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Numerical Simulation of Complex Cooling and Heating Systems

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Abstract

In cooperation with the Imtech Deutschland GmbH & Co. KG (formerly known as Rudolf Otto Meyer GmbH & Co. KG) a research project was conducted. The aim of the project is to develop a simulation tool for heating and cooling systems in building applications. This tool should enable configuration studies and dynamic system simulations with time scales from a few seconds up to one year within short computational times. Therefore, the simulation environment of Dymola, containing the programming language Modelica, is used to model complex heterogenous systems. In this paper the recent library for heating components is presented and the implemented models are subsequently used for a verifying simulation of an existing thermal power plant. Furthermore, the graphical user interface HKSIM is introduced as an applied tool for project management and post–processing, integrating Dymola for model editing and simulation only.

1 Introduction

So far, there is no simulation tool known which enables the dynamic simulation of both, complex heating and cooling systems in building applications, allowing free choice of parts and system layout. Therefore, this research project was conducted in 2001 with the goal of developing such an object–oriented library. Partners involved in this project are the Department of Technical Thermodynamics of the Technical University Hamburg–Harburg and Imtech Deutschland. From the viewpoint of a system engineer it is desirable to predict the dynamic behaviour of a complex plant during the concept and definition phase of a project. The development of running costs is due to the gas and electric power consumption of every single component, like for instance pumps, boilers etc.. These are the key optimisation numbers of such a system for the operator as well as for the system builder. Since many owners of heating (and cooling) plants neither have the knowledge nor the financial budget for a reconfiguration, *contracting* companies are commissioned with the optimisation. There are of course various kinds of contracts possible. One could be the optimisation of an existing plant, another the supply with heating and/or cooling where the customer just pays for the delivered energy and not for the plant, which has to be build for that purpose (outsourcing). The benefit resulting from that simulation tool is not only of economical nature but also a reduction of energy consumption which means a decreased production of carbondioxid. This is the background for the work which is described in this paper.

2 Concept of Simulation

Since there is already a lot of building simulation software available, like e.g. TRNSYS, BLAST and others, the development is focused on the plant components. Due to the separation of the building from the system simulation some work has to be invested in the linkage between both calculations. The simulation of the building is supposed to be done first. The results from this simulation, basically the heat demand (requirement of refrigeration, respectively) and room temperature, are stored in a data file which can be read in subsequently by a table–interpolation–model `CombiTableTime` from the Modelica–Standard–Libraries [3] (Fig.1). To the interpolation–model connects a model of a radiator, which is not a single heating element in that sense but represents one heating circuit or even a whole building. The main idea is, that the heat demand is directly translated into a corresponding mass flow rate by functions implemented to the heat consuming model. Usually, for the modeling of thermo–hydraulic control volumes two state variables are needed, like e.g. pressure p and enthalpy h. During the integration process the speed

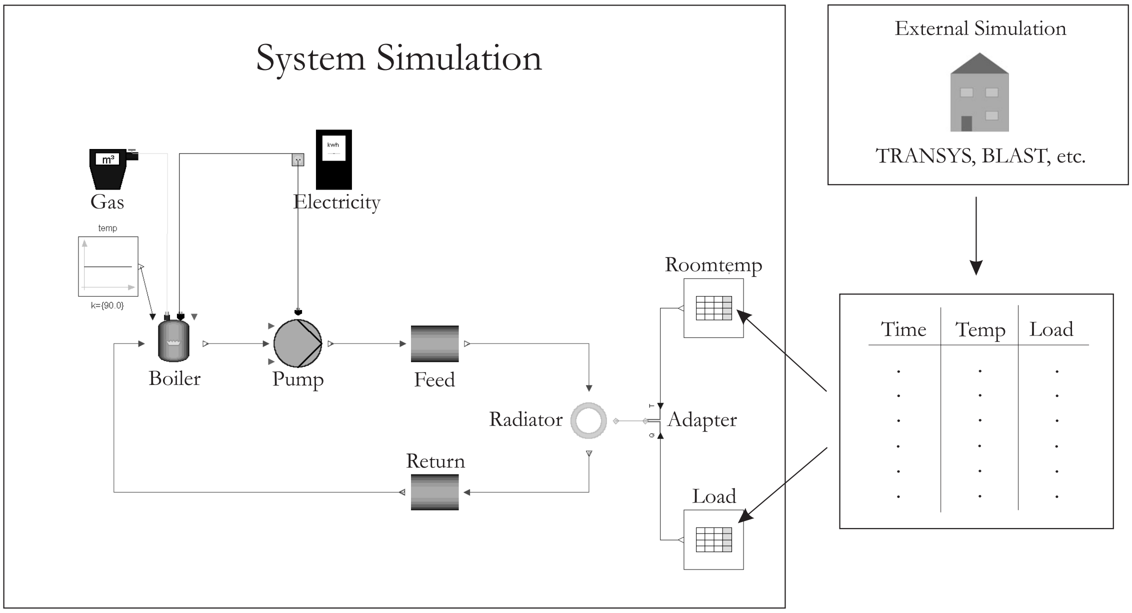

Figure 1: Concept of separated simulations

of the solver is influenced by the dynamic behavior of the state variables, or better, the time scales in which the state variables change. These time scales differ by up to three magnitudes in heating installations. This is the reason why an incompressible fluid model is selected with a simple algebraic mass balance in order to reduce the calculation time. Thus, the mass flow rate is just considered as a signal, which is not calculated by a detailed momentum balance, including the actual pressure difference between inlet and outlet, but is limited by the pumps pressure difference and maximum flow rate. The used concept results in calculation times of a few minutes for a plant simulation of one year. In addition to that, the influence of the pressure on the gas and electric power consumption of a heating installation is considered to be low so that it can be neglected. Due to these reasons only the water temperature is taken as a thermodynamic state variable of each component.

In favour of a conservative energy balance a control volume formulation is chosen and the temperature is projected downstream. In case of an adiabatic control volume V from the energy balance follows:

$$V\,\rho\,c_w\,\dot{T} = c_w \cdot (\dot{m}_{in} \cdot t_{in} - \dot{m}_{out} \cdot t_{out}) \qquad (1)$$

with the thermodynamic temperature T, the Celsius–temperature t and mass flow rate $\dot{m}$

$$\begin{aligned} T &= t_{out} + 273.15 \\ \dot{m}_{in} &= \dot{m}_{out} \quad \textit{(incomp. fluid)}\,. \end{aligned}$$

A water property model is needed to calculate the specific heat capacity c_w and density ρ. This can be done efficiently by assuming constant values or more accurately by providing polynomial functions [1] depending on temperature. Since the accuracy is hardly enhanced by less then 1% but the calculation times are increased by 300% the constant value approach is considered to be accurate enough.

For the calculation of the gas consumption of a boiler the efficiency coefficient η is needed on the one hand, which is defined as the ratio of heat output to burner output and on the other hand the feed temperature, which is provided by the controller. Boiler manufacturers usually specify η depending on different states with regard to the biggest impact, like e.g. load ratio, return temperature or average boiler temperature. The specified values can be interpolated by a characteristic diagram model which also refers electric power consumption of the burner. The common methods, functions and interfaces are implemented in a class `(BaseBoiler)`, whereas the characteristic diagram class `Characteristic Diagram` can be replaced by "drag and drop" or modified to generate a new boiler model in an convenient and easy way (see Fig.2). The same concept of an object–oriented model is also used for the modeling of other components of a heating installation, like for instance pumps or combined heat and power plants (CHP)[2].

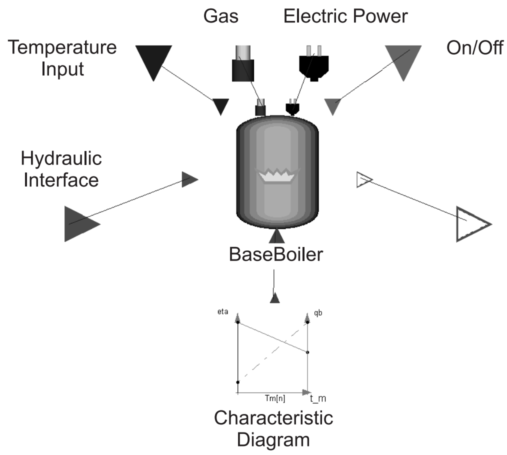

Figure 2: Diagram layer of a boiler model

3 Library Content

The recent library contains models for components of heating and cooling installations in subpackages. Since the later users of the library shall only modify the existing component classes by ”drag and drop” and parameterisation, the base classes will be stored in an extra library which cannot be modified. An important requirement for the parameterisation (and also for the component model itself) is that the needed information is made available by the manufacturer. This has been checked in the beginning of every model development. Especially, when programming components for cooling systems it was found out that the supplied information level is very low.
So far, the boiler sublibrary consists of models for a broad range of small to large gas–fired boiler types (oil fuel could be easily introduced), as there are condensing boilers and normal boilers equipped with atmospheric to modulating burners. The electric power consumption of the gas burners ventilation motor is also taken into account.
The pump sublibrary provides models for uncontrolled and controlled pumps. These models can be used for heating, cooling and service water supply.
Pipes are modeled by discretised control volumes and wall classes, which enable the calculation for heat losses. Usually, these losses are neglected when the heating installation and the pipes are part of the building which has to be heated because it is considered to contribute to the heat demand. Thus, in most cases adiabatic pipes without any wall model are used to model the systems delay.
For the simulation of domestic hot water systems a sublibrary provides models for hot water storage tanks. The heat is either stored in horizontal or upright standing tanks which may have water layers with different water temperatures. The heat is transfered in internal or external heat exchangers (loading systems).
Since the combined heat and power technology is becoming more and more important – not only in very large heating installations – a model for gas driven CHP's has been added to the library.
Currently, the work focuses on the development of components for cooling systems, like water chillers and cooling towers. The previously developed components of heating systems will be reused as far as possible, for example the pump models, pipe models and storage tank models.

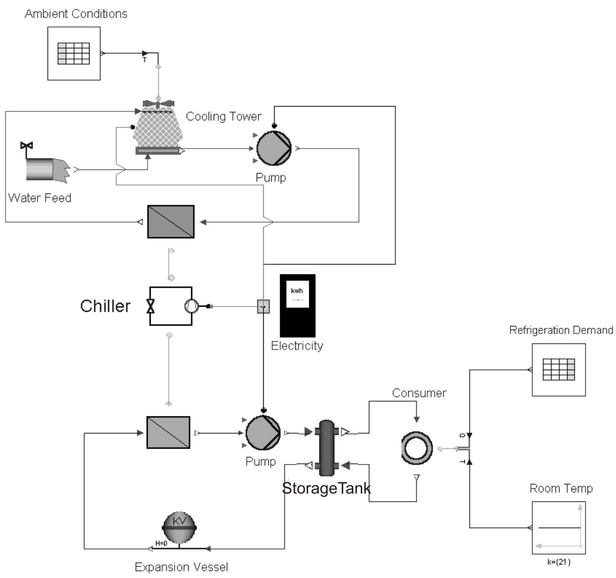

Figure 3: Schematic of a cooling installation

The water chiller model is not numerically described by a control volume because the needed state equations for this purpose include pressure and enthalpy which decrease the speed of simulation too much as discussed in section 2. Although with the current computing facilities real–time simulations of thermo–hydraulic systems are partly possible (good guess of initial conditions provided) these models are not suitable for simulations of one year. Thus, characteristic diagrams are implemented in the chiller model which refer to the used refrigerant and type of compressor. The supplied functions were derived from technical data of various manufacturers and device sizes [4] with a maximum spread of 10%. A simple model example of a cooling system is presented in Fig.3.

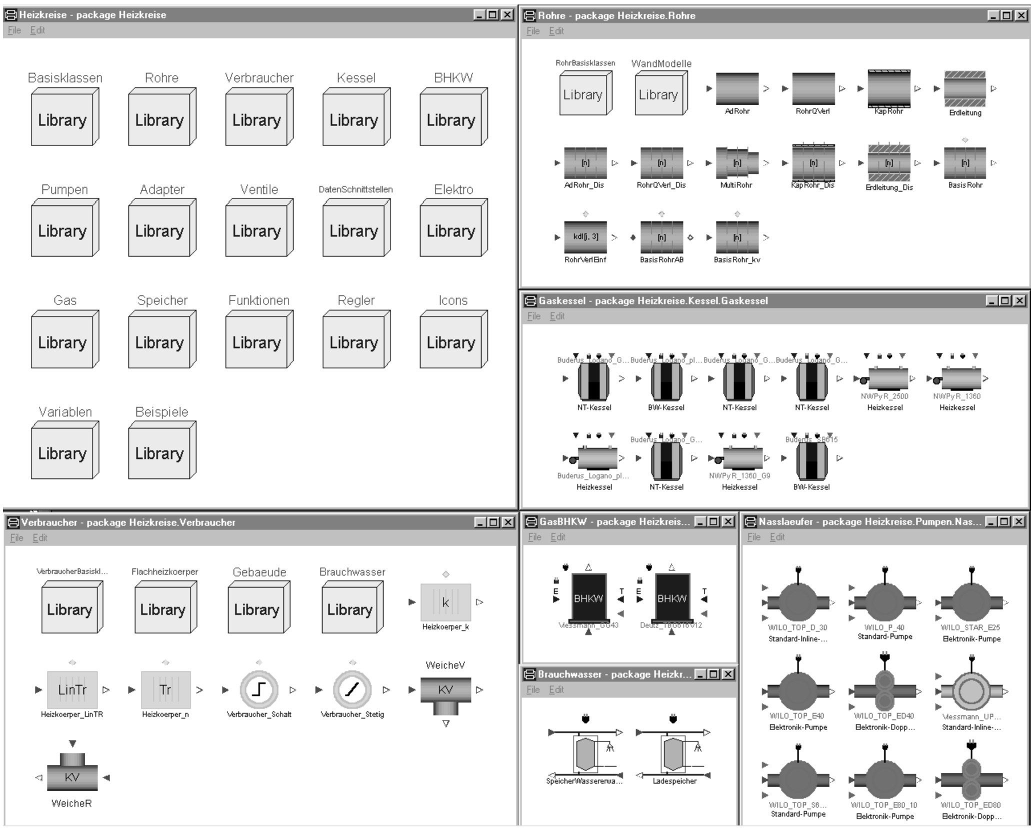

Figure 4: Recent package `Heizkreise` for heating installation components

4 Verification of Existing Models

The following section is focused on the simulation and verification of models of heating installations with measurement data. At first, the fundamental question, why a dynamic simulation environment is chosen, shall be answered by means of a simple example.

4.1 Dynamic Simulation – Why?

Due to the fact that real heating and cooling installations may have large fluid capacities a dynamic simulation of such systems is necessary. In order to demonstrate the difference between static and dynamic simulation a simple feed temperature step is performed with three different boilers and the same hydraulic input ($\dot{m} = 2.0$kg/s and $t_{return} = 60°$C). The results from the three simulations are shown in Fig.5 where the step of the feed temperature is triggered after one hour. In a static simulation, represented by the continuous line, the boiler follows the step input ideally (sufficient burner output of at least 265kW assumed). In a dynamic calculation the water volume within the boiler has to be heated up by the gas burner‘s rated output until the switch–off temperature is reached (1K below set value). Thereover, the boiler model switches into the ideal mode which means the heat input is adjusted ideally without triggering further state events by burner starts and stops. It is evident that the dynamic calculated feed temperature with regard to the static simulation increases in a slower way and that the warm–up time is influenced by the size of the boiler. The temperature rise is slowed down by the continuous mass flow rate which has a bigger impact on smaller boilers. In the case of a too small output rate of the boiler (boiler with a nominal capacity of 140kW) the feed temperature input is actually not reached.

During the warm–up of the feed temperature the gas burner operates at full capacity which means a higher gas consumption than calculated in a static simulation. In addition to that, the operation efficiency drops due to the rising water temperature, the increased load and rising exhaust gas temperature. Comparing the gas consumption for a simulation time of two hours including one temperature step a deviation of 3% (400kW) to 13% (2500kW) is found depending on the total water volume of the boiler. Therefore, a dynamic simulation of complex heating and cooling installations is considered to be necessary.

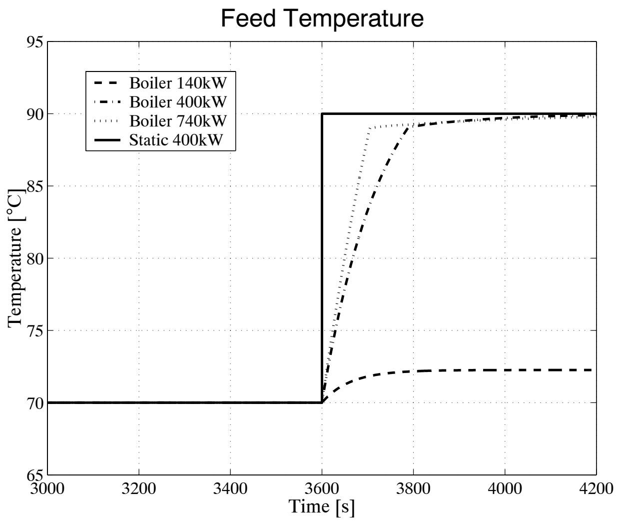

Figure 5: Feed temperature step for different boiler sizes and simulation types

4.2 Simulation of a Thermal Power Plant

Furthermore, the existing models have been used to simulate a thermal power plant which is operated by the contracting subsidiary company of Imtech Deutschland, Imtech Contracting. The schematic diagram of the heating installation model is shown in Fig.6. The measurement data with regard to mass flow rate, return, feed and ambient temperature is interpolated by the interpolation table model CombiTableTime `DataInput` and `AmbientTemp` which is supplied by the tables sublibrary of the Modelica Additions Libraries. The feed temperature input is used to compare the energy flow of the model with the real system. The source model `HydSource` represents the heat consuming part. This is done because measurement data is not supplied for the consumers and the associated buildings were not simulated. To make sure that the same amount of energy is transfered like in the real system, the mass flow rate is related to the energy flux, rising when the simulated feed temperature is falling. The shown system consists of the following components:

- `Boiler`: gas–fired boiler (nominal capacity of 1,360kW) equipped with a modulating (output can vary in a certain range) burner
- `Pump`: pump with integrated electronic speed regulation for variable head control, maximum flow rate 64m^3/h
- `AdmixingPump`: 3–speed inline pump, maximum flow rate 32m^3/h
- `MixingValve`: 3–way valve, adjusting a constant temperature difference ΔT between return and feed of 20K
- `Controller`: ambient temperature lead feed temperature controller
- `ExpansionVessel`: model is used as a data sink for the mass flow signal

Finally, the gas and electric power consumption is summed up in the gas and electric meter model.

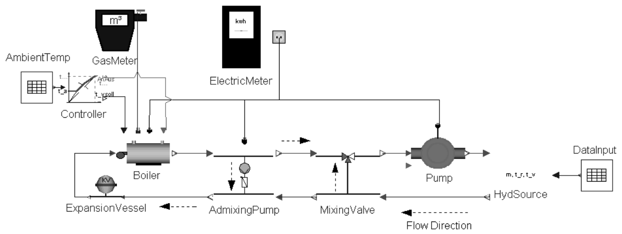

Figure 6: Schematic of a thermal power plant

Measurement data with an interval length of 15 minutes has been provided by Imtech Contracting over a period of 9 days in February. The data set contains ambient, feed and return temperature of the pipeline as well as of the boiler. Furthermore, the volume flow rate has been measured. With use of these input values the heat demand of the consumers can be calculated directly (Fig.8).

As Fig.7 reveals, the boiler feed temperature of the simulation follows the measured temperature understanding the mentioned ideal model behaviour which does not produce noise resulting from measurement tolerances and a chopping burner output below 250kW heat demand.

With regard to Fig.8 it is evident that the simulated burner output is just a little higher than the heat demand because of the boiler‘s high efficiency level of 94%. The profile of the heat demand shows typical events like a lower load at night followed by a warm–up peak in the early morning. Two times the plant was even turned off completely which was not due to weather conditions but to maintenance reasons.

4.3 Case Study

In this section a comparison of four often used boiler configurations is undertaken. Thus, the boiler model

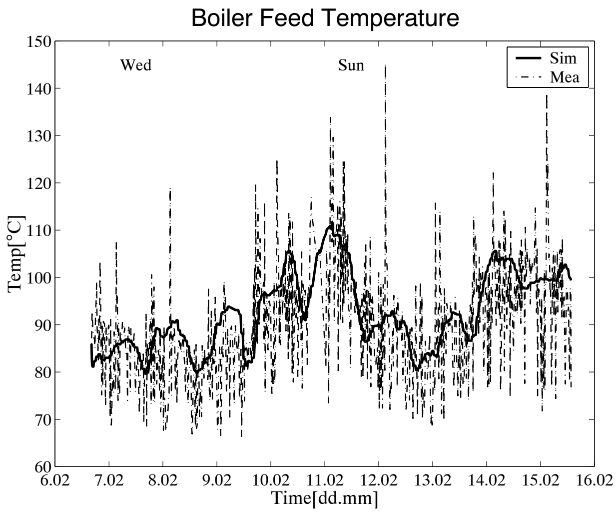

Figure 7: Boiler feed temperature simulated over a period of 9 days in Feb.

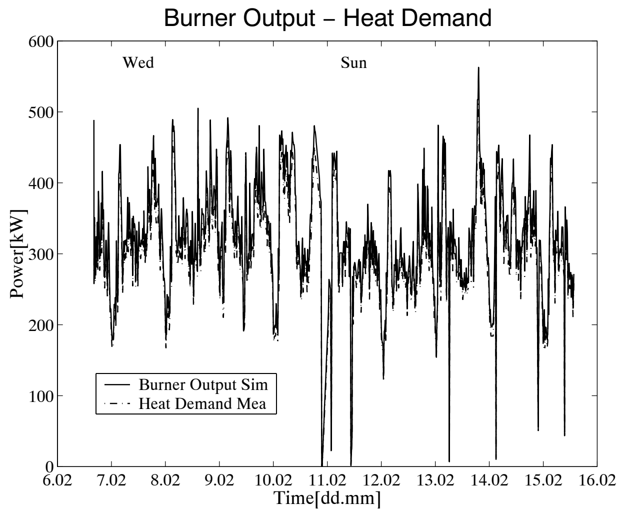

Figure 8: Simulated burner output and measured heat demand

in Fig.6 was replaced by the following configurations, which are all state–of–the–art:

- two parallel boilers (rated output 740kW each) (Fig.10)
- one condensing boiler (1350kW)
- a condensing boiler (640kW) followed by a simple boiler (740kW) for higher duties (Fig.11)

For reasons of comparison, the heat demand data of the previous simulation run was doubled by just increasing the mass flow rate. The prices for gas and electricity have been set with regard to the usual contract conditions (Gas: 3.6Ct/kWh, Electricity: 14(day)–10(night)Ct/kWh).
The outcome is presented in the chart diagram of Fig.9. Obviously, the existing configuration is also the most expensive with regard to running costs (as mentioned before the average efficiency of the implemented boiler model is up to 94%) which has two reasons. First, the gas burner of the boiler model is driven by an electric motor with a rated power of 6.5kW, which is considerably higher than that of the two installed pumps and of the smaller boilers (simple boiler: 2.6kW and cond. boiler: 1.4kW). Second, the average efficiency of the condensing boilers is 98% and would be even higher if the return temperature was lower than 60°C as in this case.
Less expensive is the configuration with two parallel boilers because of the smaller burner motor as mentioned before and the fact that only one boiler operates in part load. The gas consumption is even rising slightly, since the efficiency of a high loaded boiler drops and this effect can not be fully compensated by reduced standby losses of the second boiler.
A single condensing boiler configuration reduces the fuel costs by 230 EUR in 9 days while the electric costs are not affected, since the same burner type is implemented.

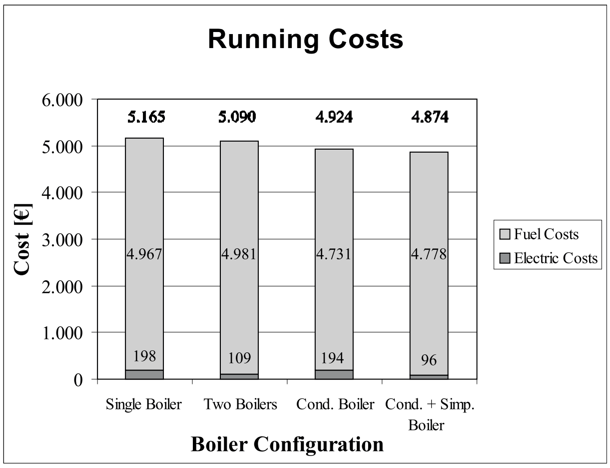

Figure 9: Running costs of case study

Apparently, the highest reduction (approx. 300 EUR or 6%) in this case study could be realised by the serial configuration of a condensing boiler with a simple boiler because it combines the positive effects of two smaller boilers and condensing technology. This is a reason why this concept is preferred by

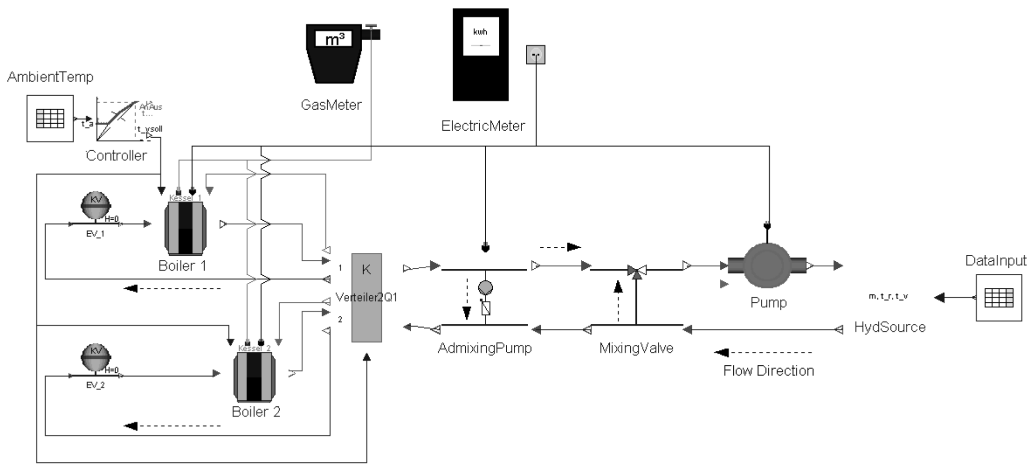

Figure 10: Configuration with two parallel boilers

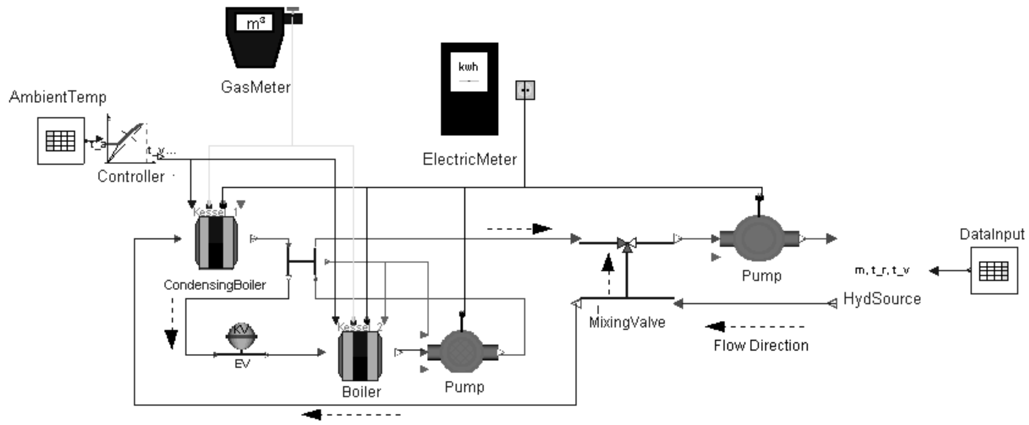

Figure 11: Configuration with one condensing boiler followed by a normal boiler

Imtech Deutschland when it comes to the design of new heating installations with low return temperatures. Nevertheless, it has to be emphasised that in this special case the calculated reduction of running costs may be to low to be worthwhile, especially if the investment costs of the more efficient configurations are much higher.

5 Graphical User Interface – HKSIM

As mentioned before a graphical user interface for Windows is developed by the Zentrale Ingenieurtechnik (ZIT) department of Imtech Deutschland for a number of reasons:

1. As an expert tool, the used simulation environment, Dymola, needs to be controlled by an applied user interface which is focused on the end–user and simulation background.
2. A data base connection is needed to save different projects and to give information about former simulations and their outcome.
3. The results from the simulations can be presented in a chart, which can be printed out as a standard information sheet for customers or can be exported to other applications.

In fact, Dymola is a powerful, but also complex simulation tool, too complex for a straightforward usage when results are needed fast. Thus, the graphical user interface is utilising the applied features of Dymola, like the model editor (system building by ”drag and drop”) and the simulator. Other applications, like the plot and animation window are faded out. Also, the end–user, for instance the project engineer, is not expected to program with use of Modelica.

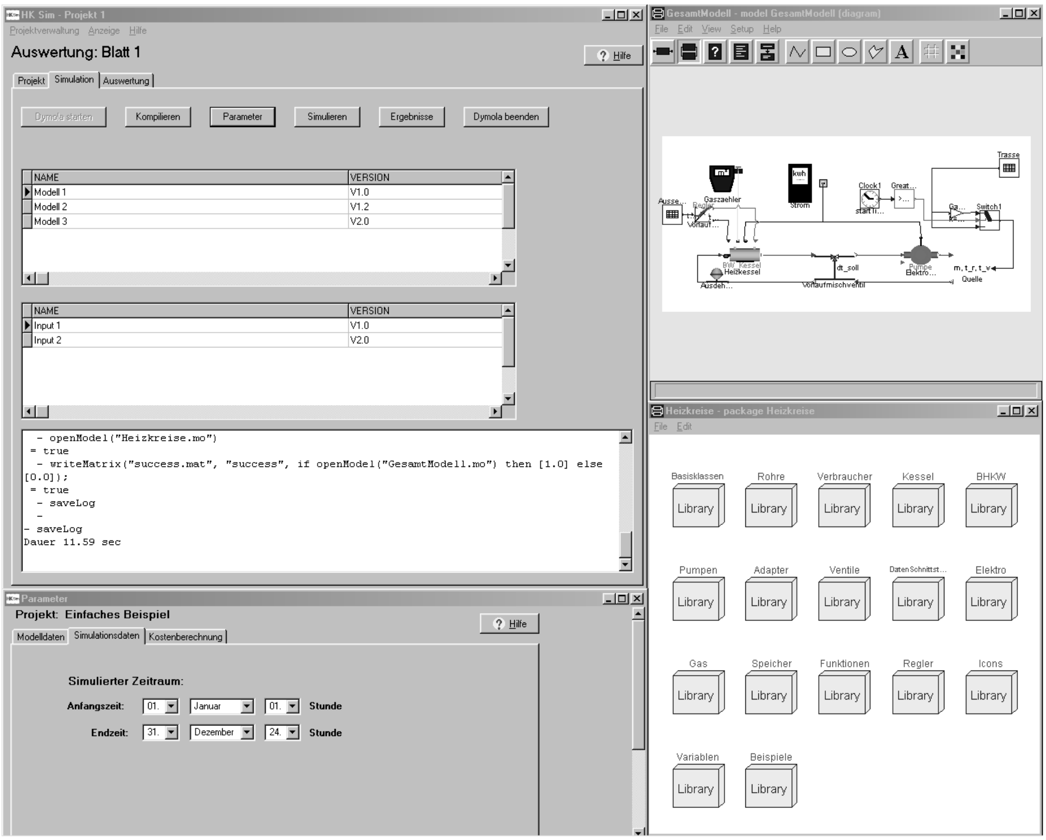

Figure 12: Screen shot of HKSIM‘s main (top l.) and parameter window (bottom l.)

The typical procedure can be described as follows: The user chooses a project from the list of existing installations (Fig.12) or a new one is opened, alternatively. It has to be emphasised that every modification of an existing project is saved under a new model name and can be restored later. Afterwards, Dymola can be started and the model library is loaded. From this point, the user can decide if the Dymola environment or HKSIM is used. After the configuration or modification of the project model is completed, parameter settings can be performed within the Dymola diagram layer. The same applies for the model translation. A convenient setting of the simulation time is enabled by means of a submenu of HKSIM, which converts start and stop times from a pull down date and hour menu to start and stop times in seconds (Fig.12). In other submenus data input files for the boundary conditions (e.g. heat demand, ambient temperature) can be chosen as well as parameters with regard to operation costs calculation before the simulation is finally started. The results are then displayed by an implemented post processing tool. For clarity reasons only a predefined choice of relevant variables can be plotted from a result browser which also offers the results of former simulation runs in numerical order. An example of a plot diagram is shown in Fig.13.

6 Conclusion

A simulation tool for heating and cooling processes in building applications is needed to calculate the performance of complex system layouts with regard to economical and ecological aspects. In this paper, the development of a system library is described and it was pointed out that a dynamic simulation in this field is necessary as a matter of accuracy. The library components can be used in an applied way as a case study in section 4.3 shall demonstrate. Since the end–users will operate this simulation tool among other applications in a predetermined way, a graphical user interface is programmed, integrating Dymola just as a model editor and simulator, while focusing more on the needs of a project engineer. So, case studies and post–processing operations can be undertaken conveniently with use of an integrated data base and chart utility.

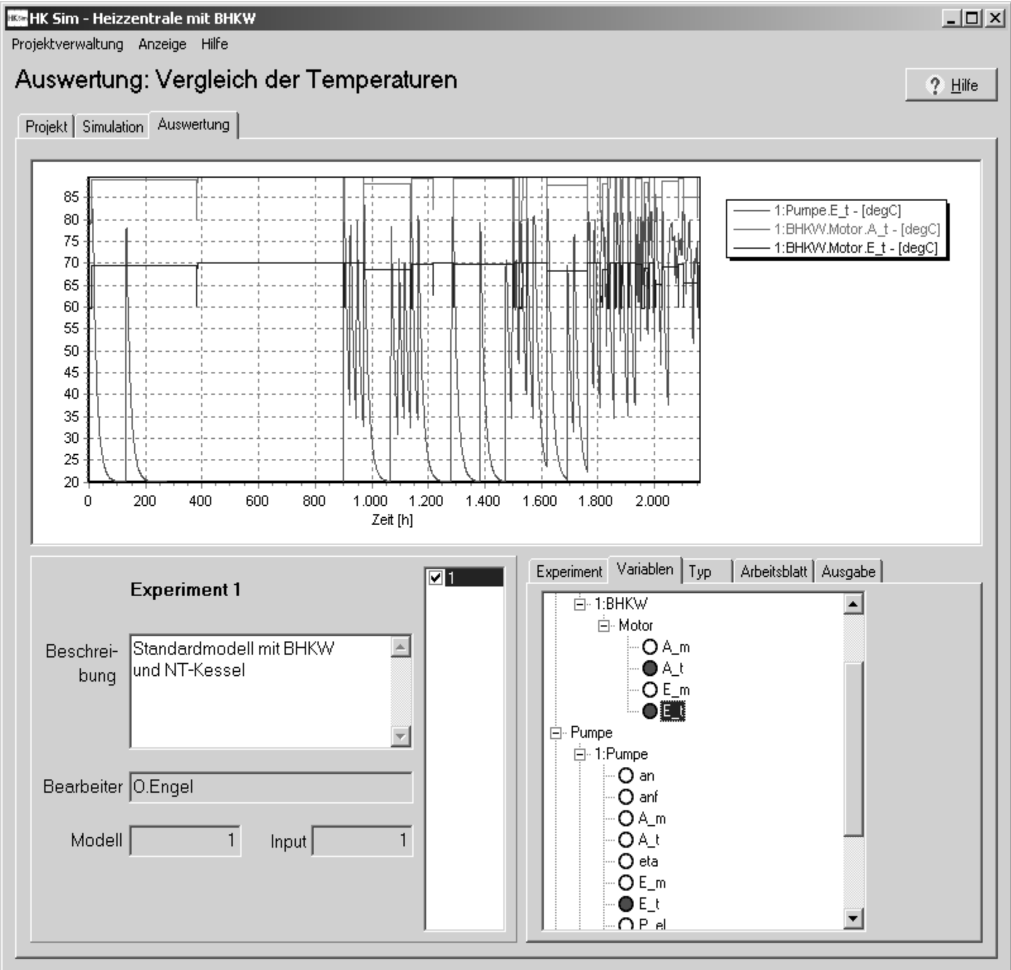

Figure 13: Screen shot of HKSIM's post processing window

7 Acknowledgement

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