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Modelling of Dynamics and Stratification Effects in Pellet Boilers

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Abstract

Optimizing solar and pellet heating systems can be performed by system simulations in TRNSYS. However; this requires detailed boiler models that can properly model the thermal behaviour of the boilers, such as stratification and thermal response. This study uses a combination of existing models for modelling of the pellet burner part (TRNSYS Type 210) and the water volume (TRNSYS Type 340). This approach addresses the thermal dynamics and internal stratification more accurately than other available models. The objectives of this work are to develop a method for parameter identification for the model and to validate this method and the model itself. Sets of parameters are identified for two pellet boilers and one pellet stove with a water jacket (extended room heater) and the model is validated with a realistic dynamic operation sequence. The results show that modelling of stratification is essential in order to model the true behaviour of residential boilers. The test sequences used were adequate to parameterise the models and to provide the desired accuracy, except regarding the heat losses to room air. The model shows good accuracy for a stove and one boiler, but slightly worse performance for the other boiler regarding dynamics and modelling of the stratification.

Keywords: System simulation; modelling; validation; pellet boiler; pellet stove.

1 Introduction

Small scale biomass heating systems can contribute to the reduced dependence on fossil fuels and electricity for heating of single family houses. The use of wood pellets for heating purposes was initially starting up in forest-rich and lumber-producing countries such as Sweden, Austria and the United States [1]. Pellet boilers can cover the heating demand and benefit by combining with solar heating since the low load operation with low efficiency and relatively higher emissions in summer is prevented [2, 3].

Measurements of biomass boiler performance in field conditions show the importance of correct design and control of the system [4-8]. In particular the parameters related to the controller settings are shown to influence the system performance. Chasapis et al. [5] report problems of the boiler controller at a real installation resulting in multiple burner start-ups that reduces the burner efficiency. Schraube et al. [6] report annual boiler efficiencies for non-condensing residential pellet boilers in solar and pellet heating systems ranging from 70 to 90 %. The highest boiler efficiency (90 %) appeared in the system with highest share of solar heating (40 %). Verma et al. [9] shows that the combustion efficiency during real life combustion is 2-5 % lower than during standard laboratory conditions at nominal load. Boiler efficiency may differ up to 7-25 % between standard laboratory conditions and real life operation [10].

Laboratory measurement studies based on systems under realistic dynamic operation of pellet heating systems [11-15] also indicate that the performance of solar combisystems are highly dependent on system design and control algorithms and there is a relatively large spread in efficiency from system to system. Simulation studies of domestic solar and pellet heating system [2, 16-19] suggest that efficiency improvements (on annual basis) can be achieved by optimizing control algorithms and the system design. However; the simulation study by Petrocelli and Lezzi [20] shows only small influence on boiler performance with control strategy.

System simulations can help to increase understanding of how to design efficient pellet heating systems and provide recommendations for manufacturers [2, 17, 21-23]. However, the reliability of such simulations is dependent on detailed and accurate models of boilers and other system components. As previously indicated by Persson et al. [24], the inability to model stratification in the water mantle caused

deviations between measurements and the model during boiler start-up and other transient operation periods for the TRNSYS boiler model type 210 [25]. This was shown as a deviation between measured and modelled heat rate to the water circuit. Petzold et al. [26] performs parameter identification for a modified version of the Type 210 where a temperature correction factor was implemented to compensate for the deviation between average and outlet boiler water temperature. Problems to model boiler cycling are also mentioned by Haller et al. [27] using the TRNSYS boiler model Type 869 [28], where comparisons between measured and simulated boiler cycling shows an overestimation of number of burner starts by about 25 % for the model. Carlon et al. [29] attempted to validate the Type 869 boiler model and showed that the deviation of energy transferred to the water circuit is up to 10 % for steady operation and up to 30 % for the model during a dynamic load cycle. These studies indicate that a multi-node boiler model with possibilities of stratification is required to better model the dynamic performance. The modification by Petzold et al. [26] may improve the outlet temperature, but it does not permit simulating the positioning of a temperature sensor at a specific height of the boiler. Thus, making detailed optimisation of systems including sensor positions and control algorithms would require a multi-node boiler model.

An overview of the characteristics of existing available TRNSYS boiler models, is presented in Table 1. None of the existing models fulfil all the requirements on handling wood fuels, thermal mass and stratification. An extended review on boiler models others than TRNSYS does not provide any other multimode boiler models [30]. Residential small scale wood- or pellet boilers utilizing heat from condensation of the flue gas is rare, thus this requirement was excluded. The TRNSYS Type 147 [31] fulfils most of the requirements as it is based on the store model TRNSYS Type 340 [32], but it would require a modification to work with biomass fuels. TRNSYS Type 869 can be attached to a water storage model using a fictive connection according to Hartl et al. [33] (proposed by Haller [22]) but this requires continuous circulation of water between the boiler and store model through a double port, which is not realistic and can cause unwanted mixing of the water volume.

In practice, with more detailed models, information is also required on how to derive the parameters for the model, especially if the model is a grey box model. This is found in the literature for some of the models listed but not regarding modelling of stratification in boilers. A new multi-node pellet boiler model using a combination of existing models is proposed that can model large volume boilers accurately and that can provide high flexibility. Compared to the existing models, the new model should provide better prediction of the stratification formed in boilers during transient operation which in turn should improve the predictions of boiler cycling and performance and enable detailed system optimisation. The range of validity for this new model should thus be greater than for the existing models. The aim of this work is to parameterise and validate this multi-node pellet boiler model. A further aim is also to develop and test a methodology for measurements and parameter identification for this model and to provide parameters for several boilers so that the model can be used more easily in future studies.

The novelty of the paper is a new modeling approach that improves the simulation of cycling in boilers with a significant water volume by explicitly modelling the stratification in this water volume. As part of this approach, a parameterization methodology is developed and presented using pellet boilers as specific cases.

2 Method

The pellet boiler model is based on a combination of the existing TRNSYS models Type 210 [25] and Type 341, a modified version of Type 340 [32]. The Type 210 is used to model the pellet burner and Type 341 is used to model the flue gas heat exchanger and boiler water volume according to Figure 1. This approach provides a model with high flexibility.

The study was performed in the following steps:

1. Detailed performance measurements of two residential pellet boilers and one pellet stove applying five different measurement sequences including steady and dynamic operation. One of the sequences simulates realistic operation during eight days.
2. Different heat exchanger positions were tried to find a lay out that could model the stratification during combustion
3. Calibration of model parameters using four of the measurement sequences.
4. Validation of the models using the realistic measurement sequence.

2.1 Boiler model

A boiler model was created based on the combination of the existing TRNSYS boiler model Type 210 [25] and Type 341, which is a modified version of the storage tank model Type 340 by Drück [32]. Since the original version of Type 340 assumes constant heat capacity (independent of temperature) and the Type 210 calculates a variable heat capacity, the heat capacity of the fluid in the heat exchangers of Type 340 was modified to become inputs instead of parameters. The heat capacity for the flue gas was calculated using the same equation as is used inside the Type 210 model [25]:

$$C_p = 1.0046661 + 0.00016844 \cdot T - 0.168154 \cdot C_{O_2} - 0.00054628 \cdot T \cdot C_{O_2} \quad (1)$$

Where T is the outlet flue gas temperature of the Type 210 model in °C and C_{O_2} is the volume concentration of oxygen in the dry flue gas.

The setup of the Type 210 and the Type 341 for the modelled boilers and the stove are illustrated in Figure 1. In this configuration Type 210 simulates the burner including the thermal mass and burner heat losses. Type 341 simulates the flue gas heat exchanger and the boiler water volume. The Type 341 allows the use of multiple water layers (nodes) to simulate the thermal mass and stratification in the boiler water volume. The heat exchangers and the water connections to radiators etc. can be assigned to a specific height corresponding to a specific node. Mass flow rates of pellet fuel and air are combusted and a flue gas temperature is calculated by the Type 210 model that simulates the burner. The thermal capacity of the burner and combustion chamber is modelled using thermal masses m_1 and m_2 and white arrows in Figure 1 indicate heat transfer. Boiler heat losses that arise from hot burner parts during combustion are emitted from thermal mass m_1 . The thermal mass m_2 was used to improve the dynamic modelling of the thermal response as it exchanges heat with the flue gas. The heat from the flue gas is transferred to the water store model as a mass flow rate of the flue gas of a certain temperature. The hot flue gas is transferred through the Type 341 via one or two heat exchangers connected in series.

The boiler water connections to buffer store or radiators are modelled using the double ports in the tank model Type 341. This is a pair of tube-connections to the boiler water volume, where water is put into and taken out of the boiler. Inlet flow rate and temperature is provided and the outlet temperature is calculated by the model. An additional heat exchanger is used to model the internal DHW-preparation for boiler B1. The heat transfer in the heat exchangers are dependent on several parameters like flow rate, temperature levels and temperature difference as described by Drück [32]. To be able to use the boiler model in simulation studies also a model for the controlling of fuel and air flow rates has been developed separately

As a stove supplies heat directly to the occupation space it will affect the comfort level and it is important that the dynamics of the heat losses are modelled in a proper way, especially if the comfort and the fraction of useful heat are to be investigated from a building simulation. In order to adjust the heat ratio to the ambient, the heat losses from the Type 341 and 210 were combined and recalculated using equation 2 that describes a time constant [34].

$$P_{out,t=ts} = \left(1 - e^{-\frac{t_{step}}{K}}\right) \cdot P_{in,t=ts-1} + e^{-\frac{t_{step}}{K}} \cdot P_{out,t=ts-1} \quad (2)$$

The model is intended for dynamic simulations of domestic heating systems with simulation time steps around a minute using the dynamic simulation programme TRNSYS [1]. The model is only applicable to pellet or wood fuel boilers and cannot handle flue gas condensation, however it may be possible to add a separate model for flue gas condensation before the chimney. This work is limited to modelling of the hydraulic and thermal part of the boiler.

2.2 Appliances and fuel

The boiler characteristics are presented in Table 2, together with those for the stove S1 which is an extended room heater with a water jacket. Boiler B1 has an integrated heat exchanger for domestic hot water preparation and the radiator circuit is connected directly to the boiler via a shunt valve. Boiler B2 has no built in hot water preparation unit and should be connected to a buffer store. All boilers/stoves automatically ignite the fuel with an electric heater.

The pellet being used are made from soft wood and certified with SS 187120 [35] for the Swedish market. The elemental composition, moisture content and lower heating values of the soft wood pellets used in the tests was analysed by an accredited laboratory (Table 3). The heating value of the pellet fuel was measured according to CEN/TS 14918:2005 [36] as well as the composition of the fuel was analysed according to the standards [37, 38]. When filling the pellet store, samples of the fuel were collected in plastic bags and the humidity of the fuel was analysed according to EN 14774-1:2009 [39]. To minimize the changes in humidity during the measurements, the fuel hopper was covered during the measurements.

The amount of unburned material in the remaining ash after the test determined as mass fraction was measured according to SS 18 71 87 [40]. The corresponding amount of energy in the ash was estimated assuming that all the unburned material was carbon. The amount was below 0.2 % for stove S1 and B2, but 1.5 % for boiler B1 where the burner cleaning routine caused higher amounts of unburned fuel in the ash. As the amount of combusted fuel was measured rather, than the consumed fuel (both boiler and fuel storage on the scale) no corrections were performed when calculating the combustion power.

2.3 Experimental set up

The experimental set up is illustrated in Figure 2. The stove and boilers including the fuel hopper were placed on a scale (WS1) and the flue gas was passed through the chimney with a volume flow sensor VFS6 and temperature sensors TS14 and TS15 which measures the boiler outlet flue gas temperature and the temperature at the flow sensor respectively. TS14 and TS15 actually consists of three sensors each distributed over the cross sectional area. The flue gas is then entering a dilution duct where it is mixed with room air and transported out using a fan. The dilution flow rate was adjusted at full combustion power to maintain the minimum chimney under pressure specified by the manufacturer. The dilution flow rate was then kept constant during the combustion tests which also generates an under pressure in the chimney of about 10 to 15 Pa during non-combustion periods.

All junctions on the chimney and the connection to the boiler flue gas outlet was sealed using a flexible and high temperature resistant silicone glue to ensure complete air tightness in the chimney. No actions are taken on the boiler itself, since the approach is to make a realistic model of the product as it is. False air intake will not affect the determination of the combustion power since an increased flue gas flow rate due to leakage will be compensated by a higher O₂-concentration (Other emissions measured in PPM-scale ignored). False air intake due to leakage in the boiler will influence the flue gas heat losses, but leakage is part of the boiler characteristics and it should be taken into account in simulations applying a model for the chimney draught and pressure drop as is described in [19, 24].

The total fuel consumption for the six day test sequence S5 and the steady combustion sequences S2 to S4 is derived from the measured weight deviations of the pellet store and boiler. The scale readings were corrected for the density variations of the water in the boiler. During the tests presented in Table 4, the boilers were connected to the conditioning rig and during the six day test sequence used for validation the boilers were connected to the buffer store and the rigs within the dashed box (Boiler B1 connected directly to radiator and DHW emulator rigs). The conditioning rig was used to condition both boiler and buffer store. To reduce the thermal losses during conditioning, it must be performed within a short time, but the flow rate must not be too high, so that it causes mixing of the water in the bottom inlet of the boiler. Recommended flow rates for conditioning of buffer stores with a volume of about 0.5 to 1 m³ are about ½ change per hour [41]. However, as boiler volumes are smaller than storages and in order to avoid heat loss to environment during conditioning the flow rate was adjusted to keep the conditioning time between 30 to 60 minutes.

Solar collector and loads are emulated using PC-controlled units that control flow rate and inlet temperature to the system (radiator emulator, DHW emulator and collector emulator). Flow rate and temperatures are measured at the boiler connections (TS1, TS2, VFS1 and VFS2) and at the connections to the store (TS3-TS10 and VFS3-VFS5) hot water and solar collector circuit. The flow sensors (magnetic) are calibrated using a scale and the estimated uncertainty is 1 %. The temperature sensors (PT100) are calibrated at different temperatures towards a calibrated reference sensor, in an insulated box filled with water under mixing. The estimated uncertainty of the temperature sensors is 0.025 °C and the combined uncertainties for the calculated heat rate is about 1.1 % to 1.4 % depending on combustion power [24]. Electric energy and power demand for the pellet burners are measured using a power meter and an energy meter (EM1). Three to five temperature sensors (thermocouples) were also placed at different levels in the boiler water volume (TS11-TS13) with an uncertainty of about 0.5 °C. For the

boilers B1 and B2 a vertical immersion tube in stainless steel was placed from the top to the bottom of the boiler. The tube was filled with vegetable oil and the sensors were placed inside the tube. This arrangement was not possible for Stove S1, where the sensors were placed on the surface of the water jacket under the cover of the stove. There were also additional sensors on the surface of the stove to be able to identify the time constant for heat transferred to the ambient air (see TS11 to TS13 in Figure 2).

The flue gas flow rate, especially during the transient periods of the start-up and the stop phases and the following cooling down period with only leakage through the chimney are lower than what most commercially available flow sensors can measure with acceptable precision [42]. Therefore, a set of multi-port averaging Pitot-tubes calibrated in combination with a pressure transducer specifically to the installed chimney was used in order to be able to measure the transient flue gas flow rate during start-up and stop phases (VFS6 in Figure 2). The sensor including the pressure transducers were calibrated using hot and cold air taking into account both density and viscosity effects. Regular cleaning and zeroing of the sensor was performed and a continuous check of the sensor signal was carried out for each measurement by comparing the total fuel consumption measured by the scale with the fuel consumption calculated by the measured flue gas flow rate and O₂ concentration.

Since the scale resolution is not high enough to provide accurate fuel mass flow rates during short sequences, the fuel consumption (combustion power) was calculated based on the flue gas flow sensor WFS6, and the measured O₂ concentration (GA1). A sample of the flue gas is extracted from the chimney through a heated filter and transported to a cooler followed by the gas analyzer. O₂ is measured on dry flue gas with a paramagnetic gas analyzer and the other components (CO₂, CO and NO, used to trim the boiler) are measured with a non-dispersive infra-red gas analyzer. Along with measurements of flue gas temperature using thermocouples (TS14), ambient temperature (TS16, TS17) and flue gas compositions from the gas analyser GA1 (O₂, CO₂, CO and NO) also the flue gas losses were calculated. The combustion calculations used in the evaluation of flue gas flow rate and combustion power assumes complete combustion with synchronised burn rate of hydrogen and carbon as described by ref [43].

2.4 Uncertainty analysis

The estimated uncertainties for the measured parameters and physical properties are provided in Table 5 and the combined uncertainty for the derived quantities are presented in 6. The combined uncertainties are calculated using the EES software [44] by implementing the equations from the evaluation sheet. The uncertainties presented in Table 5 are estimated based on the specification of the instruments used and their calibration method. Thermocouples TS11 to TS16 and 4-wire PT 100 sensors (TS1 and TS2) were calibrated in a mixed water bath in the range from 0 °C to 90 °C with a calibrated reference sensor. Water flow sensor VFS1 is calibrated by collecting the outflowing water in a vessel on a calibrated scale and converting to volume, while correcting for the water density.

The uncertainty of the scale (WS1 in Figure 2) was determined to be about 200-300 grams with the flexible tube connections. This includes the hysteresis effects and other disturbances observed during measurements. It corresponds to about 1.5 kWh energy content of the fuel which implies an uncertainty of about 3 % if a 15 kW boiler is operated for three hours, which is the target for the steady combustion tests. For the six day test period (Validation sequence S5) the fuel consumption exceeded 250 kWh and the uncertainty of the scale for the total fuel consumption was far below 1 %. The boiler is conditioned to 20 ± 2 °C in the beginning and end of the sequence in order to avoid influence on the scale from varying boiler water density.

The gas analyz

er GA1 is calibrated with nitrogen gas as zero point and with a known concentrations for each spice (zero point and span point). The uncertainty of the flue gas flow sensor is based on the calibration work performed by Paavilainen [45]. The combined uncertainties of the combustion power and flue gas heat losses are in the range of 5 to 8 % and the origin is mainly related to the uncertainty in the measured flue gas flow rate and O₂ concentration. However; the comparison of fuel consumption measured with the scale (WS1) and calculated from the flue gas flow and O₂ concentration does not exceed 5% in any validation sequence [13], which indicates that the practical uncertainty may be lower than the values presented in Table 6.

During periods without combustion and only leakage flow, the velocity in the chimney is about 0.1-0.5 m/s and the uncertainty for the flue gas volume flow rate is estimated to be from 10 % to 20 % [45]. For this reason, standby tests are also performed with the chimney blocked (Sequence S4 in Table 4).

2.5 Experimental procedure

All measurements were taken using a measurement time step of 0.005 h. Before the data were used for modelling, the data were carefully checked for measurement errors and eventual energy balance mismatch that would make the data unusable. The data was averaged to the same time step as the simulations (0.025 h).

The different measurement sequences used are summarized in Table 4. Before the tests all boilers are conditioned until a boiler water temperature of 20 ± 2 °C is reached. The purpose of sequence S1 is mainly to identify the boiler volume from the conditioning period, but the heating up period will also give information of the stratification developed in the boiler during combustion and how the flue gas heat exchanger should be positioned in the model. Sequence S2, S3 and S4 is to be able to identify the heat transfer properties of the flue gas heat exchanger for the range of the combustion power. Sequence S4 also gives information on the heat loss to the surrounding room since the chimney was blocked avoiding heat losses due to chimney draught. Sequence S5 is a realistic operation sequence used only for validation of the model and was developed for performance testing of solar and pellet heating systems [13, 15, 46]. The sequence was originally developed by Bales [47] for testing of solar combistores. The realistic six day operation sequence is based on the climate of Zürich, Switzerland, optimized so that the measured system performance of the six days would correspond to a full year operation. The six –day test sequence includes two summer days, two winter days and two spring/autumn days. The two initial days are there to condition the system before the test period and will also be included in the validation as there is no conditioning between the days. The test procedure is based on a predefined load that is to be supplied by the system. The boiler with built in DHW preparation was also measured using the sequence, but no buffer store or solar heating system were included.

2.6 Parameter identification

Parameters were identified for two pellet boilers and one extended room heater (stove with water jacket). The basic principle for the parameter identification is to compare the measured and simulated energy emitted to the flue gas and to the water circuit, and adjusting the parameters of the model until the deviations are minimized. The following measured values were used as input to the model:

- Combustion air inlet temperature and mass flow rate
- Mass flow rate of the pellet being combusted
- Power consumption of the burner including heater for ignition
- Water inlet temperature and mass flow rate
- Ambient air temperature

The following outputs of the model are compared with the following measurements

- Heat rate to the flue gas
- Heat rate to the water circuit
- Internal water temperature of the boiler

The parameters to be identified are given in Table 7, where also the final identified parameter values are presented. As the model is quite complex and several parameters are used in combination to adjust the characteristics of the model, it was decided to use a software for automatic fitting (DF and FITTRN [48]). DF uses the Levenberg-Marquardt algorithm as optimisation algorithm, which is based on the least square fitting method. The software automatically runs the measurement sequences over and over again and adjusts the parameters to find local minima. The Fittrn and DF software adjusts the parameters in order to reduce the time integration of an objective function specified by the user (equation 3) which is taking into account the deviation between the model and the measurements.

$$Obj = |P_{flue,m} - P_{flue,c}| \cdot a + |P_{wat,m} - P_{wat,c}| \cdot b + (|T_{s1,m} - T_{s1,c}| + |T_{s2,m} - T_{s2,c}| + |T_{s3,m} - T_{s3,c}|) \cdot c \quad (3)$$

The expression takes into account the deviation between measurements (m) and the calculations (c) for the flue gas losses (P_{flue}) and the heat rate to the water circuit (P_{wat}). As the focus also was to model the

stratification in the boiler during the measurement sequence, the calculated internal boiler water temperatures were also compared with the measured (T_s). Coefficients a, b and c was used to adjust the influence on the objective value from each of the terms in the objective. The best fit means that the objective value is as low as possible during the whole measurement sequence.

The procedure for the parameter identification process was the following:

- Measurement data evaluation and checking
- Making data files for parameter identification
- Determination of values for directly available parameters
- Finding a procedure for the order to identify the parameters using software in combination with manual adjustments

2.7 Model validation

The boiler/stove models were validated by quantifying the deviation between simulation results and experimental data that was not used in the parameter identification process. For the validation a test sequence used for whole system testing was applied in the test rig [13, 15]. The sequence consists of two initial days conditioning the system and six realistic operation days (Figure 3). The relative deviation in transferred energy ε_Q and power ε_P through the boiler or the heat exchanger were calculated as by Bales [47]:

$$\varepsilon_Q = \frac{Q_c - Q_m}{Q_m} \cdot 100\% \quad (4)$$

$$\varepsilon_P = \frac{\int |P_c - P_m| dt}{Q_m} \cdot 100\% \quad (5)$$

Q_c is the calculated energy that is transferred through the component and Q_m is the measured energy that is transferred through the component. This was applied to the energy quantities: heat transferred to water (Q_{wat}) and flue gas heat losses (Q_{flue}). The heat transfer to ambient (Q_{amb}) could only be compared based on the total energy balance according to equation 6.

$$Q_{amb,m} = Q_{pell,m} - Q_{wat,m} - Q_{flue,m} \quad (6)$$

3 Parameter identification results and discussion

This section describes the procedure for the proposed parameter identification process in chronological order. An overview of the identified parameters with references to the corresponding sequence is provided in Table 7.

3.1 Phase 1: Parameters determined without use of measurements

The first three parameters in Type 210 (Table 7) can be directly defined. The operation mode (Parameter no. 1) should be 2, in order to have fuel and air flow as input, Parameter no. 2, air to fuel mass flow ratio at $\lambda = 1$ is calculated from a stoichiometric combustion calculation of the current fuel used [43]. The lower heating value of the fuel (Parameter 3) is the heating value of the used fuel based on a test of a sample of the fuel by a test institute (Table 3).

The parameters calculating the power dependence on UA-values in Type 210 could not be adjusted to improve the objective value (eq. 3) for any of the boilers (parameters from 22 to 30 labelled “slope”). The reason is either that the measurement data is not sufficient, or that this part of the model differ from the measured behaviour [49]. It is therefore suggested that these parameters are put to zero. Parameter 27 (UA value between m_2 and water) should be set to a value near zero since the heat transfer to the water is not modelled by Type 210. A value equal to zero is not allowed by the model. Since the thermal mass m_2 is used to model the mass of the burner or ceramic combustion pot it must only have heat exchange with the flue gas and parameter 29 (UA-value for heat transfer between thermal masses) should also be set to a value near zero.

The radiator connection heights in boiler B1 for Type 341 (parameters 21 and 22) was set based on geometrical data. The height of the boilers was set to 1m for all boilers and in phase 2 and 4 parameter 5 was adjusted for the model to adapt to the boilers vertical conduction characteristics. The volume of the

flue gas heat exchanger in Type 341 (parameters 97 and 110 in S1 and B2 and parameter 97 in B1) was put to a value near zero (0.001 m^3) since it was found during the following parameter identification work that the objective value (equation 3) was reduced with the volume for all boilers. The height of the boiler (parameter 1 in Type 341) has only small influence on the results and can be given directly based on the boiler geometry. It is assumed that the heat losses from the side of the boiler model Type 341 are evenly distributed so parameters 8 and 9 can be set to zero and parameter 10 is set to 1, leaving only parameter 11 to be identified for the heat losses from the water circuit. The outlet of the conditioning pipe was placed in the top of the boilers and therefore parameter 26, was 1.0. The inlet conditioning port (Type 341, parameter 25) is normally put to zero, however the mixing of water at the inlet could influence the optimal position thus further optimization is performed under phase 2. The parameters defining the UA-value dependence on the temperature difference (Type 341, parameter 102 and 115) were possible to set to zero for all stoves/boilers, as this parameter can normally not be identified for heat exchangers [47]. The same applies to the time dependency for the UA values (not displayed in Table 7).

3.2 Phase 2: Water volume and number of nodes

Initially the boiler water volume, vertical conductivity, inlet conditioning height and the number of nodes are identified (Type 341 parameter 2, 5, 25 and 125 in Table 7) using the conditioning sequence (sequence S1 in Table 4). The number of nodes and vertical conductivity influences the mixing and stratification in the model. The number of nodes was adjusted, so that the calculated and measured discharge outlet water temperature matches each other. The Type 341 parameter no 5, vertical conductivity can usually not be identified using the conditioning sequence, as it is too short, so the value is set to $10 \text{ kJ}/(\text{hr} \cdot \text{K})$ at this stage. Lower objective values could be found with the conditioning inlet slightly above zero for two of the boilers indicating that there is mixing of water at the inlet, which can be compensated in the model by a higher inlet height. This part was performed manually, since there is a trade-off between number of nodes and the vertical conductivity.

3.3 Phase 3: Temperature sensors inside the boiler

The heights of the temperature sensors placed inside the boiler (Type 341 parameter 57-62) was adjusted using the conditioning sequence S1 and objective value from the temperature sensors (coefficients a and b in equation 3 put to zero). Figure 4 shows a screen plot of the sequence S1 starting after the mixing.

3.4 Phase 4: Boiler heat losses

The heat loss coefficient of the boiler water (parameter 11, Type 341,) was identified from the cooling down sequence with blocked chimney (sequence S4 in Table 4) since the heat loss to the ambient room air during steady operation at high combustion power ($15\text{-}20 \text{ kW}$) corresponds to less than 2.5 % of the combustion power. The estimated uncertainty of the combusted energy from the scale is in the same range as the heat loss to the surrounding room, which may cause mismatch in the energy balance for the sequences with steady operation. Eventual extra losses from the burner during operation cannot be identified with the cooling down sequence and must be adjusted based on data from combustion periods, though the uncertainty is high. This was done manually by comparing the measured and calculated internal boiler water temperatures during cooling down according to Figure 5. The stratification in the boiler B1 is about 15°C during the combustion period and there is a deviation of about 2°C between measured and calculated temperatures for the upper sensor. During the cool down period the modelled heat losses appear too small (trade of between boiler volume and heat loss coefficient) and the modelled stratification is almost non-existent. The stratification may be further improved by introducing a heat loss coefficient for the bottom (parameter 8 in Type 341) and by adjusting the vertical conductivity coefficient (Par 5 in Type 341) but this was not further tested.

3.5 Phase 5: Flue gas heat exchanger UA-values and heat exchanger position

Before adjusting the parameters related to the dynamic behaviour of the boiler in phase 6, the parameters for the flue gas heat exchangers needs to be reasonable set. The parameters are identified using the steady-state measurement sequence S3 with medium combustion power. The parameters to be identified are the inlet and outlet heights of the flue gas heat exchangers and the UA values (Type 341, parameters 95, 96, 100, 108, 109, 113. The tool for automatic parameter identification could not find these parameters by itself, without a strategic approach. The first step was to use the data with medium combustion power (Sequence S3) and the heat rate to the flue gas as the objective (coefficients b and c put to zero in equation 3) to find approximate UA-values and then switch to manually adjust the inlet and outlet positions of the heat exchangers (par 95, 96, 108, and 109 by observing the stratification and the flue gas temperature.

The Boiler B1 was modelled with one flue gas heat exchanger from the bottom to the top of the boiler water, while S1 and B2 were modelled using two separate heat exchangers, where the flue gas is lead from the top to the bottom (Figure 1). Several different configurations were tested for each boiler, but it may be the case that the optimal geometrical configuration was not found.

3.6 Phase 6: Start-up behaviour

The dynamic response for the start-up period was adjusted using the thermal masses in Type 210. The thermal mass m_1 and the UA value between mass m_1 and the boiler (Type 210, parameter 5 and 21) was used to delay the rising flue gas temperature so that it matches the measured flue gas temperature during boiler start up. This was adjusted manually using sequences S2, S3 and S4. For the stove S1, which has a substantial thermal mass in the ceramics of the burner and a relatively small water volume, there is a relatively high flue gas temperature after the burner has stopped increasing the water temperature in the upper part of the stove (green curves in Figure 6). The thermal mass m_2 and the UA value between mass m_2 and the burner (Type 210, parameter 6 and 23) were identified automatically as a second step in phase 6, using the previously identified value of thermal mass m_1 , and with all terms included in the objective function (equation 3).

3.7 Phase 7: Exponents for the flue gas heat exchangers

Exponents for the calculation of flow and temperature dependent heat transfer in the flue gas heat exchanger are identified to make the model valid for a wider range of combustion power. The exponents (Type 341 parameters 101, 102, 103, 114, 115 and 116) were identified along with the UA values (parameters 100 and 113) using all three combustion power steps (sequences S2, S3 and S4). The objective value was calculated from the power to flue gas (coefficients b and c zero in equation 3) The first exponent responds to flue gas flow rate, the second exponent responds to the temperature difference between the flue gas and the water and the third exponent depends on average temperature level. Initially, the first exponent and the UA value was identified using all the three data files with different combustion power.

Initially the first exponent is varied by the software. For the boilers with two heat exchangers in series, the identification has to be done by alternating to adjust the parameters for one heat exchanger while the parameters for the other heat exchanger were kept constant. No influence of the temperature difference dependency could be found, thus the second coefficient (parameters 102 and 115) are put to zero. Finally the third exponent was included in the parameters to be optimized.

At this stage also the heat exchanger position could be further optimized, but as only a few parameters could be identified at the same time, the procedure had to include shifting back and forth between optimization of heat exchanger position and UA-values. When optimizing heat exchanger position, the objective value was calculated from the internal water temperature (coefficients a and b zero in equation 3) and when optimizing the UA-values the objective value was calculated from the flue gas temperature (coefficients b and c zero).

3.8 Phase 8: The burner heat losses

The heat transfer from the boiler/stove to ambient has two components in the model: one part comes from the burner model (Type 210), the other from the water store model (Type 341) which was identified in phase 4. The burner losses are identified by adjusting the Type 210 parameter 25 using sequences S1 to S4. However, the uncertainty in the measurements for heat losses to the ambient is high, and especially so for the sequences with constant high combustion power. Including standby periods the fraction of heat loss to ambient air versus heat to water increases and the relative uncertainty decreases and thus the standby as well as combustion periods in the sequences were used for identification. To model the dynamic behaviour of heat losses to the ambient room air for the stove, the simulated power to ambient air was compared with the average measured surface temperature on three locations on the stove and the time constant K according to equation 3 was adjusted until the profile of simulated power and measured average surface temperature was similar for the transient periods.

4 Validation results and discussion

The validation results for the three boilers/stoves for the six day sequence S5 (Figure 3) are presented in Table 8 and Figure 7. The table shows the deviation in accumulated energy (equation 4) between the calculated and the measured energy for the whole measurement sequence S5. The table also shows deviation in power to flue gas and water (equation 5). The deviation in power is a measure of the absolute deviation in contrast to the deviation in energy where positive and negative energy deviation will level off. Therefore the values for deviation in power cannot be lower than the deviation in energy and boilers having a low deviation in energy may still have a high deviation in power. A large difference between energy ε_Q and power ε_P indicates that the dynamic effect is not fully taken into account, and that the average performance of the model is better than the instant performance for a single time step.

The results in Table 8 show that the deviation in energy for the validation sequence is in most cases below 5 % except for the final conditioning of the boiler B1, which deviates 8.5 %. This is the energy discharged from the boiler after the sequence and is a relatively small part of the total energy being transferred as this boiler distributes the energy directly to radiator and DHW during the test sequence. However; the deviation during conditioning indicates that the stratification in the boiler B1 is not yet perfectly modelled. Stratification mismatch is also visible in Figure 5 and Figure 7, where the simulated radiator power is fluctuating around the measured value. When the burner stops, the temperature at the radiator outlet is lower than measured and just before the burner starts, the simulated temperature is too high, thus the stratification generated during operation is too small in the model. The stratification in boiler B1 during operation is about 15 °C and the deviation between the modelled temperature and the measured temperature for the upper and middle layers is about 2 °C. The deviation during conditioning also indicates that the thermal capacity of the boiler model is too small and as the deviation in power is higher than the deviation in energy it proves that the stratification is not properly modelled.

The Stove S1 and Boiler B2 show very good results, with the highest deviation in energy to the room air of -4.5 % and 6.5 % respectively, and this is considered low compared to the expected uncertainty related to these measurements [24]. In general the results are better or in the same range as predicted by the uncertainty propagation in Table 6 which indicates that the performance measurements are repeatable. It also shows that the identification process includes the conditions that are required to model dynamic operation of pellet boilers. However; further optimisation may be possible by introducing a heat loss coefficient for the bottom (parameter 8 in Type 341) as can be seen by Figure 5.

For boiler B1, the deviation in energy to the flue gas, radiator and DHW is almost zero meaning that the model for boiler B1 predicts very well the average thermal characteristics. However the deviation in power for the radiator and DHW circuits for boiler B1 is slightly above 5 %, which indicates that the stratification in the model of boiler B1 differs from the measurements. The deviation in energy during conditioning also confirms this problem. The highest deviation in power is also found for boiler B1 for the heat rate to the flue gas indicating that the thermal mass or dynamics in the burner and flue gas heat exchanger is not modelled as well as in the other boilers.

The measurement accuracy in determining the heat losses to the ambient room air during steady combustion power is not fully satisfying as shown by the uncertainty analysis in a previous study [24]. In order to further improve the measurements and reduce the uncertainty, the room heat loss could be measured directly using a well-insulated cover and by measuring the cooling air flow rate and temperatures according to Gustavsson et al. [50] and Petzold et al. [26]. However realistic operation sequences with standby periods increase the fraction of heat losses to room air and chimney and the heat losses can be determined with a higher relative accuracy. Comparisons of the validity and accuracy of this model with stratification versus other available TRNSYS pellet boiler models [24, 27, 29] are not possible since the validation procedures differ.

Being able to use the model for system simulations also requires a model of the burner controller that calculates the fuel and combustion air consumption. Such a model was developed by Win [51] which also calculates gaseous and particle emissions. The thermal model of stove S1 has been used in system simulations by Vestlund et al. [19] together with the control and emission model by Win [51], with the purpose of system optimisation on the details of sensor positioning and control algorithms and the model proved to work well for such purpose. Since many of the parameters describe physical properties like water volume and heat loss coefficient, generic typical boilers may be created by just changing a few parameters.

5 Conclusions

A dynamic pellet boiler model that models the internal stratification in the water volume has been parameterized and validated from measurements on three pellet boilers/stoves and a methodology for the parameter identification process has been developed and tested. The boiler models with identified parameters have been validated with satisfactory results towards eight day measurements under realistic operation conditions. The proposed model describes the dynamic thermal behaviour of two pellet boilers and a stove with water jacket operated under realistic dynamic conditions with an accuracy that is in the same range as the expected uncertainty of the measurements. The models for stove S1 and boiler B2 well predict the dynamic behaviour and can simulate the stratification behaviour in the water jacket; however, for boiler B1 the modelling of the stratification shows a slightly larger deviation. The results show that modelling stratification in residential boilers is essential in order to predict correct outlet water temperatures and dynamic behaviour. A relatively small deviation in stratification between model and measurements will influence the prediction accuracy of the model. Further improvements may be possible for boiler B1. The test sequences used for modelling and validation were adequate to parameterise the models and the validation sequence shows that the measurements are repeatable and provide the desired accuracy, except regarding the heat losses to room air. To further improve the measurement accuracy a direct method to measure the room heat losses should be considered. The measurements and the parameter identification work is quite time consuming, which limits the procedure to research work. However; the presented parameters can serve as a basis for simulation of the specific boilers modelled. Also “typical” pellet boilers in a general approach can be simulated based on the parameters presented in Table 7 by modifying key parameters like the water volume and the heat loss coefficient.

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Nomenclature

a	coefficient to adjust influence from heat to flue gas on final objective value [W^{-1}]
b	coefficient to adjust influence from heat to water on final objective value [W^{-1}]
c	coefficient to adjust influence from boiler water temperature on final objective value [$^{\circ}C^{-1}$]
C_p	heat capacity of the fluid (kJ/kg·K)
C_{O_2}	volume concentration of oxygen [-]
LHV	lower heating value of the fuel [MJ/kg]
Obj	objective value [-]
P_c	calculated heat rate [W]
$P_{comb,m}$	Measured combustion power [W], [kW]
$P_{flue,c}$	calculated heat rate to the flue gas [W]
$P_{flue,m}$	measured heat rate to the flue gas [W] , [kW]
P_m	measured heat rate [W]
$P_{wat,c}$	measured heat rate to the water circuit [W]
$P_{wat,m}$	measured heat rate to the water circuit [W] , [kW]
$Q_{amb,m}$	measured energy content of the combusted fuel [J]
Q_c	calculated energy [J]
$Q_{flue,m}$	measured energy to the flue gas [J]
$Q_{wat,m}$	measured energy to the water circuit [J]
Q_m	measured energy [J]
$Q_{pell,m}$	measured energy content of the combusted fuel [J]
T	temperature [$^{\circ}C$]
T_{amb}	ambient temperature [$^{\circ}C$]
T_{bin}	boiler inlet water temperature [$^{\circ}C$]
T_{bout}	boiler outlet water temperature [$^{\circ}C$]
T_{fg}	Flue gas temperature [$^{\circ}C$]
$T_{s1,c}$	calculated water temperature inside boiler at position 1 [$^{\circ}C$]
$T_{s1,m}$	measured water temperature inside boiler at position 1 [$^{\circ}C$]
$T_{s2,c}$	calculated water temperature inside boiler at position 2 [$^{\circ}C$]
$T_{s2,m}$	measured water temperature inside boiler at position 2 [$^{\circ}C$]
$T_{s3,c}$	calculated water temperature inside boiler at position 3 [$^{\circ}C$]
$T_{s3,m}$	measured water temperature inside boiler at position 3 [$^{\circ}C$]
$\dot{V}_{flue}$	flue gas volume flow rate [l/s]
$Y_{H_2O, fuel}$	moisture content of the fuel (wet basis) [kg/kg]
ε_P	relative deviation between measured and calculated power [%]
ε_Q	relative deviation between measured and calculated energy [%]
λ	air factor [-]
ω_{O_2}	measured O_2 volume concentration in flue gas [%]
ρ_{fg}	density of flue gas [kg/m ³]
ρ_{wat}	density of water [kg/m ³]
$c_{p,fg}$	Specific heat capacity of flue gas [J/(kg·K)]
$c_{p,wat}$	Specific heat capacity of water [J/(kg·K)]
ϕ_{air}	Relative humidity in combustion air [%]

Table 1
Overview of TRNSYS hot water boiler models.

	Wood fuel	Thermal mass	Multi node model (stratification)	Integrated heat exchangers for DHW or solar
Type 6 [52]	No	No	No	No
Type 659 [53]	No	No	No	No
Type 370 [54]	Yes	Yes	No	No
Type 869 [28]	Yes	Yes	No	No
Type 869+Type 340 [22, 28, 32, 33]	Yes	Yes	Yes	Yes
Type 210 [25]	Yes	Yes	No	No
Modified Type 210 [26]	Yes	Yes	No ^{a)}	No
Type 147 [31]	No	Yes	Yes	Yes

^{a)} Correction factor is applied to compensate for thermal stratification in the boiler

Figure 1. Schematic of the boiler models (not according to scale) showing mass flow as grey arrows and heat transfer as white arrows. m1 and m2 are thermal masses, HX are exchangers and DP are double ports (direct pair of water connection) [25, 32].

Table 2
Technical data for the stoves and boilers used in the study.

	Stove S1	Boiler B1	Boiler B2
Rated combustion power	12 kW	20 kW	20 kW
Fuel feeding	Top fed	Top fed	Top fed
Burner type	Ceramic cup	Tube burner	Tube burner
Boiler type	Vertical tubes	Vertical tubes	Horizontal tubes
Weight without water	265 kg	180 kg	255 kg
Water volume	0.02 m ³	0.155 m ³	0.135 m ³
Hot water preparation	none	Internal spiral tube	none

Table 3
Elemental composition and lower heating value of the wood pellet used.

Element		
Carbon	Wt% dry	50.74
Oxygen	Wt% dry	42.52
Hydrogen	Wt% dry	6.23
Nitrogen	Wt% dry	0.10
Ash	Wt% dry	0.41
Moisture ^{a)}	Wt% wet	6.8
LHV ^{a)}	MJ/kg	17.56

^{a)} Values measured at certified laboratory. Samples from each test were collected and moisture ratio was analysed according to EN 14774-1:2009 [39] and the LHV was adjusted.

Table 4

Measurement sequences used for parameter identification. All sequences started with the boiler conditioned to 20 ± 2 °C.

Sequence	
S1	Heating up boiler to 70-80 °C + mixing + conditioning to 20 °C
S2	3.5 hr steady operation at maximum combustion power (P_{max}) + conditioning to 20 °C
S3	3.5 hr steady operation at medium combustion power ($(P_{min} + P_{max})/2$) + cool down to 30 °C with open chimney + conditioning to 20 °C
S4	3.5 to 6 hr steady operation at minimum combustion power (P_{min}) + cool down to 30 °C with blocked chimney + conditioning to 20 °C
S5	"Realistic operation" (two initial days + six days realistic measurement sequence) + conditioning to 20 °C [13, 15, 46]

Table 5

Estimated uncertainties for the measured parameters and physical properties. Values are selected to represent typical operation conditions.

Parameter	10 kW combustion power	20 kW combustion power	Unit
LHV	17.62 ± 0.1 ($\pm 0.57\%$)	17.62 ± 0.1 ($\pm 0.57\%$)	[MJ/kg]
$Y_{H_2O, fuel}$	0.0652 ± 0.002 ($\pm 2.0\%$)	0.0652 ± 0.002 ($\pm 2.0\%$)	[kg/kg]
ω_{O_2}	11.8 ± 0.46 ($\pm 0.05\%$)	6.8 ± 0.27 ($\pm 4\%$)	[%]
T_{fg}	180 ± 5 ($\pm 3\%$)	135 ± 4 ($\pm 3\%$)	[°C]
ρ_{fg}	$0.936^* \pm 0.01$ ($\pm 0.94\%$)	$0.936^* \pm 0.01$ ($\pm 0.94\%$)	[kg/m ³]
$c_{p,fg}$	$1100^* \pm 10$ ($\pm 0.9\%$)	$1100^* \pm 10$ ($\pm 0.9\%$)	[kJ/kg]
$\dot{V}_{flue}$	8.7 ± 0.52 ($\pm 6\%$)	12.9 ± 0.52 ($\pm 4\%$)	[l/s]
ϕ_{air}	30 ± 3 ($\pm 10\%$)	30 ± 3 ($\pm 10\%$)	[%]
T_{amb}	20 ± 1 ($\pm 5\%$)	20 ± 1 ($\pm 5\%$)	[°C]
T_{bin}	60.00 ± 0.025 ($\pm 0.04\%$)	60.00 ± 0.025 ($\pm 0.04\%$)	[°C]
T_{bout}	69.40 ± 0.025 ($\pm 0.04\%$)	64.00 ± 0.025 ($\pm 0.04\%$)	[°C]
ρ_{wat}	983 ± 2 ($\pm 0.2\%$)	983 ± 2 ($\pm 0.2\%$)	[kg/m ³]
$c_{p,wat}$	4188 ± 2 ($\pm 0.05\%$)	4188 ± 2 ($\pm 0.05\%$)	[J/(kg·K)]
$\dot{V}_{wat}$	0.5 ± 0.005 ($\pm 1\%$)	0.5 ± 0.005 ($\pm 1\%$)	[l/s]

*The properties of the flue gas are calculated based on measured chemical composition and temperature.

Table 6

The combined uncertainties for the derived quantities calculated based on the estimated uncertainties of the measured parameters and physical properties in Table 5.

Parameter	10 kW combustion power	20 kW combustion power	Unit
$P_{wat,m}$	8.23 ± 0.11 ($\pm 1.4\%$)	19.35 ± 0.21 ($\pm 1.1\%$)	[kW]
$P_{comb,m}$	10.2 ± 0.78 ($\pm 7.7\%$)	22.5 ± 1.6 ($\pm 7.3\%$)	[kW]
$P_{flue,m}$	1.03 ± 0.07 ($\pm 7.1\%$)	2.13 ± 0.11 ($\pm 5.3\%$)	[kW]
λ	2.28 ± 0.11 ($\pm 5.0\%$)	1.48 ± 0.027 ($\pm 4.5\%$)	[-]

Figure 2. Schematic of the measurement set up for a boiler with a solar buffer store and test apparatus for measuring with temperature sensors (TS), flow sensors (VF), scale (WS), electric power meter (EM) and flue gas analyser (GA).

Figure 3. The test sequence used for validation [13, 15, 46].

Table 7

Identified parameters for the boiler model (TRNSYS Types 210 and 341). General parameters are density of water = 992 kg/m³ and heat capacity of water = 4.18 kJ/(kg·K). "-1" indicates that the double port or heat exchanger is not used and deactivated. Parameters that are irrelevant have been excluded in the table. The column "phase" indicates in which phase of the identification process that the parameter value was identified.

Par. number	Parameter description	Unit	Phase	Stove S1	Boiler B1	Boiler B2
Type 210						
1	Operation mode	-	1	2	2	2
2	Stoichiometric air/fuel ratio	kg/kg	1	5.65	5.65	5.65
3	Lower heating value of fuel	kJ/kg	1	17.56 ^{a)}	17.56 ^{a)}	17.56 ^{a)}
5	Thermal mass 1	kJ/kg	6	30	6.48	15
6	Thermal mass 2	kJ/kg	6	16.2	1	1
21	UA value between gas and m1, fixed	kJ/(hr·K)	6	10.16	200	200
22	UA value between gas and m1, slope	kJ/(hr·K)	1	0	0	0
23	UA value between gas and m2, fixed	kJ/(hr·K)	6	28.87	0.001	0.001
24	UA value between gas and m2, slope	kJ/(hr·K)	1	0	0	0
25	UA value between m1 and ambient air, fixed	kJ/(hr·K)	8	10.16	1.85	0.001
26	UA value between m1 and ambient air, slope	kJ/(hr·K)	1	0	0	0
27	UA value between m2 and water, fixed	kJ/(hr·K)	1	0.001	0.001	0.001
28	UA value between m2 and water, slope	kJ/(hr·K)	1	0	0	0
29	UA value between m1 and m2, fixed	kJ/(hr·K)	1	0.001	0.001	0.001
30	UA value between m1 and m2, slope	kJ/(hr·K)	1	0	0	0
Type 341						
1	Storage height	m	1	1	1	1
2	Storage volume	m ³	2	0.0403	0.170	0.160
5	Effective thermal conductivity in the storage	kJ/(hr·m·K)	2, 4	59,821	20	5
8	Bottom heat loss capacity rate	kJ/(hr·K)	1	0	0	0
9	Top heat loss capacity rate	kJ/(hr·K)	1	0	0	0
10	Relative length of 1st zone	-	1	1	1	1
11	Zone heat loss capacity rate from storage to ambient	kJ/(hr·K)	4	42.61	18.25	24.43
21	Rel. height of inlet position dp 2 radiator	-	1	-1	0.6	-1
22	Rel. height of outlet position dp 2 radiator	-	1	-1	1	-1
25	Rel. height of inlet position dp 3 normal connection/conditioning	-	1, 2	0.1	0	0.166
26	Rel. height of outlet position dp 3 normal connection/conditioning	-	1	1	1	1
57	Rel. position of temperature sensor-1	-	3	0.1	0.068	0.365
59	Rel. position of temperature sensor-2	-	3	0.5	0.237	0.626
59	Rel. position of temperature sensor-3	-	3	0.9	0.472	0.947
60	Rel. position of temperature sensor-4	-	3	-1	0.770	1
61	Rel. position of temperature sensor-5	-	3	-1	0.95	-1
Heat exchanger parameters for HX3						
95	Rel. inlet position of the heat exchanger-3	-	5, 7	0.6	0.1	0.6
96	Rel. outlet position of the heat exchanger-3	-	5, 7	0.1	1	0.1
97	Volume of heat exchanger 3	m ³	1	0.001	0.001	0.001
100	UA through heat exchanger 3	kJ/(hr·K)	5, 7	150.3	169.1	122
101	Flow rate dependency for UA -3	-	7	0.888	0.0607	0.8
102	Temperature difference dependency for UA -3	-	7	0	0	0
103	Average temperature level dependency for UA -3	-	7	0.629	-0.0215	0.6
Heat exchanger parameters for HX4						
108	Rel. inlet position of the heat exchanger-4	-	5, 7	1	0.4	1
109	Rel. outlet position of the heat exchanger-4	-	5, 7	0.6	0.95	0.6
110	Volume of heat exchanger-4	m ³	1	0.001	0.005	0.001
113	UA through heat exchanger 4	kJ/(hr·K)	5, 7	6.25	135	26
114	Flow rate dependency for UA -3	-	7	-0.302	0.0874 ^{b)}	0
115	Temperature difference dependency for UA -3	-	7	0	0	0
116	Average temperature level dependency for UA -3	-	7	-0.00739	0.9965 ^{b)}	0
125	Number of nodes	no	2	20	70	50
External modelling						
	Time constant <i>K</i> for heat emitted to ambient room air (equation 2)		8	0.35	-	-

^{a)} Approximate value for the used fuel. The heating value was adjusted due to the current humidity ratio analysed regularly.

^{b)} The chosen parameters for the heat exchanger taken from Bales [47] (upper DHW heat exchanger in SERC3)

Figure 4. Screen plot from the optimization process of boiler B2 for sequence S1 starting after the mixing. Upper graph showing measured heat rate to water (Pwalm) and calculated heat rate to water (Pwalc). Lower graph showing the three internal boiler water temperatures.

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Figure 5. Screen plots from the optimization process of boiler B1 for sequence S4. Upper graph showing combustion power (Pcmbm), measured heat rate to water (Pw atm), calculated heat rate to water (Pwatc), measured flue gas losses (Pfluem) and calculated flue gas losses (Pfluec). Lower graph showing measured (Tb1m, Tb4m) and calculated internal water temperatures (Tb1c, Tb4c).

Validation results expressed as relative deviation in transferred energy ε_W calculated by equation 2 and relative deviation in transferred power ε_P calculated by equation 3.

¹⁾ The energy delivered to the ambient air is estimated from the overall energy balance from the measurement, thus deviation in power cannot be calculated.

Figure 7. Measured and calculated heat rate to water circuit during day 2 of the six day sequence for stove S1, boiler B1 and boiler B2.

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