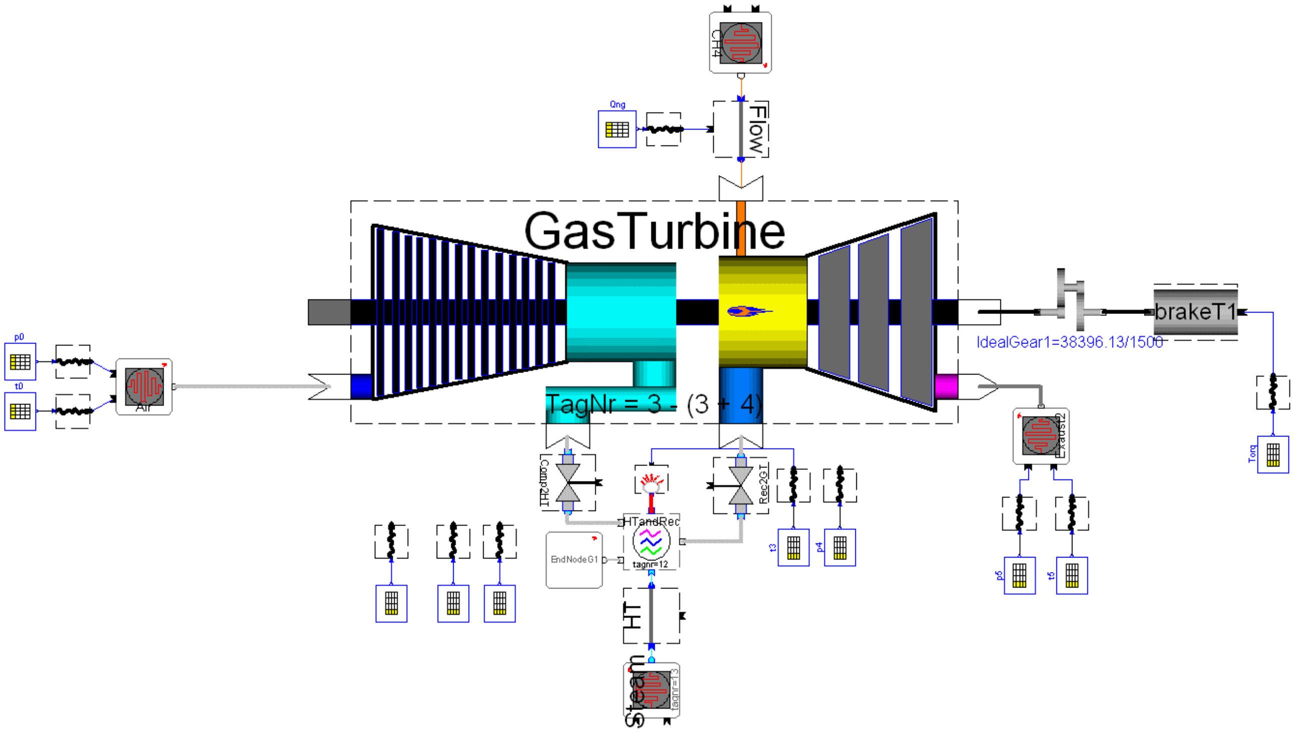

Figure 6 *The test bench for the gas turbine.*

In the test bench for the gas turbine several simplified component models had to be used to generate good boundary conditions. These simplified component models used measurements during the simulation to get the right boundary conditions. Please notice that the model is fed with measurements of the mass flow of fuel and torque and that the shaft speed is free.

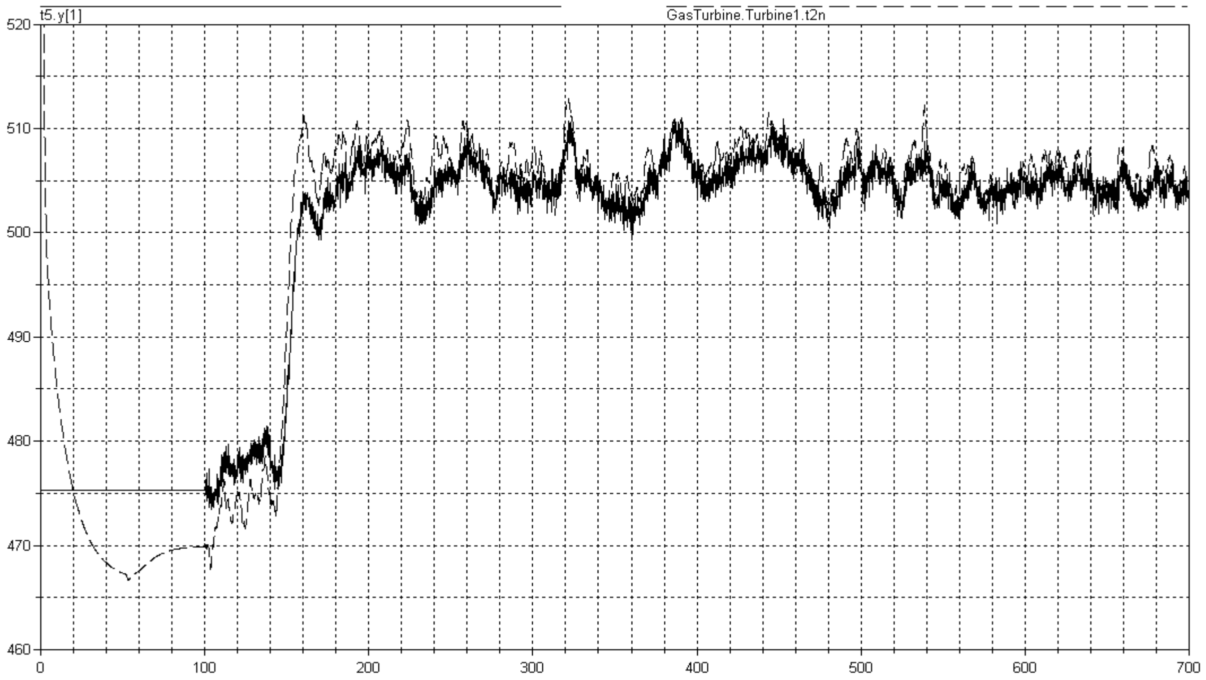

Figure 7 *The exhaust gas temperature from the gas turbine in un-validated load case. The solid black line is the measurement and the dashed line is the simulated values.*

The reason that there is a mismatch in the beginning is that the initial condition does not correspond with the load case. The load case is a load change from 50 to 60% shaft power. The faster responses that can be observed in the model are thought to depend on the transmitter, which is not included in the model.

The model shall be used to predict test runs on the pilot plant, stability tests and design tests on future plants.

Lessons Learned: The model delivers results with an error within 5% in load cases that the model was not validated against. The dynamic model of the evaporation tower delivers better results than the static design methods used.

3.4 Check of a complex pre-validated model

Customer: Värmeforsk AB (Växjö Energi)
Dynamic modeling of a direct condenser at Växjö Energi. A direct condenser is used to condense steam during a turbine trip instead of letting it out to the atmosphere. This specific direct condenser heats the district heating system, this means that the even the heat are used. The direct condenser is exposed to powerful transients almost without any preceding sign. Still it is supposed to keep a stable steam pressure and a steady temperature on the district heating water leaving the condenser.

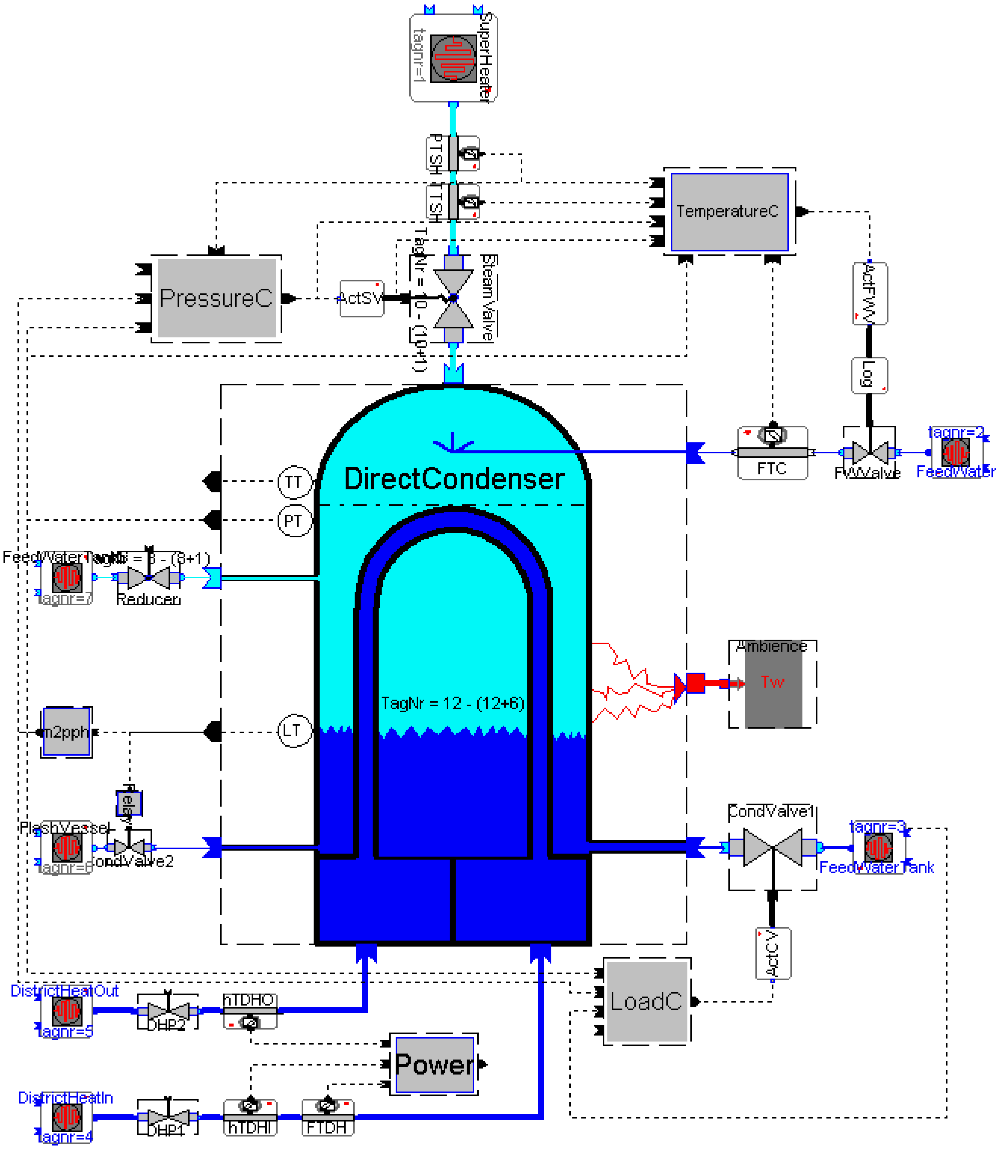

Figure 8 *The direct condenser test bench. The control system is modelled as islands according to their function.*

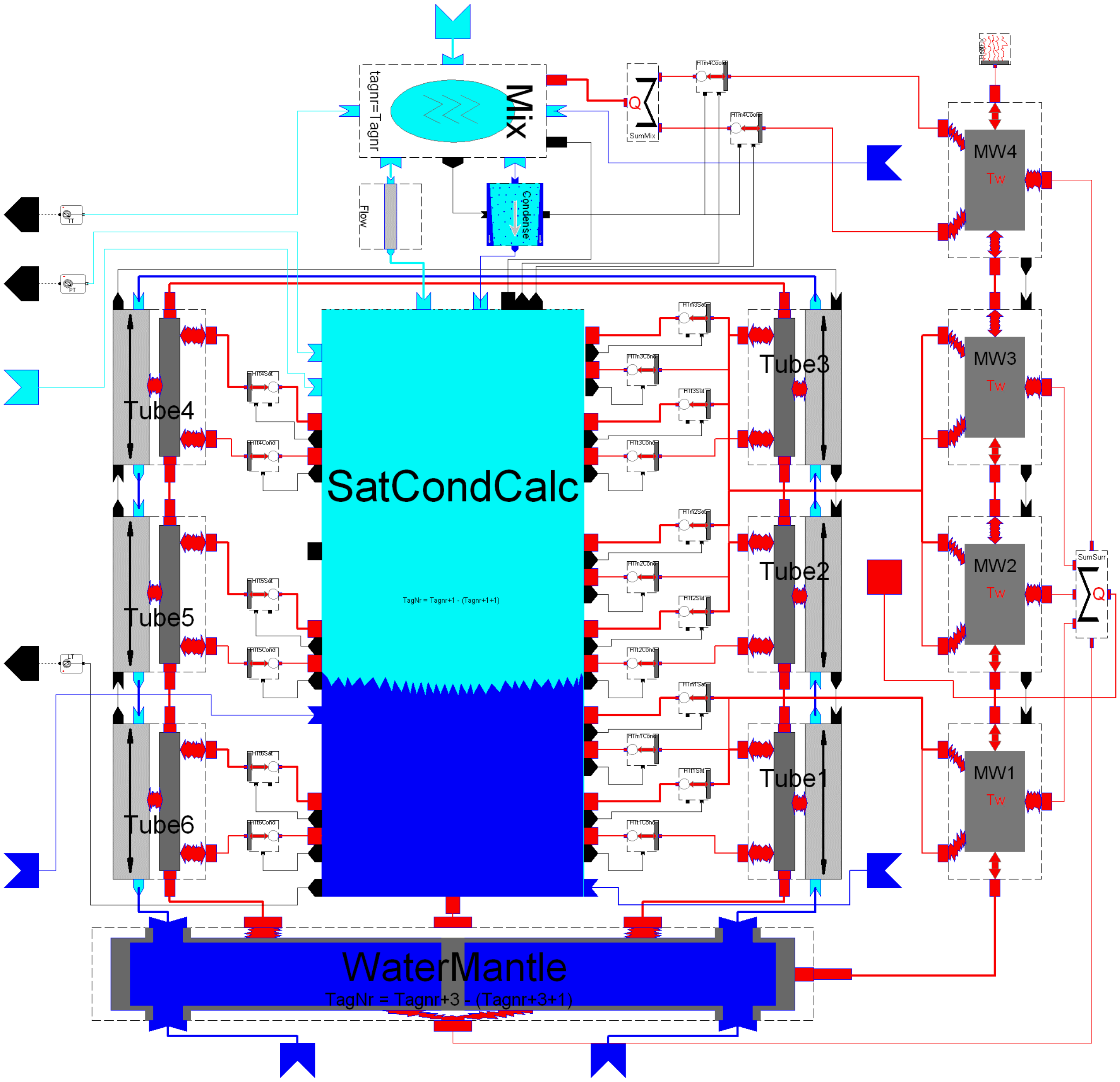

Figure 9 *Inside the direct condenser.*

The tube model used here handles several parallel identical tubes. It is divided in to six segments to get a temperature profile in the flow direction to use in the heat transfer calculations.

The condenser and the involved parts of the process and control system where modelled using only documentation available before commissioning. When Carl Bro Energikonsult AB was ready the model where sent to Värmeforsk and Växjö Energi delivered measurements from a turbine trip, to be used in the model, to Carl Bro Energikonsult AB.

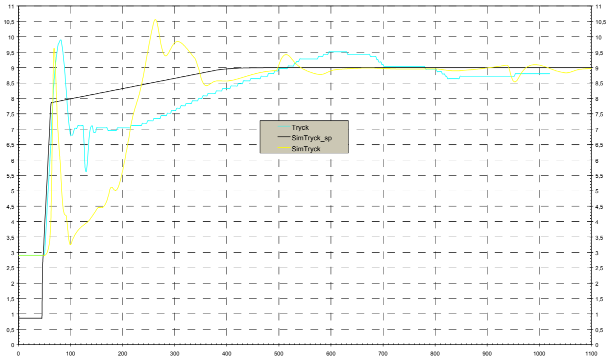

Figure 10 *The pressure in the direct condenser in bar.*

There are some assumptions, e.g. regarding the heat transfer during condensation on vertical tubes, which were not tuned to this particular case. Normally the uncertainty of a heat transfer calculation is ±10 to 20%.

In this case dynamic factors of such complex processes as the build up of the condensate film on the tubes have to be considered.

Lessons Learned: Although not a perfect fit the model delivers a result good enough to allow tuning of control parameters and preventing design and commissioning problems.

3.5 Modeling of a small project (pressed for time)

Customer: Sydkraft Värme Syd AB:
Testing of the control scheme for solar collector system with a total area of 1 200 m^2 with demands on high availability. The problem was to interconnect five separate solar panels. The panels are an integrated part of the walls on a recreation facility named Kockum Fritid.

This modeling was part-task in a project stage pressed for time and crucial for the final design of the system. As a result of the wall integration collectors faced east, south and west.

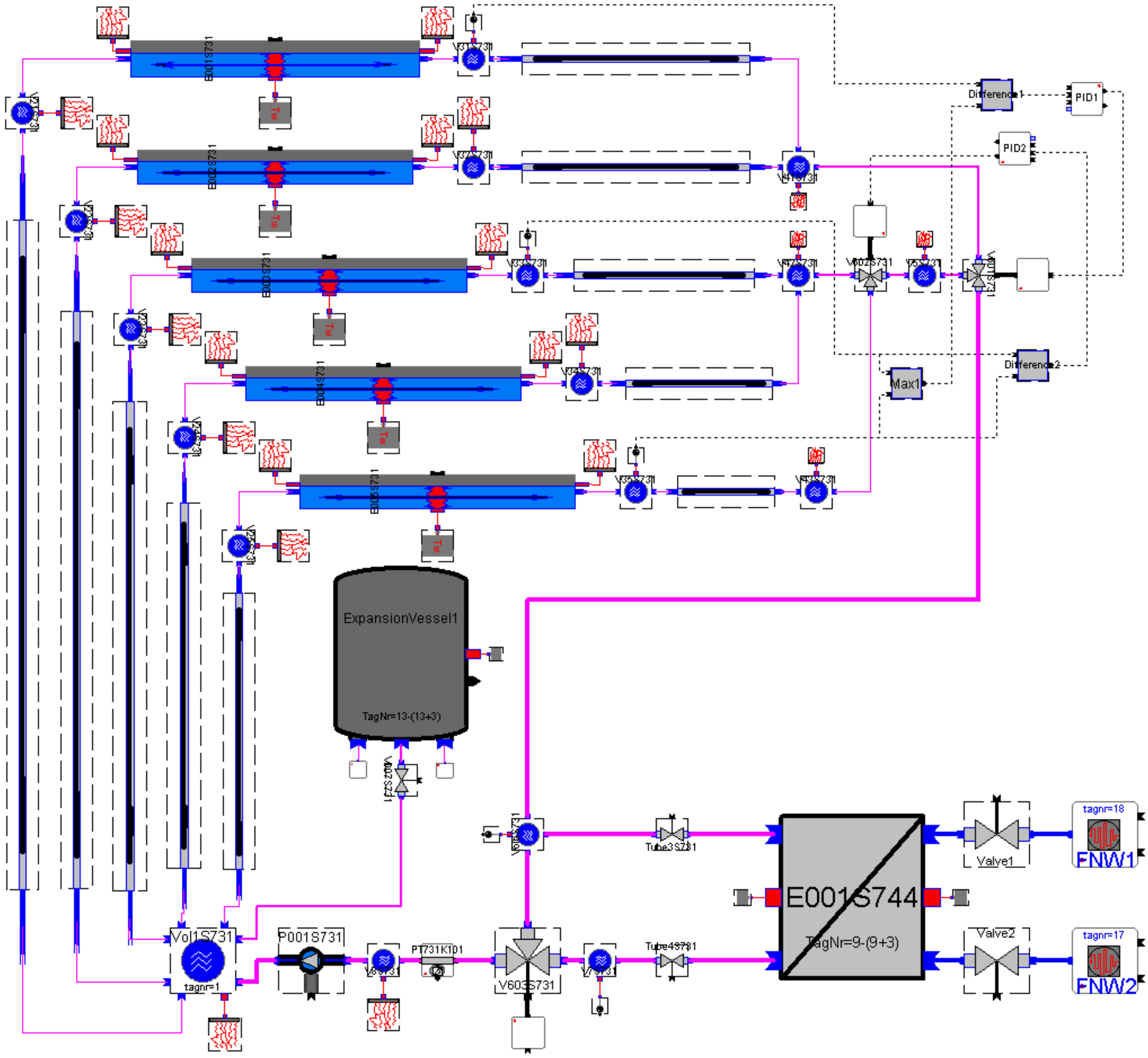

Figure 11 The model of the solar collector side of the system.

This first model was too complex to handle in this project. The decision to go right to the core of the problem was taken. This meant that the design work should carry on as in a normal project but the question if the flow from all solar collectors could be mixed should be answered through simulation. The model used to answer the core question is shown below.

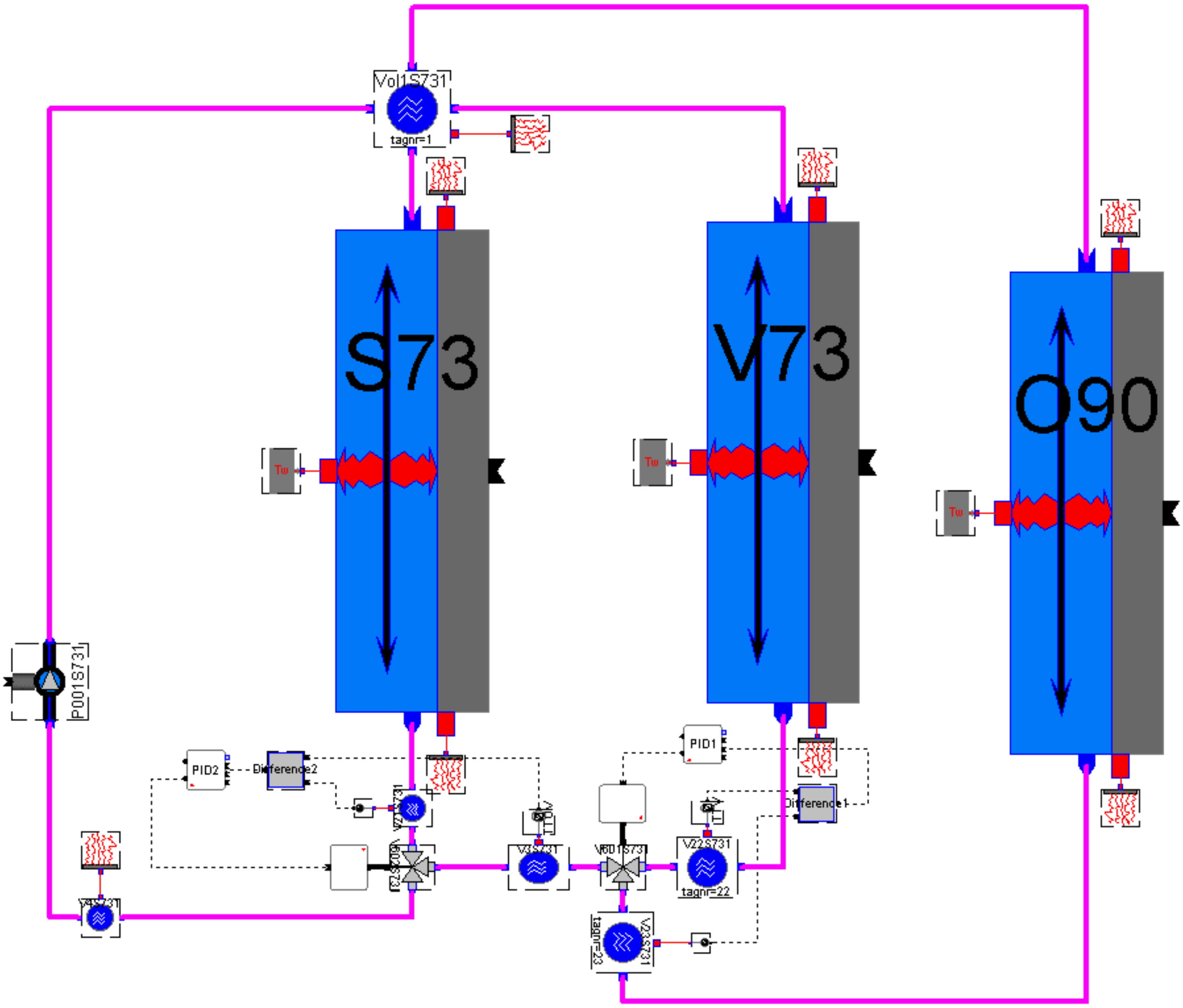

Figure 12 *The basic model of the solar collector side of the system.*

From this model the conclusion that the solar collectors could be connected to one system was taken. While the solar collector experts recommended a solution with five completely separate systems, the selected solution validated in the model, showed to be more efficient and cheaper, more robust and easier to maintain. The final system has a documented availability well above 99%.

Lessons Learned: The use of simulation can have a profound influence on the outcome when used in the early design phase of a project. Simulation can be used as a design tool even in small projects pressed for time and money.

3.6 Design through simulation.

Customer: Sydkraft Värme Syd, Kungsbacka

Simulation of a typical district heating system with several production units and an atmospheric heat accumulator, allowing evaluation of the complete process architecture, including design data and control system. The main idea behind the simulation was to study the interaction between the atmospheric heat accumulator, the boilers and the rest of the district heating system. The atmospheric heat accumulator has two functions; to store and distribute heat and maintain a constant pressure in the system.

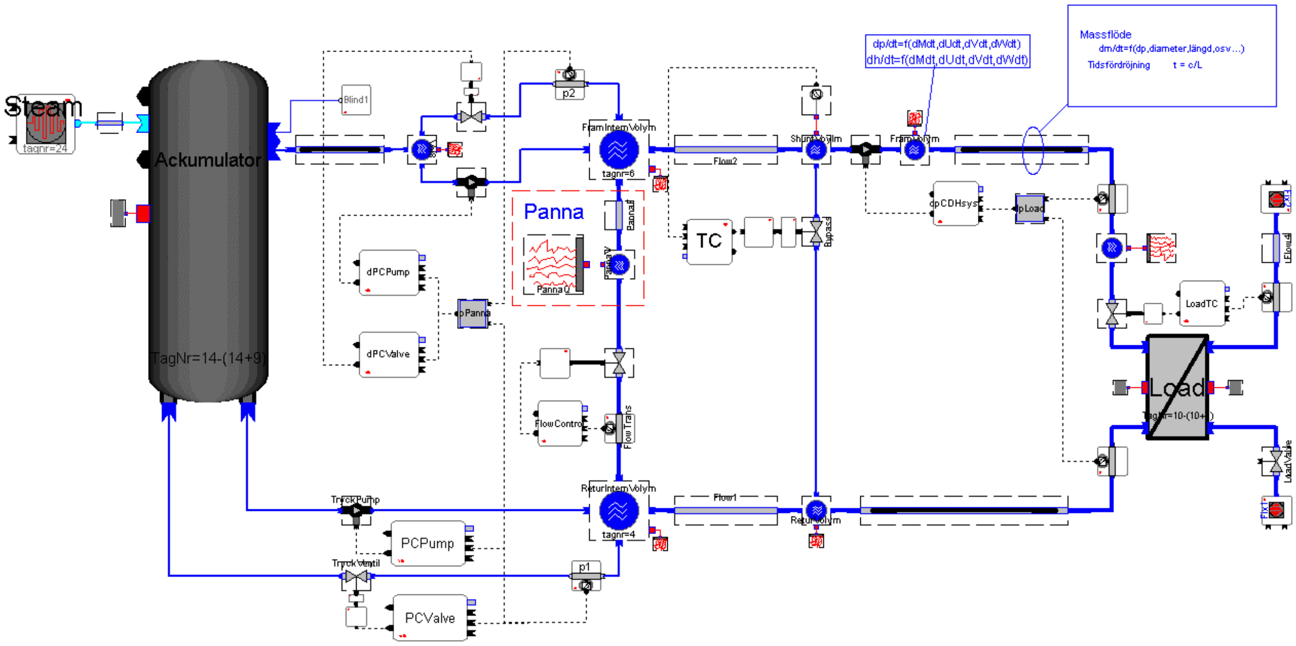

Figure 13 *The model used to simulate the interaction of the atmospheric heat accumulator and the rest of the district heating system.*

The model showed that some of the valves were too small and that there is a problem in determining the minimum pump speed. Besides this, the model delivers approximate controller parameters.

The load case shown in figure 14 and 15 is a boiler brake down during loading of the accumulator. The first transients are caused by the fact that the initial condition does not correspond with the load case.

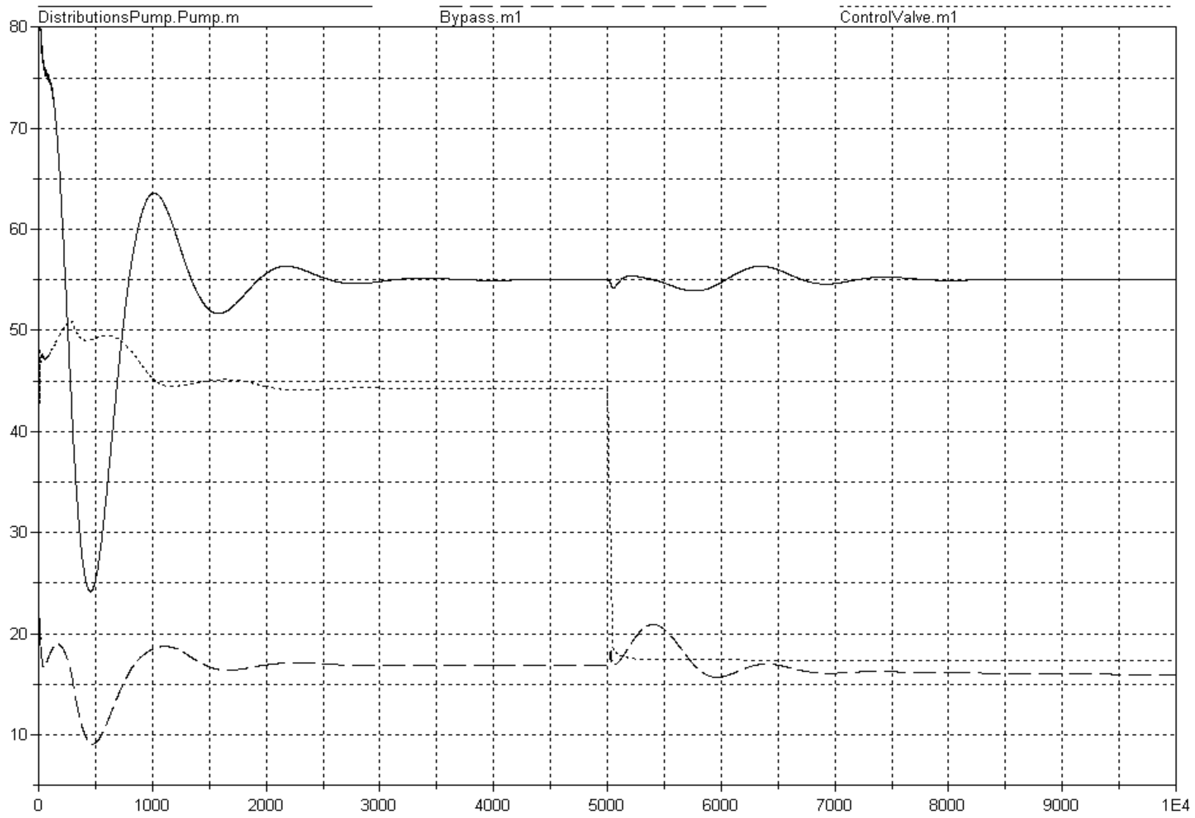

Figure 14 *The mass flows in the district heating system.*

The solid line is flow through the distribution pump, the dashed line is flow through the bypass valve and the doted line is the flow through the boiler.

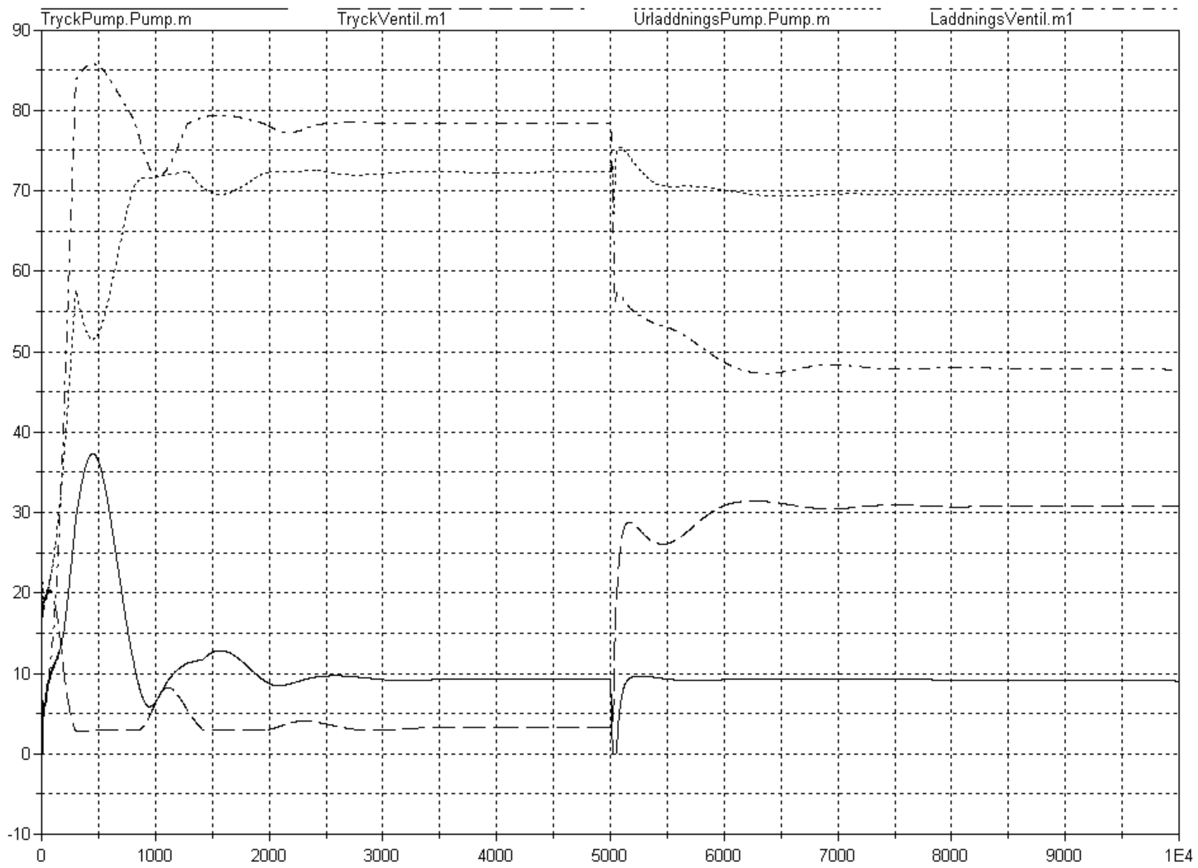

Figure 15 *The mass flows in connection with the atmospheric heat accumulator*

The solid line is flow through the pump used for pressurization and the dashed line is flow through the pressure control valve. The dotted line is the mass flow through the pump used for un-loading heat and the dash-dotted line is the flow through the valve used for loading heat.

Lessons Learned: The method works and the results where trusted.

4 Conclusions

This paper provides a number of examples that Dymola / Modelica is well suited to industrial modeling of Energy systems. Our experience shows that the technical and calculation issues can be addressed and solved, and that the simulations show a very high degree of correspondence between models and measurements.

In the projects above it has been proven that the method is commercially competitive. This is a possibility only thanks to the structured Energy library, providing not only reusable components but also thoroughly tested modeling methodology.

We still need to improve efficiency of the modeling, mainly in two areas The first one is the degree of common understandability – here mainly making systems simple enough to allow process engineers to use models in their daily work of designing, validating and commissioning.

The second is in the area of tools facilitating modeling and simulations. A tool for calculation of the initial, start-up conditions of the complex systems we work with is our primary request.

Modelica development moves certainly in the direction fulfilling our needs, and we are today fully committed to base our future modeling and library development on both Dymola tools and Modelica.