Thermal simulation of a pellet boiler and a heat storage tank for future control strategies

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Introduction
The efficiency of heating systems in buildings depends predominantly on the performance of the heat generator and the corresponding distribution system. For good system efficiencies not only the use of highly efficient parts but also their intelligent assembly has to be ensured. The interaction of different system parts is mainly influenced by control strategies, deciding the tasks of each part at any time. Hence, the influence of control units on the efficiency of the heating systems becomes an interesting field of development.

This publication is focussed on a small scale pellet boiler with a nominal power below 100 kW combined with a thermal storage tank. In comparison to a log wood boiler, a pellet boiler is able to modulate. So its current power can be fit to the heat demand. As a result a storage tank for heat buffering is no more compulsory. Nevertheless, pellet boilers are often combined with thermal storage tanks due to comfort reasons. Regarding the hot water supply, a storage tank is advantageous. Since hot water is continuously available as long as the tank is charged. Furthermore, the availability of the tank might help to avoid unfavourable operating conditions of the boiler, like frequent start/stop or very low load levels. Consequently, the efficiency could be increased. For the exploitation of this benefit, advanced control strategies will become of more interest in future. Beside, the integration of solar thermal collectors into a heating system is only possible if a storage tank is available.

By now the behaviour of a heating system and thus the efficiency only can be determined with field measurements over a long time period. To avoid such sophisticated measurements in future, a simulation model allowing calculating the thermal behaviour of a heating system is useful. In the best case, time and money can be saved as simulation is faster than real-time and measurement equipment is not necessary for such a long time. Moreover testing of different control strategies and their influence on system efficiency will become easier and faster too.

This paper adds to the research on control strategies for heating systems by introducing models for a pellet boiler and a storage tank which can be used in future control developments. Both models were established in the MATLAB/Simulink® environment which is a numerical calculation program based on matrix calculations. With the models the dynamic thermal behaviour of the boiler and the storage tank as well as their interaction can be calculated for efficiency estimation. As a result the models can be used to develop and enhance control strategies in future.

Within this paper these two models will be explained and results from simulations are shown. By the comparison of the simulation results and measurement data the models are verified. At the end a short outlook on future developments is given.

Pellet Boiler Model
As a detailed description of the pellet boiler model would go beyond the scope of this publication, only a short overview of the model is given within the following paragraphs. More information on previous work can be found in [1].

The dynamic pellet boiler model is based on thermodynamic heat and mass balances arising in a pellet boiler. The heat transfer from the hot flue gases to the water is calculated by conduction, convection and radiation. Although this boiler model is generally based on physical and chemical background some assumptions were made. The most important assumption is that complete and
instantaneous combustion without thermal losses (adiabatic combustion) is used to determine the heat generation. Additionally, empirically developed parameters are included in the model fitting it to reality. These parameters are determined by the comparison of the measurement data and the simulation results. Two examples of such parameters are: a turbulence factor for the heat transfer in the heat exchanger and a combustion rate for the ignition phase.

Figure 1 shows the scheme of the boiler model with the five main parts and the different heat flows between them. Each of these model parts is described by boiler specific parameters like geometrical and material properties.

The most important energy flows crossing the system boundary are the fuel and air input (\(Q_{\text{Fuel+Air}}\)), the inflowing and exiting water (\(Q_{\text{Water in}} - Q_{\text{Water out}}\)) as well as the losses to the ambient (\(Q_{\text{Losses Flue Gas/Door/Wall}}\)).

The fuel input is defined by the mass flow of pellets, their list of properties and heating value. Accordingly, the air inlet can either be given by a certain volume flow or with the air ratio (lambda). With these two parameters the current load level of the boiler is defined. The water volume flow and inlet temperature configure the heat demand. The efficiency of the boiler is estimated with the resulting outlet water and flue gas temperature as well as the losses to the ambient. The following short explanations of each model part should give a brief overview of the model's calculation mode.

**Combustion Chamber**

First, the adiabatic combustion is calculated in the combustion chamber. Based on the fuel and air input, the composition and temperature of the flue gas is determined. Already at the beginning of the model development, simulation results showed that the assumption of complete combustion works well for normal operation mode. However, when the boiler is in the starting phase, deviations occur. Therefore an ignition model was created for the starting phase.

The real ignition phase has a defined procedure: First, a certain amount of pellets is inserted in the combustion chamber. If the combustion chamber is filled, the pellet supply is stopped. Afterwards these pellets are ignited by an electrically driven ignition device. As soon as the pellets burn, the boiler changes into "normal" operation mode and fuel supply restarts depending on the current power operation level.

In the ignition model the fuel's step function from the real boiler is transferred to a linear one. Hence, the fuel and air input is delayed during this phase. As a result the flue gas temperature rises slowly and not instantaneously. Consequently, the water temperature increases gently too. The parameters for the linear function of the fuel supply model are depending on boiler properties like its combustion chamber and ignition parameters. Therefore they are determined with measurement data.
The second task of the combustion chamber is to calculate the heat transfer to the surrounding surfaces (walls and door). These heat transfer calculations are based on flame radiation and flue gas convection. Afterwards the flue gases are transported to the heat exchanger model.

Door

The door represents a thermal mass in the combustion chamber heated up by the flame and flue gases. Moreover losses to the ambient due to conduction through the door’s material are considered too.

Wall

The wall separates the flue gases in the combustion chamber from the water jacket. Therefore the temperature difference between these two sides causes the conductive heat transfer through this boiler part. Additionally, the thermal mass of the wall is considered too.

Heat Exchanger

The hot flue gases link the combustion chamber to the heat exchanger model. Here the remaining heat in the flue gases is transferred to the water jacket by convection before the flue gases exit the boiler.

Water

The water model pictures the amount of water in a boiler with its thermal mass. To ensure that the quantity of water does not increase during simulation, the inlet mass flow is always equal to the outlet. About one half of the conveyed heat is transferred by the wall model and the other half is transported in the heat exchanger model. The enthalpy difference between the inlet and outlet water is the generated heating power.

Heat storage tank model

The model of the heat storage tank employed in these simulations is a one dimensional multi-node-model. Within the following paragraphs the basics of this model are described. A detailed description of this numerical model is given in [2].

For the numerical solution, the storage tank is divided into a certain number of cylinders. Each cylinder is described with a node having one temperature. These nodes/cylinders design the vertical stratification of the tank. The number of nodes is a free parameter. However, it has to be considered that simulation time increases with the number of nodes. Moreover, problems with the solution of the numerical calculation can occur if the number is too high [2]. At least three nodes are needed for a calculation: one at the top (node 1), one at the bottom (node n) and one in between (see Figure 2). In the top and bottom node the water mass flow for charging and discharging is included. The nodes in between do not support mass flows from outside.

To set up a simulation geometrical properties of the tank like height and volume as well as the thickness of the wall have to be fixed. During the simulation the mass flow of the water into and out of the tank over time influences the temperature distribution.

![Figure 2: Scheme storage tank model](image)

In the simulation model the temperature profile in the tank is influenced by conductive heat transfer and simplified fluid dynamics. Therefore, the heat transfer in the tank is based on conduction, forced
and free convection. Forced convection is caused by the water mass flow into or out of the tank. If a colder layer is placed over a warmer one, free convection occurs due to buoyancy. In this case three different simulation modes can be used to describe this phenomenon: exchange of the layers, mixing the layers or an interpolation between both possibilities. Thermal losses are treated by a conduction term to the ambient walls of the tank.

Depending on the water mass flow in or out of the tank three different modes are separated: charging, discharging and storing mode. The following paragraphs give a short explanation on these modes.

Charging mode
If the water mass flow is positive, water is entering from the top into the tank (see Figure 2). As the inlet temperature should be higher than the highest temperature in the tank, the overall temperature will increase. Consequently, the storage tank is charged and heated up.

Discharging mode
When the water mass flow is negative, the discharging mode is started. Hot water is extracted from the top and cooler water is injected at the bottom (see Figure 2). As a result the average tank temperature decreases.

Storing mode
The tank is in storing mode if the water mass flow is zero. During this mode the tank temperature can change due to losses to the ambient through the tank surface. Depending on the thickness of the insulation layer the tank is cooling down either faster or slower.

Structure of the heating system
Generally the boiler and storage tank as well as the consumer are connected via the water temperatures and mass flow. The consumer consists of the heating system and the hot water demand, which are added to a load profile over time. As Figure 3 shows, there are two different modes, depending on the status of the pellet boiler. If the boiler is on, the consumers as well as the storage tank are provided with heat. When the boiler is off and heat is needed, the tank is discharged.

The illustration shown in Figure 3 is a simplified one as in a reality also pumps and valves are involved for the heat distribution. For a first estimation these parts were not included in the simulation model yet. But for testing control strategies of heating systems this will become necessary in future.

![Figure 3: Schematic connection of the heating system depending on the boiler status](image)

Simulation Results
At Bioenergy2020+ GmbH various measurements with different pellet boilers operating in diverse load cycles are available. With these measurement data the boiler model has been verified and the empirical parameters were fixed. Similarly, the storage tank model has been verified with available measurement data too.

In this publication, results of a simulated 24-hour load cycle and their comparison to corresponding measurement data are shown and discussed briefly. These figures will provide information about how the model compares to the real devices. The considered load cycle was conducted with a 25 kW pellet boiler combined with a 1,500 l water storage tank at the laboratory of Bioenergy2020+ in Wieselburg. Figure 4 shows the course of this cycle with the heat demand (red) and the load level (green dashed) in percentage of the boiler’s nominal power. The heat demand is the power needed for heating a
house on a typical sunny winter day, including a standardized tapping profile for hot water [3]. Due to the fact that usually hot water is needed during small time periods, these times are visible as seeming random peaks in the heat demand curve.

The load level is the current power of the boiler set by its control unit to cope with the heat demand. It can be seen that the pellet boiler operates at full load most of the time during the day. This operating mode is caused by the connection with the storage tank which is continuously charged. As soon as the storage tank has reached its desired temperature, the boiler is turned off. Respectively, when the control temperature of the tank falls below a certain value, the pellet boiler is started again to heat it up.

![Figure 4: Course of the regarded load cycle](image)

In Figure 5 the temperatures of the water flowing in and out of the pellet boiler are pictured. The green dashed line corresponds to the measured outlet temperature and the red one expresses the simulated values. The grey line shows the measured course of the inlet water temperature which was also used as input value in the simulation. The comparison of the measured and simulated temperatures shows a similar trend. During normal operation mode, the temperature differences stretch from only 1 up to maximum 2 K.

Nevertheless, some deviations occur during the starting phases where the calculated temperature rises a little bit slower (0-0.5 h; 6.5-7 h, 14.5-15 h, 20.5-21 h). One reason for the slower temperature raise could be the ignition model and its parameters. It seems that the delay of fuel and air supply during ignition phase is too high. As a result the heat transfer is delayed too. These deviations could be minimized by further adaption of the boiler specific parameters. Moreover, changes in the ignition model itself would also be helpful to improve the boiler behavior.

The overestimation of the boiler’s thermal masses could also be a reason for slower heating up in the simulation. This assumption would also account for the phenomenon that, the temperature decreases not as fast as in reality when the boiler stops. With the simulation of further measured load cycles of this boiler, this hypothesis will be examined.
Based on these water temperatures and the mass flow, the boiler heating power is calculated. Over the whole measurement period of 24 h about 304 kWh are measured. The integration of the simulation results lead to 296 kWh. As a result the deviation between the measurement and calculation is about 8 kWh, respectively 2.6% related to the measurement data. This energy difference correlates to the energy contained in about 1.6 kg pellets (18 MJ/kg pellets [4]).

Also the temperature distribution of the storage tank was simulated for the load cycle in consideration. Therefor the storage tank was split in 60 nodes over its height of about 2 m. During charging the temperature of the inflowing water was set equal to the outlet temperature of the boiler. When the storage tank was discharged, the temperature of the cold water was taken from the measurement data. Moreover, the inlet and outlet mass flow were also taken from measured values.

In Figure 6 the trend of the temperature distribution in the tank during the load cycle is depicted. During measurement the wall temperature inside the insulation layer was recorded at three positions (top, middle, bottom). These temperatures are compared to their calculated pendant. Here the red curves demonstrate the simulation results and the green dashed ones the measurement data.

Similar to the boiler parameters, also the temperatures of the storage tank fit quite well to each other with deviation less than 5 K. Significant deviations only occur when the charging and discharging modes start. Corresponding to the boiler’s outlet temperatures the tank heats up slower in the simulation than in reality. Consequently, the modeled tank is discharged a bit faster too. Especially the temperature at the bottom shows the impact of slower charging. During the first heating period (0-3 h), the measured temperature at the bottom differs more than 5 K from the simulation. This is caused by the less heat put into the tank during simulation (see Figure 5).
Conclusions and Outlook

Based on the presented example it is shown that the models correspond quite well to reality. As a result, the dynamic thermal behavior of a pellet boiler and a water storage tank can be calculated. Considerable deviations only occur during starting phase. Consequently, this operating phase has to be adapted and enhanced in future to further minimize the differences. Ongoing developments may have to especially focus on the ignition model. Nevertheless, water temperature differences of about 2 K show that the models are already of a satisfying level of development. Therefore, the impact of different control strategies can already be estimated by now.

For efficiency determination of the whole heating systems the addition of pipe, valve and pump models will be necessary. Moreover also an emission model could be of interest to approximate the impact on the environment in future. Regarding the tank model, the implementation of a heat exchanger and/or an additional inlet will be a future development. These changes will enable to integrate e.g. a solar thermal collector into the heating system. Furthermore, the extension of the model to a two- or three-dimensional model could improve the simulation results, but will also slow down the simulation.

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Literature


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