ENERGY EFFICIENCY OF COMBINED PELLETS AND SOLAR HEATING SYSTEMS FOR SINGLE FAMILY HOUSES

Haller M.

Institute of Thermal Engineering IWT, Graz University of Technology, Inffeldgasse 25/B, A-8010 Graz, Austria;
phone:+43 316 873 7318, fax:+43 316 873 7305, email: michel.haller@tugraz.at

Konersmann L.

SPF Institut für Solartechnik, Oberseestrasse 10, CH-8640 Rapperswil, Switzerland;
phone: +41 55 222 4827, fax: +41 55 222 4844, email: lars.konersmann@solarenergy.ch

ABSTRACT: The potential for combined biomass and solar heating systems for domestic hot water preparation and room heating is large. The energetic performance of these systems is largely influenced by hydraulic setup and control. The effect of these interactions has been evaluated with dynamic system tests in the laboratory. Simulations were performed with a measurement-validated model to assess the annual performance of different system-setups. Based on results obtained from pellet boiler measurements a new model for the boiler was elaborated, taking into account reduced efficiency under part load operation and increased electricity use in on/off cycling operation. System tests and simulation results have shown that the use of solar thermal energy in combination with a pellet heating system reduces burner starts, fuel use and electricity consumption considerably. The combined system was synergetic because solar gains reduced inefficient boiler operation during spring, summer and autumn. Thus the annual pellet boiler efficiency was higher in combination with a solar thermal system than without. Using the solar store to buffer heat from the small pellet boiler was not advantageous for the investigated system from an energy efficiency point of view. It was shown that over-dimensioning of the boiler has strong negative impacts on the overall system efficiency and on on/off-cycling rates.
Keywords: solar energy, biomass energy, pellets, residential heating, energy efficiency

1 INTRODUCTION

The Austrian Ministry of Agriculture, Forestry, Environment and Water Management has set the goal to increase biomass heating from 81 PJ in 2000 to 130 PJ in 2020 [1]. This corresponds to about 29% of the total heat demand for room heating and domestic hot water (RH & DHW) in Austria today. Following the trend of recent years, the largest increase in biomass heating is expected to be for pellet and wood chips fuels, whereas the use of log wood heating systems is not expected to increase at all. If all of these biomass heating systems were combined with solar thermal systems, the combined solar and pellet heating systems could cover more than 40% of Austria's current RH & DHW demand. If better insulation standards and heat recovery technologies will reduce the total need of energy resources for RH & DHW, the share covered by pellet and solar heating systems could even be far higher.

A pellet heating system and a solar thermal system may be combined to serve the domestic needs of RH & DHW in a number of varying configurations. The overall system performance thereafter is largely influenced not only by the performance of individual components but also by the interactions between them, i.e. the hydraulic setup and control. The effect these interactions have on the annual performance can be evaluated with short system tests in the laboratory, and subsequent annual simulations using a model that has been verified with the preceding system tests. In this paper the energetic optimization of a combined solar and pellet heating system based on laboratory tests and system simulation is described. Laboratory work has been performed at SPF, Switzerland, and simulation models have been developed in cooperation between IWT, Austria, and SPF [2].

2 METHODS

The procedure and the methods applied in this research project are shown in Fig. 1. In the first step, the efficiencies of a 10 kW pellet boiler were determined under full load, part load and on/off cycling operation. In addition, a "cooling out" test was performed similar to the heat loss tests for solar hot water stores [3].
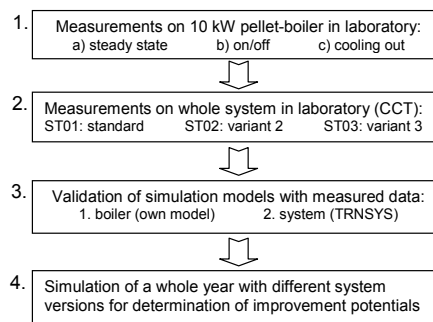

Figure 1: Schematic presentation of procedure and methods

The boiler was then combined with a solar thermal system and a full system test of 12 days under realistic weather (solar collector input) and load conditions was performed according to the "concise cycle test" procedure (CCT) described in [4][5][6][7] (second step). Each of the twelve test days within the CCT represent a typical day from the respective months. The CCT was performed for three varying system hydraulic and/or control configurations (ST01 – ST03) in which the solar collector field, the building interaction and the domestic hot water (DHW) consumption were simulated in "real time" with TRNSYS [8] and emulated in direct interaction with the installed system. Fig. 2 shows the schematic of the CCT.

Simulation models for the boiler and overall system were established and verified (third step) based on parameters acquired from the measurement results (boiler and CCT) . A new model of the pellet boiler has been developed that is able to reproduce part load efficiency as well as on/off cycling operation and their influence on thermal efficiency and electricity use. The boiler model was linked into the simulation software TRNSYS [8] in order to model the whole heating system, including the building.

Annual simulations (fourth step) were performed with the system model from which the influence of changes in system parameters (e.g. hydraulics and control) on the overall performance of the system was studied.
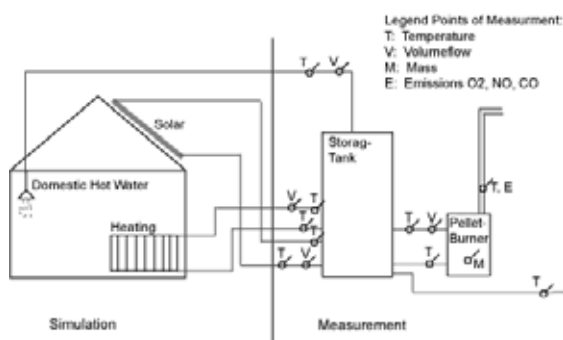

Figure 2: Scheme of the system test, adapted from [4].

3 RESULTS

3.1 Boiler measurements

Boiler measurements have shown that the flue gas temperature decreases considerably going from full load to part load operation. Nevertheless combustion efficiency does not improve at part load due to the associated increase in the excess air factor (lambda) seen in Fig. 3.
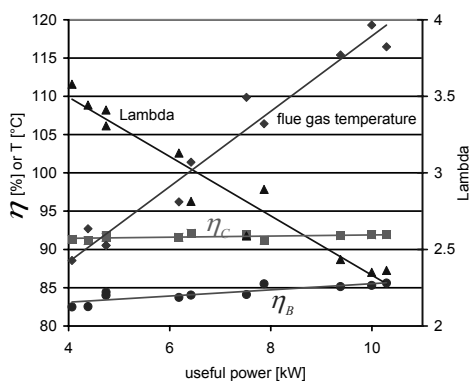

Figure 3: Combustion efficiency (η_C), boiler efficiency (η_B), excess air factor (lambda) and flue gas temperature for the analyzed pellet boiler at different loads under steady state conditions. Points are measurement results, lines are trends.

The decrease in boiler efficiency at part load operation is due to the fact that heat loss to the surrounding increases proportional to the difference in temperature between the boiler and its surrounding. Since this temperature difference does not change much by

partial loads. losses to the surrounding remain relatively constant in absolute terms. Therefore, relative heat losses are increasing with decreasing burner power.

A comparison between two tests performed at an average of 30% of the nominal power revealed that the thermal efficiency of an intermittent operation (1 hour on, 1 hour off) was about the same as under steady modulating operation at 30% of the nominal power. However, energetic performance of the intermittent operation was lower than that of the steady operation when electricity use was accounted for. The primary cause for this was the electric energy used for ignition at each start of the burning process. If the heat load was reduced to 10% of the nominal power, heat losses to the surrounding as well as electricity use for burner ignitions became increasingly important and reduced the measured efficiencies of the pellet boiler substantially (Table I).

Table I: Thermal efficiency and efficiency including electricity consumption of the measured pellet boiler under different heat loads.

	10 kW STEADY	3 kW STEADY	3 kW ON/OFF	1 kW ON/OFF
useful heat delivered	10.3 kW	3.01 kW	2.95 kW	1.00 kW
thermal efficiency	85.6%	82.8%	83.9%	62.3%
average flow temperature	59.1 °C	61.3 °C	54.4 °C	70.8 °C
electric power consumption	170 W	95 W	172 W	170 W
efficiency including electricity use *	82.1%	76.8%	73.2%	47.3%

* electrical energy was weighted with a factor of 3.

3.2 Boiler modeling

In order to be able to simulate the boiler performance at full load, part load and in on/off cycling operation, a new boiler model was developed, programmed and linked into the systems simulation software TRNSYS. The main concept of the model has been based on recommendations from [9] and is displayed in Fig. 4. The general simplifying assumption has been made that steps two and three of the model calculation do not affect the previous steps. Thus, no recursions to previous steps are necessary.
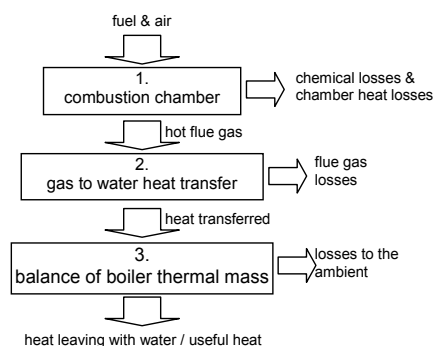

Figure 4: General concept of the pellet boiler model.

In the first stage of the pellet boiler model the combustion chamber was considered to have heat losses that are proportional to the fuel use and the hot flue gas is assumed to be at the adiabatic combustion temperature.

The flue gas to water heat transfer has been calculated according to the effectiveness-NTU method as proposed by Lebrun et al. [10] for fuel oil space-heating

boilers (second stage). In contrast to the counter-flow arrangement used for the choice of the effectiveness relationship by Lebrun et al. for the fuel oil boilers, parallel flow or shell and tube with one shell pass (water) and two tube passes (flue gas) were better able to predict the flue gas temperature at the boiler outlet in the case of this pellet boiler (Fig. 5). This was also expected from the known construction scheme of the boiler. Flue gas losses in steady state were calculated based on the flue gas temperature, fuel composition and excess air ratio.
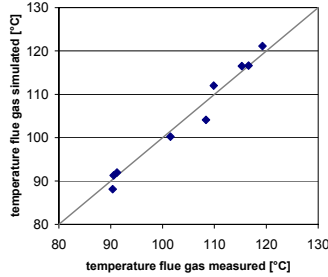

Figure 5: Measured and simulated flue gas temperatures at the boiler exit under steady state operation.

In the third stage of the model, the thermal mass of the boiler was simulated with a one-node approach assuming a uniform temperature of the boiler thermal mass that is time dependent according to:

$$T(t) = T_{inf} + (T_{inf} - T_0) \cdot EXP\left(\frac{UA_b + \dot{m}_w \cdot c_w}{m_b \cdot c_b} \cdot t\right) \quad (1)$$

where:
T   temperature, K
t   time, s
T_0 temperature at t=0, K
T_{inf} temperature the boiler would reach after an infinite time of operation under the given boundary conditions, K
UA_b overall heat loss coefficient times effective area of the boiler surface, J/sK
m   mass, kg
$\dot{m}$ mass flow, kg/s
c   (average) specific heat, J/kg K
w   water flowing through the boiler
b   boiler (mass and average specific heat both including water content)

For transient boiler simulations, stage 1 and stage 2 where calculated for steady operation under the given boundary conditions, and only stage 3 was assumed to be time dependent and therefore calculated according to Eq. (1).

3.3 System measurements with CCT

A total of three 12-days tests were performed according to the CCT method. For each of the three system tests, the following efficiency indicators (Eq. 2-5) were calculated based on space heating demand (Q_{SH}), domestic hot water demand (Q_{DHW}), energy input from pellet fuel (E_{Pellet}), heat input from solar collectors (Q_{Solar}), electricity consumption (E_{el}), and a factor for the weighting of electricity (F_{el}=3). Selected results are summarized in table II.

$$\eta_{S,pe} = \frac{Q_{SH} + Q_{DHW}}{E_{Pellet}} \quad (2)$$

$$\eta_{S,pe+el} = \frac{Q_{SH} + Q_{DHW}}{E_{Pellet} + F_{el} \cdot E_{el}} \quad (3)$$

$$\eta_{S,pe+so} = \frac{Q_{SH} + Q_{DHW}}{E_{Pellet} + Q_{Solar}} \quad (4)$$

$$\eta_{S,pe+el} = \frac{Q_{SH} + Q_{DHW}}{E_{Pellet} + Q_{Solar} + F_{el} \cdot E_{el}} \quad (5)$$

Table II: Selected results of the three 12-days tests according to the CCT method. Definition of efficiency parameters is given in section above.

	ST01 base case	ST02 variab. flow	ST03 direct feed, const. flow
number of starts	36	24	28
$\eta_{S,pe}$	102.1%	100.0%	103.5%
$\eta_{S,pe+el}$	85.8%	85.1%	87.3%
$\eta_{S,pe+so}$	75.1%	74.8%	76.6%
$\eta_{S,pe+so+el}$	65.8%	66.1%	67.4%
average solar store temperate	47.9 °C	50.1 °C	45.2 °C

The base test (ST01) confirmed the reliable functioning and good performance of the pellet and solar heating system as it was proposed by the manufacturer. The base system consisted of a 900 liter solar combistore filled with water from which heat for space heating and domestic hot water preparation was withdrawn. Solar heat was transferred to the store with two immersed heat exchangers in the upper and in the lower part of the store respectively. The pellet boiler was connected to the store, and equipped with a mixing circuit to maintain the minimum required return temperature to the boiler.

In the second test (ST02) the boiler circuit was equipped with a variable flow pump that was controlled according to the building heat load in order to be able to use the full range of boiler modulation. As expected this lead to a remarkable decrease in boiler starts and stops but an improvement of thermal performance was not achieved, mainly because the average temperature of the heat store was higher in this test, causing higher heat losses and reducing the efficiency of solar heat input.

For the third test (ST03) the boiler was feeding the heating circuit of the building directly. Heat transfer from the pellet boiler to the solar store was only used for domestic hot water preparation in times of low solar heat input. On the other hand, heat demand of the building was served with priority from solar heat in the store, and the pellet boiler was used only when this was insufficient. With this hydraulic setup, boiler starts were considerably less than in the base case, but not as few as in the optimized case with use of the buffer store. However, thermal performance was best for this case as the boiler was able to react more precisely to the heat load and storage temperatures where kept lower than in the other two tests.

3.4 System simulation

With the system simulation software TRNSYS, the complete solar pellet system was modeled and the model was compared day by day with the results of the 12-days tests (third step of Fig. 1). A whole year was then simulated with the system using weather data for Zurich, Switzerland. General parameters of the system are shown in Table III.

Table III: General parameters of the one year system simulations.

load		
space heating	150	m^2
	103	kWh/a m^2
	15'500	kWh/a
domestic hot water	2'800	kWh/a
pellet boiler		
power range	3-10	kW
solar thermal system		
store volume	900	liter
collector area	15	m^2
collector type	flat plate	
weather data		
location	Zurich/ CH	
irradiation on collector field	1250	kWh/m^2 a

From the results of the annual simulations it was concluded that the tested pellet and solar heating system uses 27% less fuel as compared to a pellet heating system with the same boiler but without the solar thermal collectors and without the heat store. More fuel was saved than could be expected from the value of the net heat input from the solar collectors. This was for two reasons: first, the energy contained in the pellet fuel was converted to useful heat with an average efficiency of 80% in the base case. Second, the seasonal efficiency of the pellet boiler increased by 3% (relative) due to the fact that in combination with the solar thermal system, the pellet boiler could be shut off during extended periods in spring, summer and autumn. As heat load is lowest and standby periods longest during these seasons, boiler efficiency is lowest during these seasons too. At the same time, 17% of electricity consumption was saved due to the fact that total electricity use for the solar pump was considerably less than the electricity spared by not running the boiler during times with sufficient solar heat. Also the number of burner on/off cycles was reduced by 25%.
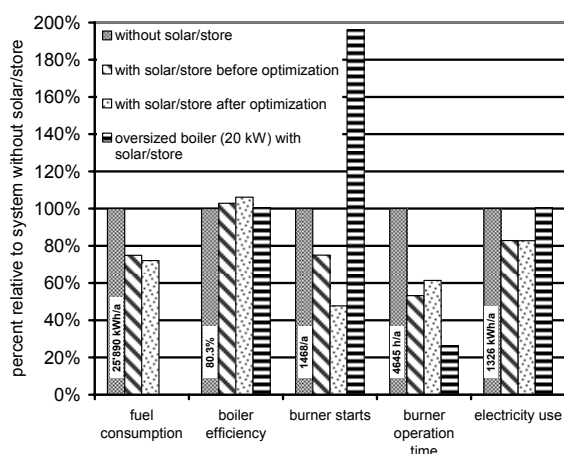

Figure 7: Relative performance of two systems with solar/store compared to a system without solar/store. The optimized system had variable flow in the boiler circuit, better insulation, and lower excess-air for combustion. Fuel consumption is not shown for the system with the oversized pellet boiler since this system was delivering substantially less energy for room heating due to the time needed to switch the burning process off and on again.

Further simulations showed that the tested pellet and solar heating system could be improved with the following adjustments:

- using the boilers full modulation range (by variable flow)
- better insulation of pellet boiler and pipes
- better insulation of heat store
- reduction of excess-air for combustion (lambda = 2.3 for full and part load)

With these improvements, pellet fuel savings were 32%, and burner on/off cycling was reduced by more than 50% compared to the system without solar (Fig. 7). In this case seasonal boiler efficiency was 6% (relative) better than in the system without solar.

Simulations with a system containing an over-dimensioned boiler (20 kW instead of 10 kW) showed that this had a strong negative influence on the number of starts and stops, the annual efficiency and the electricity use of the pellet boiler (Fig. 7).

4 CONCLUSIONS

If a boiler is operated within its range of modulation exhaust gas losses usually predominate. However, if heat load is decreased far below nominal power, losses to ambient that depend on the temperature of the boiler water will remain constant, whereas the heat load and thus the useful energy are reduced. In this case, losses to the ambient may exceed exhaust gas losses by far for a small pellet boiler. Additionally, electric startup ignition may increase electricity use considerably if frequent on/off cycling is taking place. With the new boiler model developed within this project, these effects and the dynamic behaviour of a pellet boiler were reproduced well in simulations.

Pellet boilers usually require minimum return and minimum flow temperatures to avoid condensation of water vapour in the flue gas heat exchanger. The mass flow of heating water through the boiler is often fixed as well. These three parameters define the actual minimum boiler power that can be achieved without raising the return temperature further. For this reason in practical installations, boiler modulation may not go down to the minimum power the boiler is capable of providing without on/off operation, but rather to the minimum given by the hydraulic setup. In this case, an adjustable flow in the boiler circuit makes it possible to use the full modulation range.

If a pellet boiler is combined with a reasonably sized solar thermal system for SH & DHW, about 25-32% of pellet fuel may be saved in a moderately insulated single family house located in Central Europe. It has been shown that pellet fuel savings may be far higher than solar gains. This is for various reasons:

- Energy contained in the pellet fuel is only converted to "useful heat" with an efficiency of 80-90%, whereas energy input from solar collectors is used more efficiently.
- Annual efficiency of the boiler is increased if it is combined with a solar thermal system. The reason for this is that the boiler can be shut off completely during spring, summer and autumn if solar heat is sufficient during these seasons. These are the seasons where the boiler is most inefficient because of little heat load and long standby periods. Therefore, the average boiler efficiency increases.
- The number of starts and stops of the boiler is reduced

much more than the fuel use. This is also true for cases where the boiler is not using the heat store as a buffer. Thus, electricity consumption may well decrease after installing a solar thermal system since electricity spared by the reduction of burner starts and runtime may be more than electricity needed to run the solar pump.

Care has to be taken to choose the proper control of the heat input from the boiler to the heat store. A temperature sensor within the store is indispensable for proper control. A suitable hysteresis has to be chosen to switch the boiler on and off depending on the temperature in the store. The lower the hysteresis, the more the boiler will cycle. The higher the hysteresis, the more the temperature of the store will be raised and its heat losses increased. It has been shown that loading the solar heat store by the pellet boiler may decrease the overall thermal efficiency because of two effects caused by higher store temperatures:
• higher heat losses of the store
• reduced efficiency of solar collectors (higher return temperatures), and less potential for heat input from solar collectors.

Therefore, using the solar heat store for buffering heat from a pellet boiler is not necessary in cases where the pellet boiler is not oversized with respect to the heat demand.

Oversizing the boiler compared to the heat demand of the building results in frequent on/off cycling of the burner and lower system performance, including also higher electricity consumption.

Optimizing hydraulics and control of a combined solar and pellets heating system reduced pellet fuel demand and boiler cycling considerably, even for the case of a well working system.

ACKNOWLEDGEMENTS

REFERENCES
[1] Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (BMLFUW). Nationaler Biomasseaktionsplan für Österreich – Begutachtungs-entwurf, 2006
[1b] L. Konersmann, M. Haller, PelletSolar - Leistungsanalyse und Optimierung eines Pellet-solarkombinierten Systems für Heizung und Warmwasser – Schlussbericht BFE, http://www.bfe.admin.ch/ dokumentation/energieforschung/index.html?lang=de, 2007
[1c] prEN12977-3:2006, Thermische Solaranlagen und ihre Bauteile – Kundenspezifisch gefertigte Anlagen – Teil 3: Leistungsprüfung von Warmwasserspeichern für Solaranlagen, CEN, Brüssel

[4] SPF Institut für Solartechnik, Jahresleistungs-ermittlung von Solarsystemen mit der Concise Cycle Test (CCT) Methode, http://www.solarenergy.ch/publ/ systeme/KombiPruefmethodeCCT.pdf, 2004
[5] P. Vogelsanger, M. Haller, Beitrag 15. Symposium Thermische Solarenergie (Bad Staffelstein), Kompakte Kombisysteme auf dem Prüfstand unter Einbezug der Zusatzheizung, 27. 4. 2005
[6] SPF Institut für Solartechnik, Das Pilot- und Demonstrationsprojekt Kombi-Kompakt+ , http:// www.solarenergy.ch/publ/systeme/KombiKompakt.pdf, 2004
[7] SPF Institut für Solartechnik, Referenzbedingungen: Klima, Wärmelast, Kollektorfeldausrichtung und Referenzsystem zur Leistungsbestimmung von Heizsystemen für Raumheizung und Wassererwärmung, http://www.solarenergy.ch/publ/systeme/Referenzbeding ungen.pdf, 2004
[8] S.A. Klein et al. TRNSYS 16, a transient system simulation program – reference manual. Solar Energy Laboratory University of Wisconsin – Madison, http://sel..me.wisc.edu/trnsys, USA, 2000
[9] ASHRAE Handbook of Fundamentals, SI-Edition, Chapter 32 – Energy estimating and modeling methods, 2005
[10] J. Lebrun, C. Saavedra, F. Hore, M.M. Grodent, P. Nusgens (1993) Testing and modeling of fuel oil space-heating boilers – synthesis of available results, ASHRAE Transactions 99(2), pp. 455 – 464