Combined Solar and Pellet Heating Systems for Houses: Improvement of Energy Efficiency and Reduction of Boiler ON/OFF cycling

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Abstract

Annual simulations of combined solar and pellet combisystems have been performed based on measurements of two pellet boilers and a burner integrated into a solar thermal energy storage (TES). The results show that the investigated burner integration is more energy efficient in comparison with the external pellet boiler solution. The flue gas losses were the predominant losses measured for steady state burner operation, but heat losses to the ambient were predominant in the annual simulation results. The number of ON/OFF cycles of the pellet burner depends to a high degree on the control strategy implemented to adapt the power modulation to the current demand, and varied from almost 3000/a in the worst case to less than 900/a in the best case simulated. Based on parametric simulation studies, it was determined that the fractional energy savings of both systems could be increased from around 20% to 30% for a house with 4.6 kW heat load at climate Zurich without increasing the area of 10 m2 flat plate collectors or the TES volume of 850 litres. A comparison with a hypothetical TES of the tank-in-tank design showed additional potential for improvement due to a smaller area of the TES that has to be kept at high temperatures for DHW use.

1. Introduction

Pellet boilers as well as solar thermal systems are considered to be key technologies for the reduction of non-renewable energy use for space heating (SH) and domestic hot water (DHW) preparation. The main advantages of the combination of both are considered to be a) the avoidance of non-renewable energy use to cover heat demand that cannot be covered by solar heat alone with moderately sized solar thermal energy systems, b) the possibility to switch the pellet boiler OFF during summer and part of autumn and spring where the boiler efficiency would be low due to a low heat load and intermittent operation, and c) significant fuel (pellet) savings in this heating system, thereby saving fuel costs and creating the possibility to use the saved pellets in another heating system. Solar and pellet heating systems were investigated by several authors [1-3]. It has been shown that decreasing the number of burner starts may decrease also emissions of a pellet boiler [4]. However, if the number of boiler starts is decreased by operating the boiler on part load (effective power modulation), annual emissions may also increase if emissions at part load operation are higher than at full load operation [5,1]. In the work presented here, the focus was set on possibilities to increase energy savings and decrease ON/OFF cycles of the pellet burner for solar combisystem with a collector area of 10 m^2 and an 850 litre TES by means of improved components, hydraulics, and control strategies.

2. Experimental

2.1. Pellet boilers and burners

Measurements have been performed in the laboratory for two pellet boilers and one pellet burner integrated into a solar TES in steady state and in cycling ON/OFF operation mode. Details about the measurement procedure and the uncertainty calculation can be found in [1]. A newly developed space heating boiler simulation model described in [9] has been parameterized based on the results of the laboratory measurements. A detailed list of these parameters can be found in [10]. The results of the boiler measurements showed that flue gas losses are the main heat losses under full load operation for these boilers. On the other hand, the fraction of heat lost by convection and radiation increased with decreasing heat load of the boiler, and electric energy needed for fuel ignition may become significant for some boilers while serving a low heat load in cycling operation.

2.2. Thermal energy storage tank

A solar thermal energy storage tank (TES) with integrated pellet burner has been installed and tested in the laboratory [10]. These tests, their results, and the parameterization of the multiport store model Type 340 [11] are described in detail in [10].

3. Annual Simulation Results

3.1. Comparison of different hydraulic approaches

Annual system simulations have been performed for solar and pellet heating systems with the heat load from the IEA-SHC Task 32 reference system SFH60 with the climate of Zurich, described in [12]. Key figures of the heat load and the reference heating system are shown in table 1.

Table 1. Key figures of the reference heating system SFH60 for the climate of Zurich.

Key figures of the reference heat load (remain unchanged)	***Value***	***Unit***
Space heating demand / DHW demand	8.48 / 3.04	MWh
Design heat load at ambient temperature of -10 °C	4.6	kW
Design supply/return temperature for SH at ambient temperature -10 °C	40/35	°C
Parameters of the reference heat supply system (for comparison)	***Value***	***Unit***
Annual boiler efficiency relative to the NHV / GHV	76.0 / 70.6	%
Electricity demand of the boiler in % of useful heat delivered	2.34	%

For the comparison of energetic efficiency of different control strategies for boiler charging, the results of different system simulations are compared with the reference pellet heat supply system (table 1) that is equipped with a pellet boiler and a domestic hot water storage, but without solar thermal energy. Fractional thermal energy savings ($f_{sav,therm}$) are used to compare the fuel energy savings of these different heating systems, and extended fractional energy savings ($f_{sav,ext}$) are used for the comparison of energy savings including the primary energy for electricity that is used by the system, calculated with a primary energy factor of 2.5. The definition of these performance indicators is explained in detail in [12].

The parameters for the simulation of the solar thermal collector loop shown in table 2 remain unchanged for all simulations shown.

Table 2. Parameters of the solar thermal collector loop

Parameter	*Value*	*Unit*
Field aperture area	10	m^2
Slope / orientation (-90 ° = east)	45 / 0	°
Optical efficiency or "zero heat loss efficiency" (based on aperture area)	0.741	-
Linear heat loss coefficient (based on aperture area)	3.311	W/m^2K
Quadratic heat loss coefficient (based on aperture area)	0.012	W/m^2K^2
UA-value of collector supply and return lines (each)	2.9	W/K

Fig. 1 shows the two different hydraulic setups that have been simulated: a) A solar thermal heating system with a TES integrated pellet burner (**Int.), ** and b) a system with a solar TES that is charged by an external pellet boiler (**Ext.**).

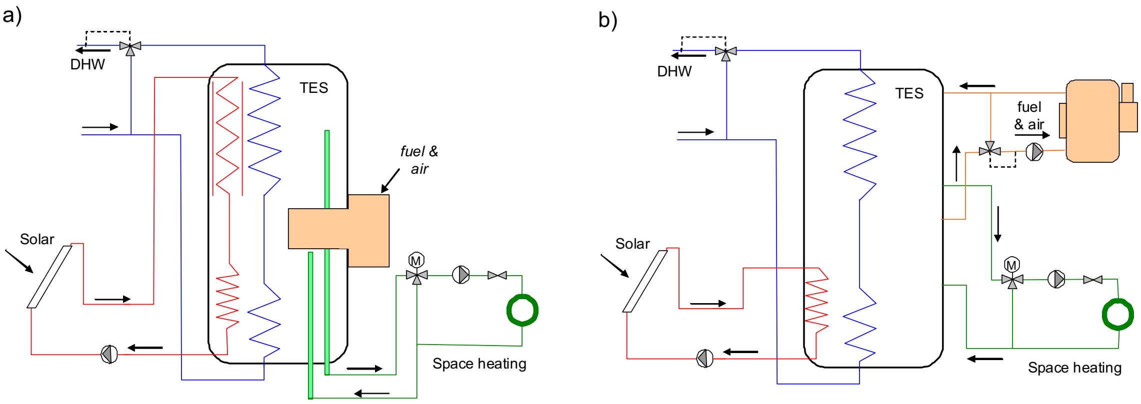

Fig. 1. Hydraulic schematic for the simulation of the system with a pellet burner integrated into the TES (a) and the external pellet boiler system (b).

For the integrated burner system (Fig.1a), the parameters of the base case system (**Int. base**) correspond to the ones determined in the laboratory test for the TES with the integrated burner. For the system with the external pellet boiler (Fig. 1b) the pellet boiler of the base case (**Ext. base**) is parameterized based on measurements performed on two small pellet boilers with maximum capacities of around 10-12 kW heating power [10]. The TES of the external burner system corresponds to a TES that is similar to the one with the integrated burner with exception of:

- Lower heat losses in the top zone (1/3) and mid-zone (1/3) of the TES: 0.63 W/K each instead of 2.89 W/K (top-zone) and 3.17 W/K (mid-zone).
- Different height of return from space heat (relative height from bottom 25% instead of 45%) and no heat transfer from immersed space heating pipes to the surrounding water within the TES.

For the improved system with integrated burner (**Int. imp.)** and the improved system with external boiler (**Ext. imp.**), the following improvements or changes have been assumed for both systems:

- Power modulation down to 30% of maximum combustion power instead of no power modulation (Int. base) and 41% of maximum combustion power (Ext. base).
- Constant excess-air factor (λ) of 1.8 over the whole range of power modulation instead of 1.4 - 1.8 (Int. base) and 2.35 - 3.25 (Ext. base).
- Losses from the combustion chamber (to ambient and to ash) of only 0.9% of fuel energy instead of 2.2% (Int. base) and 1.8% (Ext. base).

- All heat transfer capacity of the solar loop heat exchangers moved to the bottom part of the TES, and relative height of collector loop sensor lowered.
- Heat transfer capacity of the internal DHW heat exchanger increased by 50%.
- For **Ext. imp.**, Losses from the boiler water (heat exchanger) to the ambient reduced from 6.8 W/K to 3.4 W/K.
- For **Int. imp.**, heat losses to the ambient of the two upper 1/3 of the volume reduced from 2.89 to 1.39 W/K and from 3.17 to 1.94 W/K, respectively.
- For **Int. imp.**, lower height of return from SH (relative height from bottom 25% instead of 45%) and no heat transfer from immersed SH pipes to the surrounding water within the TES.

Fig. 2 shows that the predominant heat losses of these systems are heat losses by the boiler and the TES to the ambient. It also shows that although the TES with the integrated burner has far greater heat losses due to the difficult insulation in the region of the burner integration, these heat losses are still lower than the combined heat losses of the TES, the boiler, and the connecting pipes in the external boiler system. For the improved systems, the difference in energetic losses of the integrated system and the external boiler system becomes smaller.

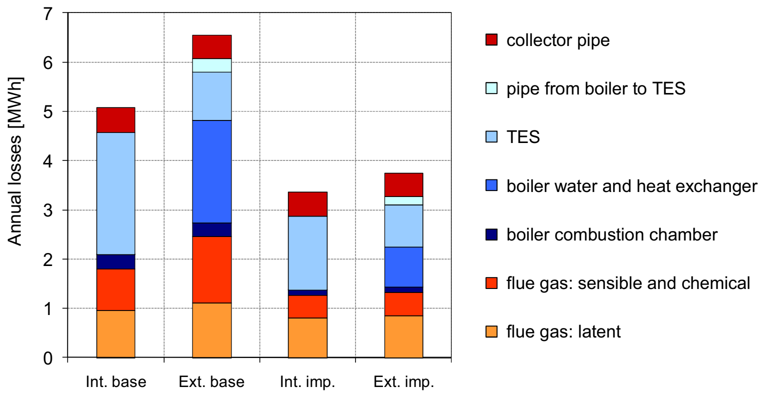

Fig. 2. Simulated annual losses of two versions of the two different hydraulic solutions.

3.2. Control Strategies for TES charging by an external pellet boiler

Several studies have shown that in small systems where a pellet boiler is charging a TES, even boilers that are capable of reducing their continuous heat output to 30% of their nominal value often fail to reduce their heat output to the current demand and run on maximum heat output until the OFF-criteria of the controller is reached [13,14]. The reason for this is seen in the fact that the TES decouples the heat load from the pellet boiler, in combination with an inadequate or an inexistent control strategy for the adaption of the boiler firing rate to the current heat demand. Therefore, a detailed simulation study of different control strategies for the power modulation of the external pellet boiler was performed, using the same parameters for heat load, TES and boiler simulation as in the previous section (Ext., Fig. 1b).

Fig. 3 shows different options for controlling the charging of a TES by an external pellet boiler. Control strategies with a grey background have been included in the simulation studies presented here. To keep the boiler warm over the whole heating season is not recommended in systems where solar thermal heat may cover the heat demand for several days, thus giving the possibility to keep the boiler cold during these days. Therefore, the decision to start the burner should always be made based on a temperature measurement within the TES.

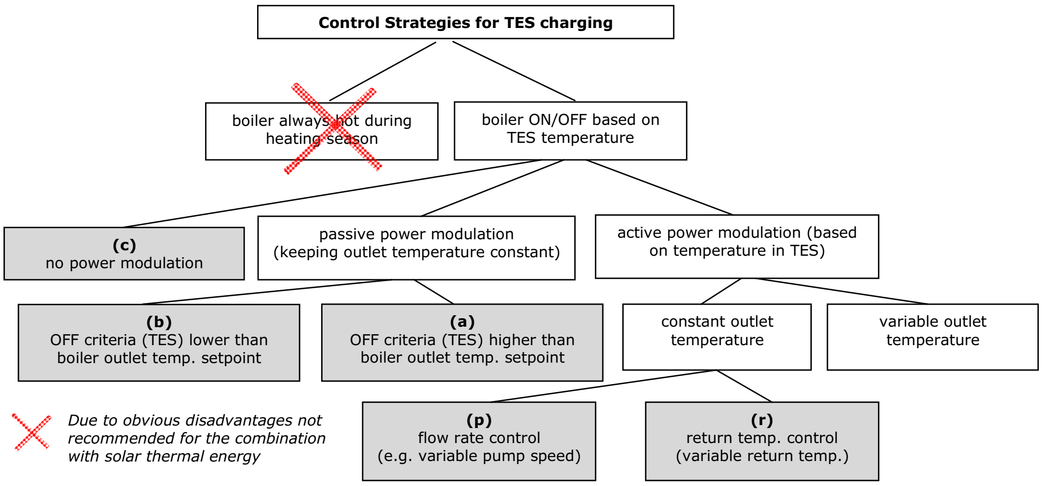

Fig. 3. Control options for external pellet boilers charging a TES; grey background = simulation studies presented in this work.

For a solar combisystem, the upper part (DHW zone) of the TES has to be kept at a certain minimum temperature, e.g. 62°C, to fulfil the criteria for comfort and hygiene for DHW. At the same time, the middle part (SH zone) of the TES should be kept at a temperature that is above the required SH supply temperature, which is well below the required DHW temperature for state of the art heating systems for houses. Whenever the measured temperature within the TES drops below the respective ON-criteria of the boiler, the boiler starts burning fuel and the circulation pump is switched on. As soon as the temperatures within the TES have risen above the OFF-criteria, the boiler stops feeding fuel and the circulation pump is switched off with a certain time-delay. If power modulation is desired, the most difficult part of the procedure is between the ON- and the OFF-signal, where a modulating boiler should find the fuel combustion rate that matches the heat load and thus keeps running for a longer time.

3.2.1. Passive or no power modulation

If only one temperature sensor within the TES is used for the ON/OFF control of the pellet boiler, this sensor has to be placed low enough to detect when the space heat zone gets discharged, but the temperature levels for auxiliary heating have to be based on the temperature requirements for DHW. Thus, the space heat zone of the TES is kept at a higher temperature than actually needed. It is important that the boiler does not turn OFF immediately when its supply temperature ($t_{B,out}$) surpasses its set-temperature ($t_{B,set}$), but only if the TES temperature reading ($t_{S,sensor}$) surpasses the OFF-criteria ($t_{S,OFF}$). Fig. 4 to Fig. 6 show simulation results of strategies where the ON and OFF criteria are based on one temperature sensor in the SH zone of the TES and a hysteresis. The differences between the shown control strategies are:

a) passive power modulation with OFF criteria (TES) 1 K higher than boiler supply set point
b) passive power modulation with OFF criteria (TES) 1 K lower than boiler supply set point
c) no power modulation

Fig. 4 shows that the boiler runs on maximum power until the return temperature from the TES ($t_{S,out}$) surpasses the setpoint for return temperature mixing of 50 °C (strategy a). Then, combustion power is reduced in order to keep the outlet temperature of the boiler $t_{B,out}$ at $t_{B,set}$. Only when the lowest possible combustion rate is reached and the return temperature continues to increase, the outlet temperature surpasses $t_{B,set}$ and consequently, after some time, also the temperature in the TES ($t_{S,sensor}$) reaches the OFF criteria that is 1 K higher than $t_{B,set}$. Fig. 5 shows the same behaviour, but the burner is switched off earlier due to the OFF-criteria of the TES temperature sensor that is reached earlier (strategy b). With this control strategy, the running time of the boiler is shorter, but the temperatures of the boiler and the TES remain lower. Fig. 6 shows an example for no power modulation (strategy c) where the running time of the boiler is shorter than with the other two strategies and at the same time the temperatures of boiler and TES are higher.

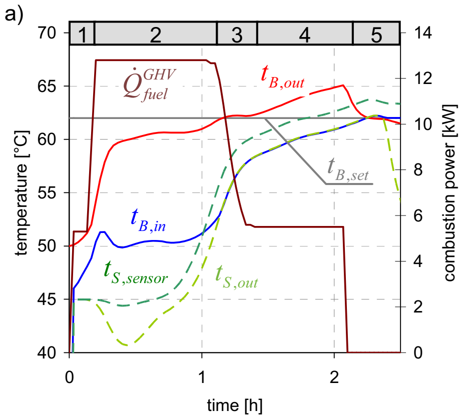

Fig. 4. Passive power modulation, $t_{B,set} < t_{S,OFF}$.

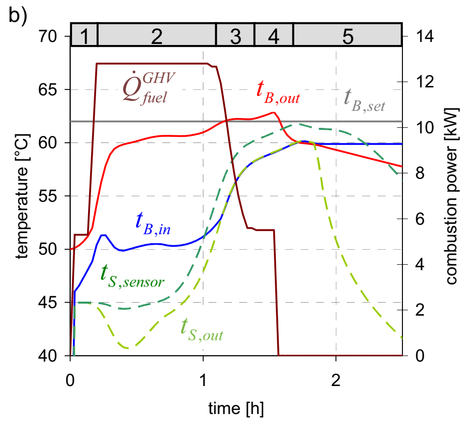

Fig. 5. Passive power modulation, $t_{B,set} > t_{S,OFF}$.

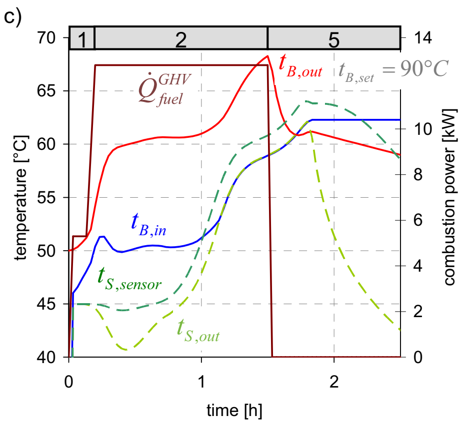

Fig. 6. No power modulation.

3.2.2. Active power modulation

Assuming that the boiler controls its combustion rate to maintain a constant set temperature ($t_{B,set}$) of the boiler water supply ($t_{B,out}$), decreasing the heat output can be achieved by two strategies:

p) reducing the flow rate of the water circulating through the boiler by pump speed control
r) increasing the return temperature to the boiler with a mixing valve

Water flow rate reduction by means of a speed controlled pump has the advantage of electricity savings due to lower electricity consumption at lower pump speeds. Both control strategies (p and r) use a temperature measurement in the TES for controlling the return temperature or the pump speed. In order to be able to use the full modulation range of the boiler, the maximum and minimum mass flow rates for the pump speed control are determined as:

$$\dot{m}_{B,max} \approx \frac{\dot{Q}_{B,wat,out,max}}{cp_{wat} \cdot \left(t_{B,set} - t_{B,rt,set,min}\right)} \tag{1}$$

$$\dot{m}_{B,min} \approx \frac{\dot{Q}_{B,wat,out,max}}{\dot{Q}_{B,wat,out,min}} \cdot \dot{m}_{B,max} \tag{2}$$

In the case of active power modulation by return temperature set point change, the relationship between the minimum and maximum return temperature set points is:

$$t_{B,set} - t_{B,rt,set,max} \approx \frac{\dot{Q}_{B,wat,out,min}}{\dot{Q}_{B,wat,out,max}} \cdot \left(t_{B,set} - t_{B,rt,set,min}\right) \tag{3}$$

For both control strategies, the process variable for the PID controller is the delta-T between the set point and the measured TES temperature of the sensor that is more critical for not reaching its set point:

$$dT_{store,ctr} = MIN\left[t_{store,ms,DHW} - t_{store,set,DHW}; t_{store,ms,SH} - t_{store,set,SH}\right] \tag{4}$$

The process variable $dT_{store,ctr}$ is positive when both temperatures measured are above the corresponding set points, but negative when one of them drops below its set point. The set point for $dT_{store,ctr}$ is zero, with decreasing action on boiler pump speed, or increasing action on return temperature. This means that the boiler pump speed is reduced or the return temperature increased when the value of $dT_{store,ctr}$ gets larger.

3.2.3. Simulation results for control strategies

Fig. 7 shows simulation results for 4 series of simulations. These series are:

C1 only one TES temperature sensor for ON and OFF control with hysteresis
C5 two TES temperatures for ON/OFF control (sensor for ON placed lower than sensor for OFF)
C6 one sensor for ON/OFF control and power modulation for charging the DHW zone, another one for charging the SH zone
C7 average temperature measurement of DHW zone for ON/OFF control and power modulation for charging the DHW zone, another average temperature measurement of SH zone for charging the SH zone

Each series is sub-divided into strategies **a** to **c** or **p** and **r** as described in the previous sections.

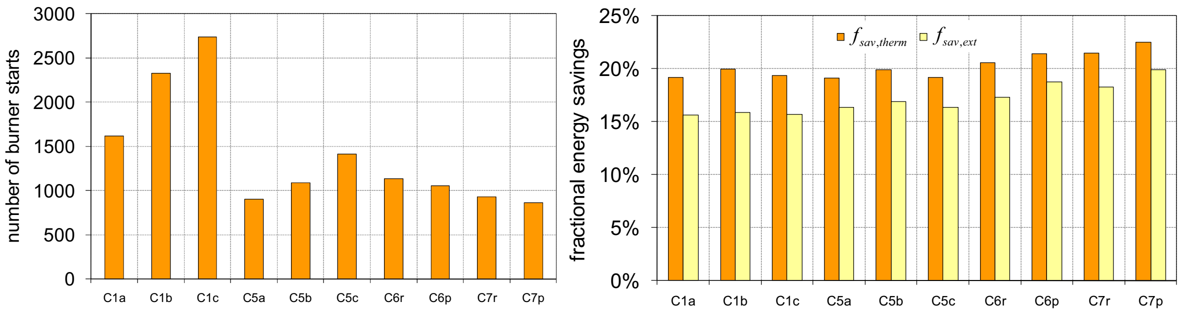

Fig. 7. Number of burner starts and energy savings for different control strategies of TES charging.

4. Conclusion

Annual simulation studies have been carried out based on measurements performed on stand-alone pellet boilers as well as on a TES-integrated pellet burner. The simulations show that a combined solar and pellet heating system may be more energy efficient if the burner is integrated in the solar TES. In the investigated systems, the higher TES heat losses of the integrated system were lower than the combined heat losses of a better insulated solar TES in combination with the external pellet boiler. Considerable improvements of the energy efficiency can be achieved by better insulation of the TES and the boiler, as well as by keeping the excess air for combustion low even at part load operation of the boiler. A simulation study on different strategies for the charging of a solar TES by an external pellet boiler showed that control strategies with active power modulation based on temperature measurement in the TES not only achieve lower number of burner starts, but also the highest energy efficiency. However, other studies show that the reduction of burner starts by effectively using power modulation does not automatically decrease emissions. Decreasing emissions by this measure can only be achieved if the boiler is able to run with a low excess air factor and low emissions also in part load operation.

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