HEAT LOSSES AND THERMAL PERFORMANCE OF COMMERCIAL COMBINED SOLAR AND PELLET HEATING SYSTEMS

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Abstract - Various pellet heating systems are marketed in Sweden, some of them in combination with a solar heating system. Several types of pellet heating units are available and can be used for a combined system. This article compares four typical combined solar and pellet heating systems: System 1 and 2 two with a pellet stove, system 3 with a store integrated pellet burner and system 4 with a pellet boiler. The lower efficiency of pellet heaters compared to oil or gas heaters increases the primary energy demand. Consequently heat losses of the various systems have been studied. The systems have been modeled in TRNSYS and simulated with parameters identified from measurements. For almost all systems the flue gas losses are the main heat losses except for system 3 where store heat losses prevail. Relevant are also the heat losses of the burner and the boiler to the ambient. Significant leakage losses are noticed for system 3 and 4. For buildings with an open internal design system 1 is the most efficient solution. Other buildings should preferably apply system 3. The right choice of the system depends also on whether the heater is placed inside or outside of the heated area. A large potential for system optimization exist for all studied systems, which when applied could alter the relative merits of the different system types.

KEYWORDS: Pellet heating systems, heat losses, flue gas losses, leakage losses

1. Introduction

A variety of system concepts for solar heating systems for new one- and two-family houses can be found on the European market. In Sweden electrical heaters are often used as the auxiliary heat source but the use of wood pellets in pellet stoves and pellet boilers is becoming more and more popular. Sweden is already today the most developed European market for pellet heating systems for one-and two-family houses. Approximately 30000 pellet heating units have been installed by the end of 2001 (Hadders, 2002). There are several Swedish manufacturers active on the market but also a number of manufacturers from other countries. For this study two Swedish, one Finnish and one German product, all marketed in Sweden, have been investigated.

The efficiency of pellet heaters varies significantly between different manufactures and designs and is due to the more complex combustion of the wood fuel, and is generally lower than for comparable gas or oil boilers (Fiedler, 2004). For this reason the heat losses from these units are important parameters to evaluate the complete heating system.

2. Method

The systems investigated in this work are considered to represent typical solutions within a wide range of design variants. The systems are for the most part taken as they can be found on the market whereas system 4 is somewhat an exception. This system is
not available as a complete system but at least the pellet boiler and the store are standard products.

This study uses the results of comprehensive measurements on two pellet stoves, one pellet boiler and a storage integrated pellet burner at the Solar Energy Research Center SERC. Several tests have been performed to evaluate the performance of these units and to acquire data enabling an identification of characteristic parameters (Nordlander and Persson, 2003). The investigated system designs have been modeled in the simulation environment IISiBat/TRNSYS (Klein et al., 2002) based on a simulation model created for IEA task 26 Solar Combisystems (Bales, 2003). The same house model (Streicher and Heimrath, 2003) and other standard boundary conditions have been applied.

For the modeling of the pellet heating units TRNSYS type 210 that has been recently developed by Nordlander (2003) has been used. This dynamic model can be used to simulate pellet stoves, pellet burners and to a certain extent also pellet boilers and gives flue gas losses during operation and in standby mode (leakage losses), as well as heat supplied to water in a mantle and to the surroundings. The applied parameters are obtained from the parameter identification and have been validated by simulations comparing simulated and measured data. The models for the pellet heating units have been integrated into the system models and yearly simulations have been performed for a building with an annual heat demand for the Stockholm climate of approximately 12200 kWh (87 kWh/m²) and a hot water demand of 3100 kWh. The results from these simulations have been analyzed and used to compare the four systems.

3. Studied systems

In total four rather different systems have been investigated, two systems with a pellet stove (system 1 and 2), one with a store integrated pellet burner (system 3) and one with a pellet boiler (system 4) (see also figure 2 and table 1).

System 1 is the simplest system using separate units to provide domestic hot water and space heating. A pellet stove transfers the heat to the building by convection and radiation. This requires a building with open interior design in order to allow a good heat distribution to the building. The power of the stove is automatically and continuously modulated according to the room temperature, but has a limiting minimal power. In the specified power operation range between 2 and 6 kW the stove reaches efficiencies between 83 and 89 % under stationary conditions (Persson, 2004). The domestic hot water is provided by a solar hot water system comprising a 280 liter store and 5m² of solar collectors. The solar circuit is coupled to the storage by an immersed heat exchanger in the bottom of the store. The auxiliary heat is provided by a electrical heater in the top third of the store.

System 2 is rather similar to system 1 but the pellet stove delivers heat to the building in two ways: directly by convection and radiation as in system 1; and indirectly through an inbuilt heat exchanger to the water based radiator system. Approximately 80% of the produced heat can be transferred to the radiator system when the stove is operated under stationary conditions with the
maximum combustion power (figure 1). The stove is on/off controlled by the room temperature, operating by default with the maximum power.

System 3 is a solar combisystem with a store integrated pellet burner and a water based radiator system. All required heat for hot water and space heating is taken from the combistore, the water for space heating directly and the domestic hot water by two immersed heat exchangers placed in the bottom and the top of the combistore. The heat from the solar heating circuit is transferred by another immersed heat exchanger to the bottom of the store. The store integrated pellet burner delivers heat by a water to air heat exchanger consisting of horizontal pipes in the upper part of the store. The burner is on/off controlled by a sensor placed in the storage tank above the burner. The pellet burner has a maximum power of 25 kW, enough capacity even for single family houses with a rather high space heating demand. The burner can be adjusted for summer operation to half of the maximum combustion power. The collector area for system 3 and 4 is about 10 m² which somewhat typical for Swedish solar combisystems.

System 4 is also a combisystem but uses an external pellet boiler as the main auxiliary heat source. The pellet boiler is coupled to the store by another immersed heat exchanger in the upper part of the store. The boiler is on/off controlled and has an internal water volume of 140 liter. The boiler contains an integrated heat exchanger for hot water preparation, but his was not used. No connections are available to couple the boiler to a solar circuit. Consequently only the space heating part of the boiler was used and connected to a combistore.

Fig. 2. Investigated system designs. Two systems with a pellet stove (system 1 and 2), one with a store integrated pellet burner (system 3) and one with a pellet boiler (system 4).
4. Modelling in TRNSYS

The modeling of pellets stoves, burner and boiler has been realized with a new TRNSYS-component type 210 that, unlike other models, takes the dynamic behavior during the start and stop phase into account. Type 210 has been developed for pellet burners and pellet stoves and can be even used for boilers where no internal hot water preparation needs to be modeled. The model is calculating the fuel consumption, combustion air flow and the exhaust gas flow and provides data for the delivered energy to the ambient, the heating circuit connected to the water jacket and to the exhaust gas. The model calculates also the air leakage losses when the burner is not in operation, the number of starts and stops and the consumed electricity.

The model separates the pellet heater into two main thermal masses. \( \text{M}_1 \) represents the part of the stove that transfers the heat to the ambient and \( \text{m}_2 \) representing the water jacket of the stove/boiler. Fuel and combustion air entering the stove, combust and form a combustion gas that transfers heat first heat to \( \text{m}_1 \) and then to \( \text{m}_2 \) before leaving the stove. Heat transfer coefficients define the heat transfer between the hot air mass flow, the thermal masses, the ambient air and the fluid in the water jacket.

For the two stoves and the integrated burner verification has confirmed the correctness of the identified parameters. Simulation tests with parameter for the pellet boiler showed good energetic accordance to the measured data, but no exact verification has been performed thus this boiler is being considered as a generic boiler.

<table>
<thead>
<tr>
<th>Table 1. Overview main system size parameter</th>
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<tbody>
<tr>
<td>System 1</td>
</tr>
<tr>
<td>Collector area</td>
</tr>
<tr>
<td>DHW/combi store size</td>
</tr>
<tr>
<td>Store height</td>
</tr>
<tr>
<td>UA-value store top</td>
</tr>
<tr>
<td>UA-value store bottom</td>
</tr>
<tr>
<td>UA-value store sides</td>
</tr>
<tr>
<td>Max. (min.) power pellet heater</td>
</tr>
<tr>
<td>Burner control (manufacturer default)</td>
</tr>
<tr>
<td>Leakage air mass flow at ( \Delta T=50K )</td>
</tr>
<tr>
<td>Max. radiator heating power</td>
</tr>
<tr>
<td>Design temperature radiators</td>
</tr>
</tbody>
</table>

¹ UA-value for the bottom half of the sides
² UA-value for the top half of the sides

System 3 uses type 210 as a pellet burner, where all heat except the heat losses from the burner itself is transferred to the flue gas before entering the air to liquid heat exchanger of the combistore. Consequently the total flue gas losses for this system need to be calculated separately using the exhaust gas temperature of the air to liquid heat exchanger outlet.
\[ Q_{\text{flot}} = m'_{g} \cdot c_{p, g} \cdot (T_{\text{ohxb}} - T_{\text{room}}) \] (3)

where \( m'_{g} \) is during the combustion phase calculated by type 210 and after the burner is out of operation by equation 2 using the temperature difference between the gas leaving the heat exchanger in the store and the outdoor temperature. The leakage losses have been determined by:

\[ Q_{\text{leak}} = \left| m'_{g} \cdot c_{p, g} \cdot (T_{\text{ihxb}} - T_{\text{ohxb}}) \right| \quad \text{for } T_{\text{ohxb}} > T_{\text{ihxb}} \] (4).

A modification has been accomplished for the model of system 3 where the factory settings for the placement of the temperature sensor of the pellet burner have been adapted. The simulations showed that the sensor was placed too far in the top of the store causing a delayed start of the burner and thus giving in the meanwhile the electrical heater the possibility to heat up the store. To prevent the electrical heater turning on during normal operation the sensor was placed lower and also the set temperature of the electrical heater was reduced to 55°C, the same value as for system 4. Moreover the maximum heating power has been simulated with the lower summer adjustment (12 kW).

In the model of system 4 the control settings for the boiler pump have been changed so that almost all the heat of the boilers water volume is transferred to the combistore once it is heated.

For the simulation a one zone building model has been used, which implies that the results for system 1 are only relevant if good heat distribution can be achieved from the stove to the whole building. The losses from the store and, in the case of systems 3 and 4, also from the boiler, are not used as heat input to the building model. The domestic hot water load has been modeled with the load profile developed by Jordan and Vajen (2002) assuming a daily hot water demand of 200 liter. All four DHW-stores and combistores have been model with TRNSYS type 140 (Drück and Pauschinger, 1996).

5. Heat Losses

Four main types of heat losses have been studied in this article. *Flue gas losses* are mainly determined by the construction of the pellet burner, the area of the heat exchanger, the dimensions of the flue gas passages etc. Parameters such as combustion power and the surplus air influence strongly the flues gas losses. Flue gas losses are considered to be *leakage losses* when the burner and the fan have stopped, after the stop phase of combustion has been completed. In order to prevent confusion the flue gas losses are defined as the total flue gas losses minus the leakage losses.

\[ Q_{g} = Q_{\text{flot}} - Q_{\text{leak}} \] (1)

For leakage losses, the air mass flow through the burner is calculated by type 210 as follows:

\[ \dot{m}_{g} = \dot{m}_{g50} \cdot \sqrt{\frac{T_{\text{ob}} - T_{\text{outd}}}{50}} \] (2)

where \( \dot{m}_{g50} \) is the flue gas mass flow at 50 K temperature difference between the gas leaving the burner (\( T_{\text{ob}} \)) and the outdoor temperature (\( T_{\text{outd}} \)). The total leakage losses depend strongly on the thermal mass of the stove or boiler.

The *store heat losses* depend on the quality and tightness of the store insulation, the store envelope area and the temperature difference between the store content and the ambient. The UA-values for the stores that have been used in the simulations can be found in table 1. The values for the hot water stores in system 1 and 2 are based on theoretical calculation, but also match well with UA-values from measurements for rather well insulated DHW-stores (Vogelsanger, 2004). The combistore of system 3 has been tested at SERC and two mantle UA-values, one for the top part where the pellet burner is located and one for the bottom part, have been determined. Also the UA-values for the top
and the bottom of the tank have been obtained from measurements and theoretical calculations. The UA-values for the combistore of system 4 are given by Bales (2003). The boiler/burner heat losses are obtained from an output of type 210 calculated based on identified heat loss coefficients.

6. Simulation Results

The four systems have been simulated for a one year period and the results were summed up to monthly and yearly values. The total flue gas losses are also calculated during off periods of the burner and thus contain the leakage losses.

The simulation results from figure 3 show that the flue gas losses are in a range between 9% and 16% of primary energy for all systems. For system 2 and 4 the highest flue gas losses are observed, also when considering the absolute values in figure 4. When looking at the leakage losses the influence of the hot water volume in the boiler of system 4 and the combistore of systems 3 becomes visible. System 1 has almost no leakage losses and system 2 can be found somewhere in between.

![Graph showing flue gas and leakage losses](image)

**Fig. 3.** Annual flue and leakage gas losses in proportion to the pellet consumption (left). Annual store heat losses in proportion to the energy input of the store and annual burner/boiler heat losses in proportion to the pellet consumption (right).

The absolute monthly heat losses for each system can be seen in figure 4. Systems 3 and 4 have the highest total heat losses, but also the largest store volume and pellet consumption. For this reason it is interesting to compare the respective losses in proportion to the stored energy and the fuel consumption. For example the store in system 3 has the highest absolute heat losses, almost three times more than the other systems, but in proportion to the stored energy system 1 and 2 are much worse. The heat losses are mainly due to the rather poor insulation of the store near the burner and the exhaust gas outlet. System 4 has the lowest relative store losses but the pellet boiler causes high heat losses. The absolute monthly values in figure 4 show that the flue gas losses dominate the heat losses, but the store and boiler/burner heat losses play a major role.
Fig. 4. Monthly heat losses of four combined solar and pellet heating systems simulated for house with annual space heat demand of 87 kWh/m² located in Stockholm. The store, boiler and burner heat losses do not contribute to the space heating.

From figure 4 it can be also seen that the boiler and burner of system 3 and 4 respectively operate also in the summer months when only a domestic hot water is required that can be covered by the solar system and an electrical heater as a backup. Consequently the question was how much energy can be saved by a seasonal operation of the pellet heating units. Moreover it was interesting to investigate to what extent the heat losses contribute to the space heating when the store and boiler are placed in the heated area. For this reason two more variants of the systems have been simulated: variant 2 where the system is placed in the heated area; and variant 3, which is the same as variant 2 but with a seasonal operation of the pellet heating units. This means the burner is turned off from the middle of May until the beginning of September.

In figure 5 the total auxiliary energy demand and the effective store heat losses are illustrated for the simulation variants, where variant 1 is the previous simulation variant with the heating system located outside the heated area of the building. The total auxiliary energy consumption consists of the used pellet fuel energy (lower heating value) and the auxiliary electricity. It can be seen that system 1 is the most energy efficient system for variant 1 under the premise that the heat losses from the DHW-store do not contribute to the space heating, the building has only one zone and that each kWh electricity has the same worth as one kWh pellet fuel. Under these conditions system 4 with the pellet boiler is the worst solution, mainly due to the poor boiler efficiency. Nevertheless the differences could be even higher if the higher solar gains of the combsystems did not balance it out to a certain extent and the average room temperature during the heating season would be exactly the same and not 0.5 °C to 0.8 °C lower. System 2 needs significantly more auxiliary energy than the similar system 1. The analysis of the simulation results showed that this is mainly due to the lower efficiency of the stove in system 2.
Figure 5 shows that the total auxiliary energy and the effective store, boiler and burner losses can be reduced drastically when placing the heating system in the heated area. The effective storage losses are defined as the storage losses occurring when the room temperature exceeds 24 °C. Again, this assumes that the heat losses can be distributed effectively to the whole building. Significant are the energy savings for system 3 when operating the burner only in the heating season. In the other systems almost no effect could be seen since the stoves/boiler have anyhow not been operated in the summer months. The effective losses in variants 2 and 3 are an indicator for the overheating problem that will occur in the summer months.

![Graph showing total auxiliary energy and effective store, boiler, and burner heat losses for four systems.]

The auxiliary electricity consumed has been taken into account with a conversion efficiency of 100%. More realistic for a global consideration would be to use a primary conversion efficiency of about 70% for Swedish electricity production. However, the auxiliary electricity consumption of the system is not including any parasitic electricity for pumps, controller, pellet conveyor etc. Neither are the electricity demand of the pellet heating units in included.

<table>
<thead>
<tr>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total auxiliary energy</td>
<td>17761</td>
<td>19721</td>
<td>18872</td>
<td>19770</td>
</tr>
<tr>
<td>Average annual boiler/stove efficiency</td>
<td>86.9</td>
<td>83.7</td>
<td>85.0</td>
<td>70.8</td>
</tr>
<tr>
<td>Number of start/stops</td>
<td>117</td>
<td>593</td>
<td>1125</td>
<td>1276</td>
</tr>
<tr>
<td>Average room temperature during heating season</td>
<td>20.3</td>
<td>20.3</td>
<td>19.5</td>
<td>19.8</td>
</tr>
<tr>
<td>Solar fraction</td>
<td>8.6</td>
<td>7.5</td>
<td>12.1</td>
<td>9.5</td>
</tr>
</tbody>
</table>

The evaluation of the solar gains for such different systems is not an easy task. A very interesting method was proposed by Letz (2002) using a reference system to calculate fractional solar savings. Due to the lack of a suitable reference system and the rather
different studied system designs a simpler method was used expressed by the obtained solar fraction.

\[ SF = \frac{Q_{\text{sol}}}{Q_{\text{aux, tot}} + Q_{\text{sol}}} \]  

(5)

This equation is assigning not all the system losses to the solar system. It expresses the ratio of solar energy supplied to the store and the total energy supplied to the store. In case of system 1 and system 2 the auxiliary electricity could be used to calculate the solar fraction for the pure solar DHW-system.

7. Conclusions

Four commercial combined solar and pellet heating systems have been investigated and evaluated according to their thermal performance particularly with regard to the heat losses of the system. The total auxiliary energy demand for heating (bought energy) is about 17800 kWh for the best system that is also the simplest system (system 1). The other systems require between 6 and 12 % more energy for heating. If the house has an open design with no obstructions for the heat transfer to ambient air system 1 is the best solution. For houses with more than one zone system 3 is a better solution. If the whole heating system is placed within the heated area system 3 and 4 have almost the same energy demand as system 1 provided that all the losses from store and boiler/burner can unresisted be distributed in the building. For this solution the overheating problems have to be studied more closely.

All systems offer potential for improvements. An intelligent controlling of the pellet heaters would reduce the number of starts and stops. System 1 with a power modulating stove proved that although the stove was not operating on maximum power the efficiency was still better than all other systems. Further investigations are necessary to evaluate the potential of emission reductions. Moreover the interaction between boiler/burner and storage need to be improved to prevent unnecessary electricity consumption and to keep the temperature in the store as low as possible with a good stratification. The poor performance of system 4 can to a large extent be attributed to the low average boiler efficiency, which in turn is due to relatively high total flue gas losses (including leakage) and the very high boiler losses to ambient.

Flue gas and leakage losses also can be reduced by optimizing the combustion air settings or using an automatic combustion air control (lambda sensor). Leakage losses can be reduced by 6% to 25% when closing the chimney during the summer month when the burner/boiler is turned off. From 35 to 90 kWh primary energy can then be saved for system 2 to 4 if the leakage losses can be reduced to zero.

The solar savings for all systems are very low. With relatively simple modifications it would be possible to achieve higher solar fractions.

Acknowledgement

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