INCREASING EFFICIENCY AND DECREASING CO-EMISSIONS FOR A COMBINED SOLAR AND WOOD PELLET HEATING SYSTEM FOR SINGLE-FAMILY HOUSES

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ABSTRACT: This study focus on how wood pellets and solar heating systems for single-family houses should be designed and controlled to reach high efficiency and to reduce the CO-emissions. A recently developed TRNSYS model was used to simulate the wood pellet boiler. Parameters for the model were identified from laboratory measurements on a boiler. A detailed simulation model of a complete solar combisystem was created and annual simulations were performed. Assuming that all heat losses to the room are waist heat, the results show that the most important factors to achieve high system efficiency are that the boiler and the buffer store should be well insulated. The sensor controlling the boiler should be placed in the store; the pump between the boiler and the store should only be in operation together with the burner and for some time after the burner have stopped to take care of the after burning heat. For boilers with relatively large start and stop CO-emissions modulating power may be an efficient measure to reduce CO-emissions. Especially for boilers using an ON-OFF control, the dominating contribution of CO-emissions may be during the start and stop phases, thus reducing emissions during operation may have little influence on the annual CO-emissions.
Keywords: boilers, efficiency, emissions, emission reduction.

1 INTRODUCTION

There is an increased interest in wood pellet heating systems for single-family houses in Sweden due to the rising oil and electricity prices. Most of the installations of pellet heating systems are performed without solar heating systems. It is suggested that with solar heating in combination with a boiler, the boiler can be turned off during the summer period and the operation conditions with the lowest efficiency can be avoided. However the solar heating system requires a buffer store that may cause further heat losses from the system; therefore this is uncertain.

This article focuses on how the efficiency and CO-emissions of a combined solar and wood pellet heating system is influenced by different system designs, control strategies and different construction parameters like boiler characteristic and store heat loss coefficient, etc.

1.1 Previous work

A study by [16] and [18] using a TRNSYS model to simulate a wood pellet stove [12, 13] have shown that the annual efficiencies of water jacketed stoves can be increased significantly if modulating power control is applied (combustion power varying with the heat demand). It is also shown that the annual efficiency at full power is not at all representative of the annual efficiencies, which can be both higher and lower. [5] compare the efficiency between boilers and stoves and the results indicate that a system with only a simple stove and a solar DHW-system has the highest annual efficiency compared with water jacketed stoves or boilers. However the conclusions drawn by [5], that the use of modulating power control decreases the efficiency for a system with a water jacketed stove, are contrary to those of [16], [18].

The main reasons for these differences are that the combustion air settings (air factor) for low combustion power is much higher and that the savings in the number of starts and stops are much smaller in the study from [5]. [5] used a one-zone house model whereas [15] and [17] used a multi-zone model. The discrepancy in the results means that it is difficult to draw generalized conclusions and that further studies are required to understand how different characteristics of stoves and boilers influence the annual efficiency of wood pellet heating systems.

[19] measured and simulated solar heating systems with boilers and concluded that the fuel savings for oil boilers and gas boilers can be larger than the solar gain if a solar heating system is connected to the boiler. This is because electricity is used as backup heating and the boiler could be turned off completely during the summer period. Also [3] measured very low efficiency of boilers during summer conditions.

Results from [9] indicate that the total system heat losses of wood pellet boilers during winter conditions always increase if a buffer store is connected; however emissions may decrease for burners operating in on-off mode, due to fewer starts and stops. Modulating operation of the burner seems to increase the efficiency of a boiler connected to a store during winter conditions

2 METHOD

Measurements of the wood pellet boiler Thermia Biomatic (Also tested by [10]) were used to find parameters for the dynamic boiler model TRNSYS Type 210 [12], [13]. This boiler is designed to be coupled to a buffer store and has relatively small water content (50 l). A full description of the parameter identification process and the parameters of the boiler model are given by [17]. The boiler model simulates the start and the stop sequences as well as the thermal capacity of the boiler, and the characteristic of the boiler model is illustrated in Fig 1. It takes 5.9 hours (105 MJ fuel) of constant operation at a combustion power of 5 kW to create the same amount of CO-emissions as one start and stop. For 12 kW the values are 13.4 hours and 580 MJ fuel.

The boiler model was implemented in a model of a complete solar heating system for a single-family house (Fig. 2) using the dynamic simulation program TRNSYS [7]. Different control algorithms and different hydraulic connection principles of the boiler were tested to try to increase the annual boiler efficiency and decrease the emissions. Also parametric studies were performed for important boiler parameters such as air factor and heat loss coefficients.

NOMENCLATURE

UA	Heat loss coefficient [W/K]
W_{DHW}	Heat used for domestic hot water [J]
$W_{el,aux}$	Auxiliary electricity used in buffer store [J]
$W_{el,boil}$	Electricity used for operation of the burner [J]
W_{pell}	Energy content of combusted pellet [J]
W_{pump}	Electricity used for operation of pumps [J]
W_{rad}	Energy used for radiator heating [J]
$W_{sol,store}$	Heat contribution to store from solar collector [J]
η	Efficiency of the system [-]
η_{el}	Electricity generation efficiency = 0.4 [-]

2.1 Simulation model

The combisystem (Fig. 2) was simulated for the climate of Stockholm, Sweden using synthetic hourly data from [11]. A heat load profile for Stockholm from the Task 26 Project [20], (SFH 60) gives an annual load of 43.9 GJ (12.2 MWh). The design temperature for the radiator heating system is 40°C supply temperature (flow temperature) and 35°C return temperature at design outdoor temperature of -17°C for Stockholm. The supply temperature is adjusted using a four-way valve, (CV3 in Fig. 2) that preferentially takes water from below the auxiliary heated water.

The domestic hot water load is on average 0.2 m^3/day with maximum peak loads of 0.253 kg/s for 0.1 h. The load file is produced by the program from [6]. The hot water load is 11.20 GJ/yr (3.11 MWh/yr). The ambient room temperature is constant 21°C and the heat losses from the system are not included in the heat load and are therefore considered as waste heat.

A typical flat-plate collector of 10 m^2 with optically selective coated absorbers and a slope of 45° towards the south were used for all simulations. TRNSYS type 132 [14] was used for the simulations and the parameters were obtained from [20].

The buffer store has been simulated using the non standard TRNSYS Type 140 [4]. The store is a typical Swedish buffer store with internal heat exchangers for collector circuit and domestic hot water preparation. Parameters have been taken from a parameter identification study for this type of store, "SERC3", by [1]. The heat exchanger preheating the domestic hot water has been moved down to the bottom of the store as recommended by [8] and the heat loss coefficient has been taken from "SERC1" [1]. A well insulated store with connection pipes going down to the floor under the insulation. The heat loss coefficient for "SERC3" is extremely low and is not considered to be possible for real products on the market.

Pipes in the collector circuit and in pipes between the boiler and the buffer store are simulated using TRNSYS type 31 [7], which takes into account the thermal capacity of the water and the heat losses, but not the heat capacity of the pipe material and the insulation. Heat loss coefficients for the pipes are obtained from [16]. All pipes are insulated with 19 mm of insulation.

The valve controlling the input temperature to the boiler (CV1 in Fig. 2) is modelled as a self actuating valve with a set temperature of 65°C causing the input temperature to the boiler to vary between 60 and 70°C depending on the incoming water temperatures to the valve. [15] describes how the valve is modelled. The water flow rate through the boiler is 0.222 kg/s.

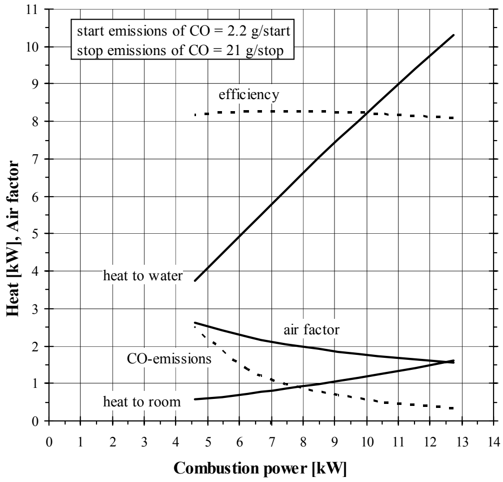

Figure 1: The characteristic of the simulated boiler [17].

The CO-emissions are summed up from the start and stop sequence and from the combustion periods as a function of the combustion power. The stop-emissions for this particular boiler come from a 6 hour long period with glowing pellet bed [17]. The emissions are interrupted if the boiler starts again within this period.

2.2 System concepts

The different system variants that are simulated are described in Table I and the system descriptions V1 to V11 are related to Fig. 2. As a reference system V0 without solar heating only a boiler with built in DHW preparation is simulated. This boiler is simulated using the same parameter settings as is used for the boiler in systems V1 to V11, except from the thermal mass that is three times larger to be able to cover the hot water load. Due to the larger water volume, the heat loss coefficient to the ambient is assumed to be 50% higher. The DHW preparation is simulated using a model of a DHW unit [2]. The boiler is simulated with an ON-OFF operation between 65 and 75°C (V0 in Table I) and with a modulating power control trying to maintain 65°C (V0-M in table I). The boiler starts at 65°C and stops at 75°C if the

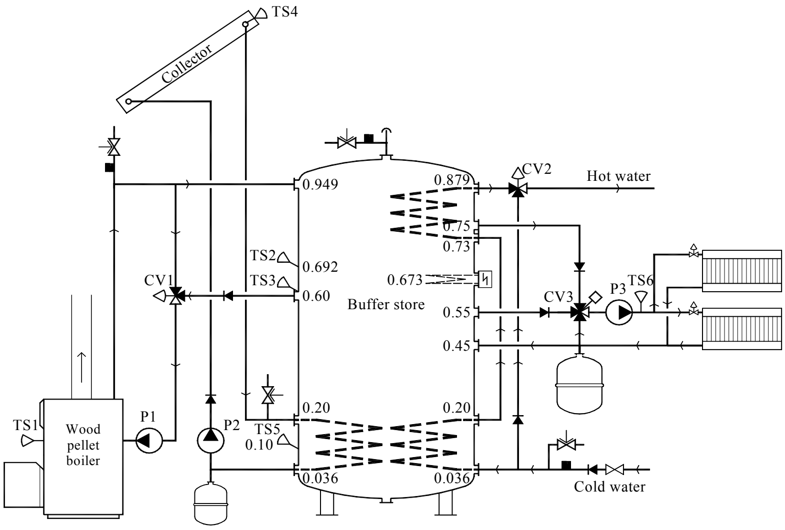

Figure 2: The simulated solar combisystem with connection heights on the store.

Table I: The different concepts that are simulated.

V0	Reference system, wood pellet boiler with ON-OFF control (65 to 75°C) without solar and buffer store.
V0-M	As V0, but with a modulating power (variable heat rate) trying to keep the boiler at 65°C. ON-OFF: 65 to 75°C.
V1	As Fig 2, with ON-OFF control using TS1 between 61 and 71°C. Continuous operation of pump P1 and no electric auxiliary heater.
V2	As V1, but the sensor controlling the boiler is TS2 in the buffer store.
V3	As V2, but the pump P1 is only in operation together with the pellet burner.
V4	As V3, but the electric auxiliary heater is used in the store instead of the boiler during the summer period where ambient temperature is above 10°C and radiator heat load is zero.
V5	As V4, but the pump P1 operates for 0.5 hour after the burner stops to take care of the after burning heat.
V5-M	As V5, but with a modulating power to maintain 61°C at TS2. Start on 61 and stop on 71°C.
V5-Ma	As V-5M, but the stop temperature is 66°C.
V6	As V5, but TS2 is used to start the burner on 61°C and TS3 to stop the burner on 71°C.
V7	As V6, but with a new control and connection strategy that cools the boiler after the burner stopped using cold water from the bottom of the buffer store. The boiler is again filled with hot water from the store when the burner starts to avoid cold starts every time.
V8-M	As V5-M, but only half as much heat losses from the boiler to the room.
V9-M	As V8-M, but 70% lower air leak flow rate through the boiler at no combustion periods.
V10-M	As V9-M, but the lowest possible heat loss coefficient for a 750 l buffer store, UA = 1.44 W/K [1].
V11-M	As V10-M, but only 10 litres boiler water volume instead of 50 litres. 140 kg of steal is remained.

temperature rises above 75°C though the boiler operates at minimum combustion power.

The basic combisystem (Fig. 2 and V1 in Table I) uses a simple on-off control for the burner using temperature sensor TS1 in the boiler (61°C to 71°C). The pump P1 operates continuously. Further changes to the system concept are described in Table I.

3 SIMULATION RESULTS

The simulated annual energy values, system efficiency emissions and energy costs for the different system concepts are given in Table II. The efficiency is defined as

$$\eta = \frac{W_{DHW} + W_{rad}}{W_{pell} + \dfrac{W_{pump} + W_{el,aux} + W_{el,boil}}{\eta_{el}} + W_{sol,store}} \qquad (1)$$

The reference system V0 without solar heating uses 82.0 GJ wood pellets per year and the overall efficiency is 63%. The annual CO-emissions are 60.1 kg and the dominating part (50.5 kg or 15 g/stop) comes from the stop sequence. This is smaller than the value in Fig. 1, which means that many stops are truncated by a new start. This is relatively high stop emissions compared to many other burners or stoves which can be from 1.2 to 6.4 g/stop [17]. The stop emissions are high because the pellets feeds from below and when the burner stops the pellets left in the feeder are slowly combusted. Maybe emptying the feeder completely at high combustion power at every stop would reduce CO-emissions effectively. During operation the boiler has extremely low CO-emissions compared to the other boilers and stoves tested by [17], however this has small influence as the stop emissions dominate completely.

Due to the very large emissions during the stop sequence, the major savings in CO-emissions can be achieved by reducing the number of starts and stops. The modulating power control is therefore a successful method to reduce CO-emissions, see V0-M and V5-M in Table II. To effectively reduce the number of starts and stops when combining the boiler with a solar heated buffer store and using ON-OFF control the sensor controlling the boiler must be placed in the buffer store, or use of modulating power (V2 and V5-M in Table II). To effectively reduce the heat losses from the boiler when combining with solar heating, the pump P1 should be turned off when the boiler is not in operation and a one way valve blocking self circulation should be mounted in the pipe. (V3 in Table II), but preferable be in operation

Table II: The simulated annual pellet and electricity demand, heat losses, the number of starts and stops, CO-emissions and annual energy costs assuming a wood pellet price of 0.4 SEK/kWh and an electricity price of 0.95 SEK/kWh [10], [16].

	Solar heat to store [GJ/yr]	Pellet heat [GJ/yr]	Electricity [GJ/yr]	Heat to boiler room [GJ/yr]	Heat to flue gas [GJ]	System eff. [%]	Number of starts [-]	CO start [kg/yr]	CO operation [kg/yr]	CO stop [kg/yr]	CO total [kg/yr]	Energy-cost [SEK/yr]
V0	0.0	82.0	2.3	23.7	5.3	63%	3 352	7.4	2.2	50.5	60.1	9 726
V0-M	0.0	78.8	2.1	20.4	5.2	65%	1 601	3.5	15.1	27.2	45.8	9 311
V1	12.7	62.8	5.3	22.4	4.0	62%	5 698	12.5	0.9	60.0	73.4	8 386
V2	12.7	64.5	4.8	23.0	4.7	62%	1 447	3.2	2.0	25.1	30.3	8 448
V3	11.3	63.8	3.1	18.8	4.3	66%	2 992	6.6	1.6	37.2	45.4	7 909
V4	11.3	63.1	3.3	18.4	4.2	67%	2 972	6.5	1.6	36.7	44.8	7 886
V5	11.3	61.9	3.3	17.8	4.0	68%	1 758	3.9	1.8	28.0	33.7	7 761
V5-M	11.3	60.3	3.5	16.5	3.7	69%	675	1.5	11.6	11.5	24.6	7 624
V5-Ma	11.4	60.1	3.6	16.5	3.6	68%	1 331	2.9	9.1	19.0	31.0	7 622
V6	11.3	62.9	3.2	18.3	4.3	67%	1 437	3.2	2.0	24.6	29.7	7 842
V7	9.8	62.6	2.9	16.7	3.8	69%	1 066	2.3	2.0	19.8	24.2	7 729
V8-M	11.3	55.7	3.4	11.9	3.6	73%	816	1.8	10.8	13.6	26.2	7 102
V9-M	11.3	55.5	3.5	12.0	3.3	73%	819	1.8	10.8	13.7	26.2	7 075
V10-M	10.8	54.8	3.3	10.7	3.3	75%	815	1.8	10.7	13.5	26.0	6 963
V11-M	10.8	54.5	3.3	10.4	3.2	75%	852	1.9	10.7	13.9	26.5	6 929

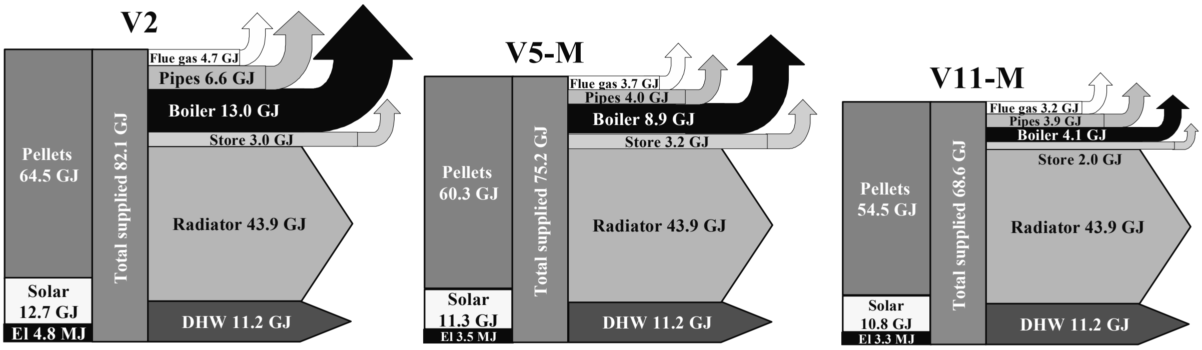

Figure 3: The simulated energy balance in the systems V2, V5-M and V11-M from Table I.

for some time after the burner has stopped to better utilize the energy from the boiler (V5 in table II). To avoid that the boiler starts up just to deliver a very small amount of energy, it can be better to use electricity during the summer period (V4 in Table II). It can be seen that the energy savings (pellets + electricity) is much larger than the solar contribution comparing V0 with V5.

The use of a second temperature sensor to stop the burner (V6 in Table II) decreased the number of starts and stops, but increased the pellet consumption as the auxiliary heated part of the store is larger and hotter on average. It is likely that stratified discharge using external DHW units, heights of connections, heat exchangers and sensors influence the number of starts and stops with a one sensor control, and further simulations should be performed to investigate if and when a two sensor control is motivated.

The advanced charge and discharge strategy (V7 in Table II) does not seem to save any wood pellet, however a small saving in CO-emissions could be seen as the number of starts and stops decrease.

The saving in pellet fuel that is achieved by the actions in V8-M to V11-M in Table II show the potential for further possible development of the boilers and stores including better insulation of stores and boilers, lower leak flow rates and smaller water volume in the boiler. Better insulation of the boiler seems from the simulations to be the most important parameter as the buffer store is already well insulated. Minimising the leakage losses would have a larger influence using the ON-OFF control as stand by time would be longer.

Fig. 3 shows diagrammatically the differences between the basic solar heating system (V2), the advanced control version (V5-M) and a hypothetical case with lower boiler and store losses as well as small water volume in the boiler (V11-M). The majority of the energy savings are due to reduced losses in the boiler and store, which can be accomplished by both physical measures and improved control. Fig. 4 show how the store heat losses and energy cost is influenced by the heat loss coefficient of the buffer store. By improving the insulation from 6 W/K (which is common today) to 2.6 W/K approximately 350 SEK/yr can be saved in energy costs. For a heat loss coefficient above 16 W/K the energy cost for the base case system V0-M with only a boiler is the same as for the solar combisystem V5-M.

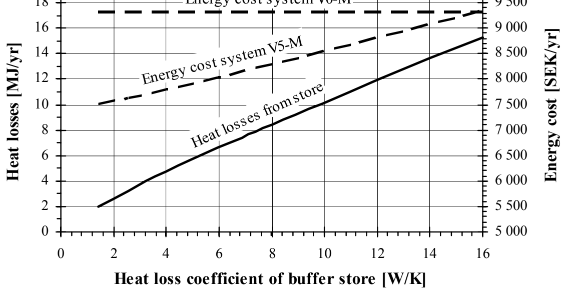

Figure 4: Annual heat losses from store and energy costs as a function of the heat loss coefficient of the store for system V5-M. According to [1] *UA* ≈ 6 W/K corresponds to 100 mm mineral wool + air tight cover + pipe connections straight through insulation. UA ≈ 2.6 W/K corresponds to 150 mm rubber foam + air tight cover + pipe connections under insulation down to the floor.

As a final comparison, versions V5 and V5-M were simulated with other CO-emission factors measured from a prototype boiler "Rebus" by [17]. The results (see Fig. 5) show that the total CO-emissions are significantly lower for the Rebus boiler, due to the much smaller stop emissions. There was very little difference in CO-emissions between the on/off and the modulating control using these parameters.

4 DISCUSSION AND CONCLUSIONS

For the studied boiler and heating systems it was shown that modulating operation of the boiler without thermal storage decreased both pellet consumption by 4% and CO-emissions by 24%. The inclusion of a well insulated thermal store (UA = 2.6 W/K) with 10 m^2 flat plate solar collectors improved the overall system efficiency by up to 8% if ON-OFF control is used as well as reducing pellet consumption by 25% and CO-emissions

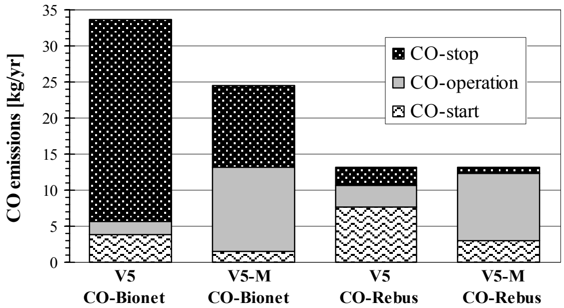

Figure 5: Comparison of annual CO-emissions for the ON-OFF control (V5) and the modulating power control (V5-M) for the boiler used in the study (Bionet) and for the same boiler with other CO-emission factors (Rebus). Rebus has slightly higher emissions during operation and start (4.4 g) but lower stop emissions (1.4 g) [17].

by 44%. Using a proper control strategy and system design and a well insulated store, the energy savings are much larger than the solar gain. This is due to the low efficiency for boilers during the summer and the same trend has previously been reported by [3] and [19] for oil and gas boilers.

By improving the storage heat loss coefficient from today's standard (≈ 6 W/K) to realistic levels (≈ 2.6 W/K), the energy costs can be decreased by 4%. If the store would have a heat loss coefficient of 16 W/K no energy cost savings from the solar heating system would be achieved for the studied system.

The most important factors to achieve high system efficiency are that the boiler and the buffer store should be well insulated. The sensor controlling the boiler should be placed in the store; and the temperature difference between the start and stop temperature should be at least 10°C independently on type of control system (ON-OFF or modulating) the pump should only be in operation when the burner is in operation and for about 0.5 hr after the burner had stopped to take care of the after burning heat. Use of an electric heater in the store instead of the boiler during the summer result in small primary energy savings and energy cost savings. An advanced strategy to discharge the boiler with cold water from the bottom of the store and to fill it again with hot water before the boiler starts could not be proven to save energy.

Use of modulating power control may increase the system efficiency; however this is dependant on the power dependency of the air factor and the flue gas temperature and the leakage losses and needs further investigations. For boilers with relatively large start and stop CO-emissions and if the emissions at low combustion power also are low, modulating power may be an efficient measure to reduce CO-emissions.

An important result is also that the total CO-emissions from a residential pellet boiler cannot be estimated only from looking at the emissions during operation. Especially for boilers using an ON-OFF control, the dominating contribution of CO-emissions may be during the start and stop phases.

ACKNOWLEDGEMENTS

This work has been financed by Formas (the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning) and Högskolan Dalarna, Sweden. We are grateful to Thermia for providing the Bionet boiler used for measurements in this study and to Thorsten Gerberich from Germany, who performed the measurements during a practical semester at SERC.

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