HOLISTIC SYSTEM TESTING – 10 YEARS OF CONCISE CYCLE TESTING

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Abstract

Combisystems are often pre fabricated and composed of a number of components that have to interact elaborately. To evaluate in a laboratory the performance of a system as a whole a test cycle called the Concise Cycle Test (CCT) was developed at SPF. It utilises the boundary conditions of climate and a typical load from a reference year in a 12 day test cycle to emulate realistic conditions. More recently the SPF test facility was upgraded to a fully automated test rig that fulfills the special requirements of the CCT test method. Subsequent to the physical test sequence the acquired data is then used to generate a measurement-validated simulation model that is further used to evaluate various system setups in light of annual performance summaries.

This paper summarises the main features, results and insights gained from 10 years of advanced CCT combisystem testing with gas, oil and pellet burners including measurement of emissions. By using the CCT method it could have been revealed that the assessment of proper system operation is of utmost importance as systems often malfunction at the interface to the auxiliary heater or induce unnecessary cycling of the burner. Extending the test facility e.g. for the integration of heat-pumps is planned for the near future.

1. INTRODUCTION

Still, most solar collectors are used for domestic hot water (DHW) preparation. But solar systems are not only restricted to this area. The combination of a growing environmental awareness, thermally well insulated buildings and subsidies for the use of solar energy leads to a growing share of systems for combined DHW preparation and space heating, so called solar combisystems.

But although the energy delivered by the sun is free of charge and CO2 neutral, the lion's share of the heat demand in pre fabricated systems in combination with the conventional building standards is still covered by an auxiliary heater. The challenge thereby is to integrate two different heat sources into a single system and cover the comfort requirements for space heating and DHW in a reliable and cost-effective way. There are various methods to solve this problem but also diverging opinions about it. The lack of scientific knowledge in the area of combisystems and their testing were taken as incitement to start an international research project within IEA's solar heating and cooling programme in Task 26. From autumn 1998 to December 2002, 35 experts from nine European countries and the USA and 16 solar industry companies have been working together to further develop and optimize solar combisystems and give proposals for the international standardisation of combisystem test procedures (Weiss, 2003). Within these efforts was the development of a test cycle called the Concise Cycle Test (CCT) developed at SPF to evaluate in a laboratory the performance of a system as a whole. Opposite to the CTSS-Test Method (component testing – system simulation) where all components of the system are tested individually and then brought together in a simulation the CCT method emphazises the holistic view of the system in dynamic operating conditions also during the measurements. One of the main reasons for this approach is that the performance of the most important component, the auxiliary heater, strongly depends on interaction with other system components. Thus, an isolated test of the auxiliary heater is likely not to reveal the boilers efficiency when integrated into the system. Neither would a test of the system without the auxiliary heater yield a good indication of the overall system performance. For this reason, auxiliary heat source and its controller should be considered as part of the system when testing solar combisystems. Primarily, the scope of using the CCT method is the optimization of the system performance rather than the implementation for a systematic comparison of different systems.

A more detailed description of the CCT Method is described in the next chapter. The advantage of this approach is the ability to detect malfunctions and to reveal the potential for optimisation which is documented later on in this paper where some accomplished projects are described.

2. THE CONCISE CYCLE TEST METHOD – A TWELVE DAY SYSTEM TEST

The development of the CCT method was - beside others - inspired by the „Combitest“ method presented by Bales (2002) that consists of two parts, a “Direct Characterisation” where performance indicators can be derived directly from measurements, and an “Annual Calculation” with parameter identification and long term system simulations. These two basic steps also exist within the CCT method but have been extended and/or adopted.

Test Procedure

The main part of the measurements is a system test where the combisystem must be installed completely by an installer on the test rig. Only the collector is not installed: As the 12 days of the CCT measurements are representing the operation conditions of a whole year, the collector has to be tested in advance using the standard testing procedure of EN 12975. During the CCT procedure, the collector is emulated in the test rig using an electrical heating and cooling circuit so that the actual realistic collector output is delivered to the system. The building load and the domestic hot water demand are implemented by a real-time TRNSYS simulation that is controlling a cooling circuit. The test procedure starts with an initial conditioning of the thermal energy store (TES) to bring both, auxiliary heated (upper) and lower part of the tank to reasonable temperatures. After that the fully automated 306 hours-lasting CCT is started where the system must completely act autonomously to cover the heat demand of the building and the draw-offs. The meteo data represent the typical climate of Swiss midlands during one year packed to a representative 12 day data file. In the beginning of the CCT, the last 18 hours of the core test sequence are put in front before starting the core phase. These 18 supplementary hours are called the cycle conditioning phase to make sure that energy stored in the tank and, more important, the energy stored in the virtual building and its slab heating is nearly equivalent at the beginning and at the end of the core phase. Experience has shown that the cycle conditioning phase effectively adjusts the tank temperatures so that the influence of the temperatures after initial conditioning is minor. The decisive quantity that is used to characterise the system performance later on is the measurement of the auxiliary energy consumption. This is up to now possible for fuel oil, natural gas and wood pellet.

Performance indicators for the 12 day period can be derived directly from these measurements. However, a multiplication of the measured 12 day performance data by 365/12 in order to simply achieve the annual system performance is not giving the exact annual fuel consumption. This is for two reasons:

- The test cycle is shorter than one year. The shortening of the seasonal fluctuation increases the effect of thermal storage. This leads to a higher solar yield and slightly smaller use of auxiliary energy respectively.
- In the test cycle the cumulated energy consumption for space heating between various tested systems is (slightly) different. Each tested system with its specific dynamic behavior and especially its controller determines the energy consumption for space heating itself. Both the flow and the temperature will be determined by the system and delivered to the building while the return temperature is a result of the building behavior. If the consumption of different systems of auxiliary energy (fuel) and auxiliary power (electric energy for auxiliary

equipment such as pumps, control, fan, etc.) should be comparable to each other the energy consumption for space heating would have to be concordant.

Therefore, annual performance data are calculated in simulations performed using the TNRSYS simulation environment. Basis for the simulations is a model that is parameterised in a first estimation by manufacturer’s data and some preliminary tests accomplished at the beginning. These preliminary tests are necessary in order to avoid inaccuracies that would occur if all of the system parameters for the simulation would only be fitted by using the results of the CCT core phase. The preliminary tested components are the auxiliary heater and the TES. Data of these preliminary tests are used for the simulation model later on.

The simulation model is then adjusted by a parameter identification process. The boundary conditions are the measured values of the heat delivered to the building (power, return temperature, flow rate) and the DHW load (mains water temperature, power). In the parameter identification process, the differences of measured to simulated daily totals of fuel consumption, solar yield and parasitic energy consumption are minimised. If measured data and simulation accord to each other the annual simulation can be performed and annual performance data can be calculated. Figure 1 gives an overview about the proceeding of CCT.

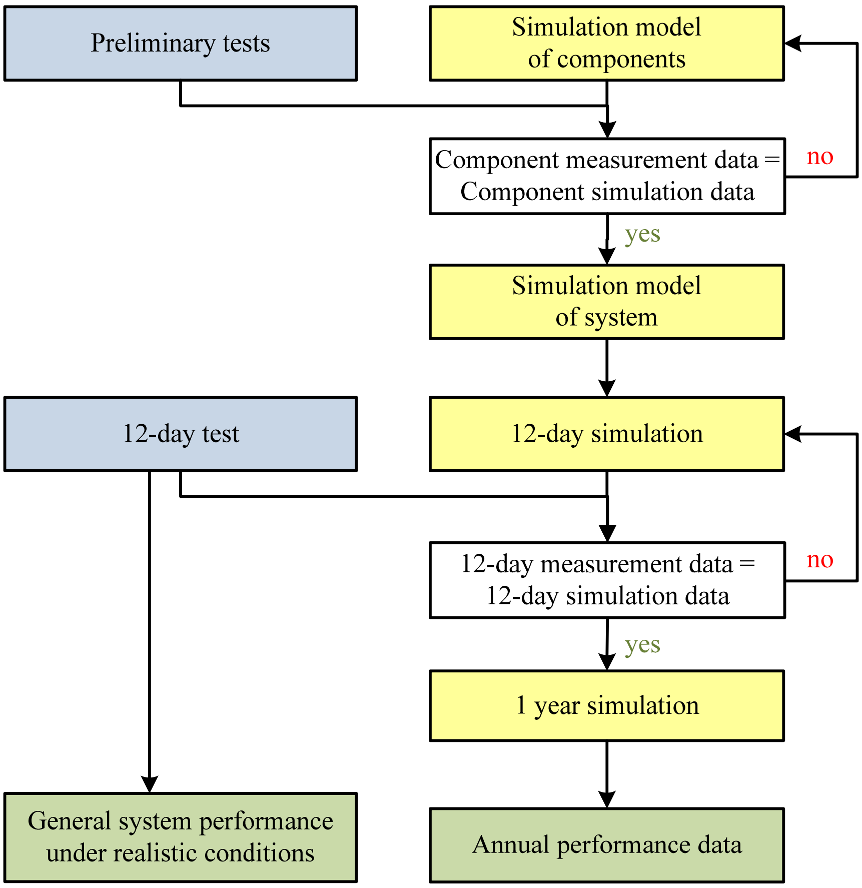

Figure 1: Steps and results of the CCT method.

Reference Conditions

Because the CCT indicates the system performance for only one single climate and load, it is important to choose a representative set of annual reference conditions. The conditions were evaluated to be as representative as possible for single family homes in Switzerland. Much effort was spent defining these conditions for the hot water load and the mains water temperatures, the building load and its characteristics and the climatic conditions. Once established, the annual conditions were used as a basis to define the conditions of the CCT as described below.

Climate

With verification of the proper functioning of the system being one main objective of the test, it was desirable to use more dynamic radiation data than the standard hourly data. Therefore, measured data were used. A set of weather data was assembled through selecting months from five years of measured data with a time resolution of 10 minutes. In the source data, solar radiation was provided as global radiation on the horizontal plane. The solar radiation processor of TRNSYS was used to calculate radiation values in the collector plane that was defined to be at a tilt angle of 45°, oriented south. The weather file includes global horizontal solar radiation, relative humidity, sky diffuse solar radiation, wind speed and wind direction.

The 12-day weather data file to run the tests was compiled from the annual file. At first it was considered to select the day according to simple principles like choosing the day which best fits the corresponding month. However, this would inevitably result in a series of days with unrealistically low fluctuations from day to day. Hence the following approach was used:

First, the daily sums of radiation and the average daily temperatures were extracted. The same was done for seasons. The typical fluctuations of radiation from day to day, pairs of days to the next (subsequent) pair of days, etc. were assessed. The selection criteria were to match the following properties between annual and 12-day files: The sums (radiation) and means (temperature) of the seasons on the one hand and the fluctuations (of radiation) on the basis of daily sums and sums of multiple days on the other hand.

After selection of the 12 days, the temperature profile was smoothened around the end and the beginning of each day, to avoid a step transition at any day change.

Domestic hot water load and mains water temperature

The basis to define the DHW load was the single family home draw-off file which was provided in Task 26 (Weiss, 2003). In the context of the CCT, different categories of the draw-off have been defined. A category called “small load volumes” was split into categories with load volumes less and more than 1.6 litres per occurrence. The occurrences with less than 1.6 litres load volume are considered as “volume-type draw-off”. Each occurrence of this type is terminated when the specified volume has left the tap, no matter what the temperature at the tap is. All other occurrences are considered as “energy-type draw-off”. These occurrences are terminated when the specified energy has been removed from the system via the tap. The energy is counted only if a threshold temperature is reached. As a result of a survey of the situation in Switzerland, the mains temperatures were defined individually for each category of occurrences with each category having its own annual fluctuation. Lowest mains water temperature is 8°C and its highest value is 19°C.

Building load and building load characteristics

A single-family house was defined to provide the building heat load. The house has an annual heat demand of 12500 kWh/a if it is heated to 20 °C by an ideal heater. However, during the test phase and the annual simulation it is heated via the floor (slab) dividing the two stories. With good settings of the controller to assure 20 °C indoor air temperature, it consumes about 15500 kWh/a. The building is modelled with TRNSYS type 56, the floor or slab heating is modelled as active layer. The design supply temperature to the slab heating is about 39°C at a design ambient temperature of -10°C and a flow rate of 550 litres per hour. With both its mass and its window areas being moderate, the house benefits moderately from passive solar gains (Vogelsanger, 2002).

The indoor test facility at SPF

The test facility should allow for installation and operation of the combisystems to be tested as completely as possible. Therefore the system is installed completely with exception of the collector array and the building in a designated area in the indoor test facility. All controllers including their sensors are installed. The system controllers are set up to operate as under normal in-field conditions.

Under normal circumstances there are only two exceptions: Because there are no collectors, the temperature sensor of the collector loop controller cannot be installed in the collector. Instead, it is installed in the collector emulator. The output of the collector loop controller, usually connected to the collector loop pump, is instead received by the test facility. The test facility then controls the collector loop pump. In order to be able to simulate the test later on the collector and the building load emulators are controlled using TRNSYS. Therefore, special TRNSYS components have been programmed at SPF to exchange information between simulation and the computer program which controls the test facility. Figure 2 shows the division of simulated respectively emulated and real installed components of the system.

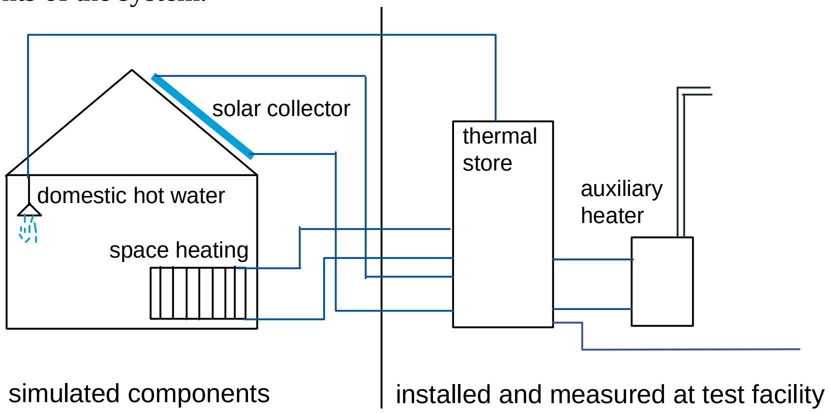

Figure 2: Simulated and installed components of the indoor test facility.

The collector array is emulated using an electrical heating element and a plate heat exchanger for cooling. The collector power is modeled with TRNSYS. The simulation predicts the power for every simulation time step based on inlet temperature and flow rate from measurements and ambient temperature and radiation data provided from a file. The calculated collector output power is then transferred to the test facility and used as a set value for the emulator where the temperature sensor of the collector loop controller is installed.

Emulation of the building load is to a high degree identical to emulation of the collector. Here, an outlet temperature (not power) is transferred from the TRNSYS simulation to the test facility controller and used as a set value. The system controller normally determines the supply temperature to the building heat distribution based on ambient outdoor air temperature. Optionally, indoor air temperature may be used too. If the supply temperature is too high a thermostatic valve that is controlled by the test rig dependent to the indoor temperature in the virtual building reduces the flow rate of the supply line. The outdoor air temperature, which the system shall assume, is generated in a small temperature simulation box. The system's sensor is located in that box during the test. Another box optionally accommodates a sensor for the indoor air temperature.

3. SELECTED MEASURMENTS CONDUCTED WITH THE CCT-METHOD

Since the CCT method has been developed a number of combisystems have been tested. If the test was successful in terms of a faultless system behavior and a reasonable reduction of fuel consumption compared to a non-solar reference system and the manufacturer agreed to the publication of results, test reports were written that can be found on the SPF webpage (www.solarenergy.ch). In the following, selected measurements are presented that have been conducted in the context of research projects.

KombiKompakt^{+}

From a manufacturer’s point of view, system testing is especially worthwhile if a sufficiently high quantity of the product is manufactured. Then the cost for testing is justified and the potential for energy savings is high. This is the case for largely prefabricated combisystems for DHW preparation and space heating. Additionally, the integration of two different heat sources to such a heating system leads to a comparably high potential of malfunction. Hence the analysis by system testing with a holistic approach is advisable. Therefore, a pilot and demonstration project called “KombiKompakt^{+} “ was accomplished by SPF in which a large number of such prefabricated systems that were commercially available in Switzerland were tested with the CCT method.

During this campaign a large number of combisystems has been analysed. The system to be tested had to meet a number of conditions for the campaign, such as:

- The TES and all other parts of the system can be transported through a door with 0.79 m width and 1.95 m height. The room height necessary for installation, operation and maintenance of the heating system is 2.25 m.
- The gross collector area shall not exceed 15 m^2.
- The system includes all aggregates that are necessary to produce and to store thermal heat and DHW, including the auxiliary heater.
- The system works fully automatically.
- The system must cover the comfort requirements for space heating and DHW in a typical Swiss single-family house. A detailed description can be found under www.solarenergy.ch.

The performance testing has been completed for a large number of solar combisystems within this campaign. Apart from the common characteristic of compactness and the source of auxiliary energy a multitude of different approaches and schemes were tested on the indoor test facility. Only a few of the tested systems showed both a good functionality and a high effectiveness. Crucial for the success of a test was not a specific concept but a functional interaction of the individual components. The concepts of successfully tested systems are manifold. Some of the successfully tested sub concepts are shown in Figure 3 (see also Vogelsanger et al., 2005):

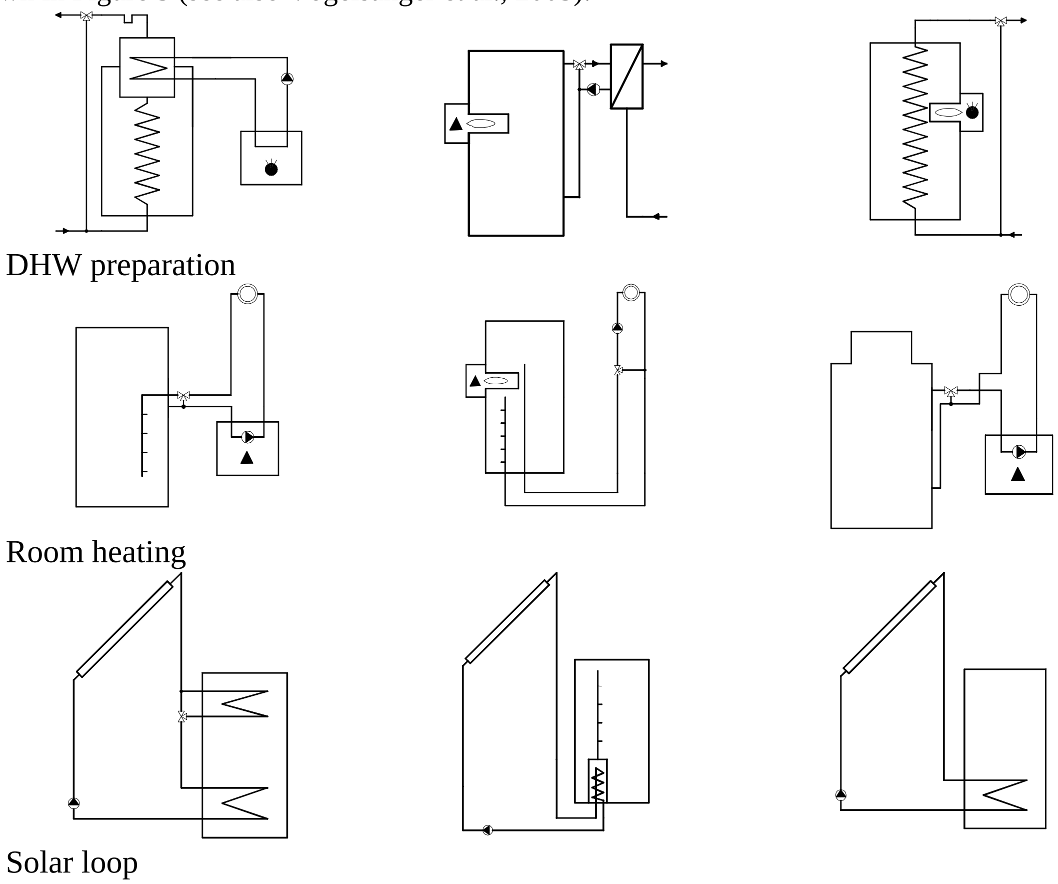

Figure 3: Sub concepts of heating systems.

The results were extended to annual performance figures by parameter identification and system simulation, however, only in case of a successful test. The energy consumption of each tested system is compared to the consumption of a typical reference system without solar collectors. The difference is the energy savings which serves as a performance indicator. Combisystems using natural gas are compared to another reference system than those using fuel oil. The definition of the reference systems depends on the current best available technology. Condensing technology is actual considered as state of the art. Therefore older systems without condensing technology show a higher energy consumption than newer ones. In Figure 4 the results of successfully tested systems are shown.

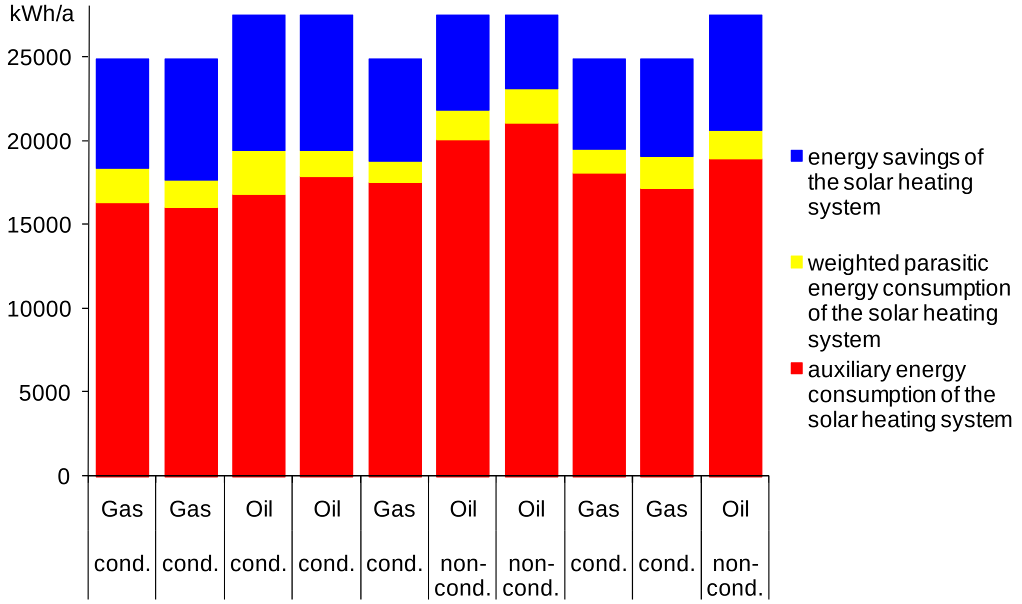

Figure 4: General results of the combisystem testing within the project "KombiKompakt^{+}". The total yearly energy consumption of 10 combisystems is presented. The energy savings are derived from a comparison with a reference system (different reference systems for gas or oil) without solar. Only combisystems are presented that have been successfully tested.

Upon project completion it can be summarised that the test procedure is well suitable to detect malfunction and to evaluate the performance of heating systems. However, a noncritical comparison of results could be misleading. An alignment of comfort is neither possible before the test through adequate controller settings nor afterwards through simulation. The simulations have no claim to reproduce the system in every detail.

Keeping in mind the high number of systems that did not pass the test it can be added that performance testing of complete systems is desirable and that an essential requirement of any combisystem test method is the assessment of the proper operation of the system.

PelletSolar

With rising costs of fossil fuels and an increasing environmentally awareness alternatives to fossil fuels for room heating and DHW preparation are becoming more attractive. One possibility for heat generation that is realised completely with regenerative fuels are automatic boilers using wood pellets combined with solar collectors. The market share of combined systems for single and multi-family houses is strongly increasing over the recent years in a number of European countries such as Germany and Switzerland.

To analyse the proper combination of both technologies two projects within the topic of pellet-solar systems were started at SPF. The main goals were to reveal the potential for energy savings and to detect possible improvement potential.

Prior to the measurement of combined pellet-solar systems the indoor test facility at SPF had to be extended to meet the special requirements of solid fuels. The continuous measurement of wood pellet consumption had to be realised by new built-in components as well as the conditioning of the air temperature and humidity within the wood pellet reservoir as shown in Figure 5. A humidity control is necessary because the upper heating value of wood pellets is bound to the moisture content of the fuel.

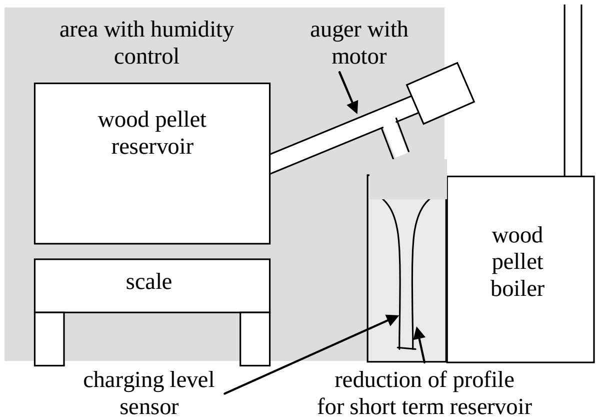

Figure 5: Schematic view of measurement setup extension to measure the accurate fuel consumption of wood pellet boiler.

The focal point of the PelletSolar project was a very detailed analysis of one single pellet-solar system. The main instrument of the survey was the CCT test method. The approach was supplemented with extended preliminary tests of the boiler. Besides the measurement of steady-state boiler operation and losses due to radiation to the environment, the cycling operation performance was measured with particular interest in parasitic energy consumption to evaluate the boilers energy efficiency in different running modes. The data gained by this means were used to parameterise a new model in TRNSYS to simulate the boiler (see Haller et al., 2009). This new model was motivated among other things by the fact that existing boiler models consider neither the electricity consumption depending on the operating condition nor effects of different running modes. However, this information are very important especially in case of wood pellet boilers as the energy efficiency of this devices that incorporates a high thermal mass is very sensitive to the operation mode. Furthermore, wood pellet boilers have a high demand for parasitic energy during boiler start to enflame the fuel. For the later determination of annual performance summaries this model was then integrated to the simulation environment. It turned out that, comparing the measured steady state operation to on-off operation with the same load, the steady state was more efficient, mainly due to a reduced electricity demand.

The second step in CCT testing, the 12-day measurement of the system, was accomplished using a hydraulic scheme in accordance with the manufacturers. This test showed that the system worked without interruption and covered the heat demand for space heating and DHW preparation without any restriction of the comfort requirements. However, the test revealed that the modulation of the boiler was restricted to 70 % of the nominal power in consequence of the system integration although the range of the boiler model would allow to modulate the power down to 30 % of its nominal power. Having detected this barrier it was possible to optimise the system. A second test with an optimised hydraulic scheme showed a significant reduction of the boiler’s start and stop cycles during the 12 day test period. Figure 6 visualises the gradient of measured values on the third day of the 12-day test period. Beside the optimised system are two more systems shown in this figure.

The third step of the approach was a measurement validated simulation model established to perform seasonal simulations according to the CCT method. The results showed that the pellet-solar combination of an 800 liter store and 15 m^2 of flat plate collectors used 27 % less wood pellets compared to an non-solar reference system using the same boiler. The fuel reduction is composed of the solar gain on the one hand and an improved boiler efficiency on the other hand. The latter is due to the fact that the boiler barely has to start for DHW preparation during summer and that the solar part covers part of the low heat demand for space heating in the transition periods in autumn and spring which would require a very inefficient operation of the boiler otherwise.

Once the simulation model is validated it can be used for further investigations. During the pellet solar project a great number of influencing variables was analysed. Thereby it was shown that it would be possible through improvements in insulation of piping, control strategy and hydraulics to save up to 32 % of pellets and 17 % of electricity without changing the components and sizing. Then, the boilers start-stop cycle reduction amounts to 50 % compared to the non-solar reference system with effects to parasitic energy consumption and emissions. Further results of the investigations can e.g. be found in Konersmann et al. (2008).

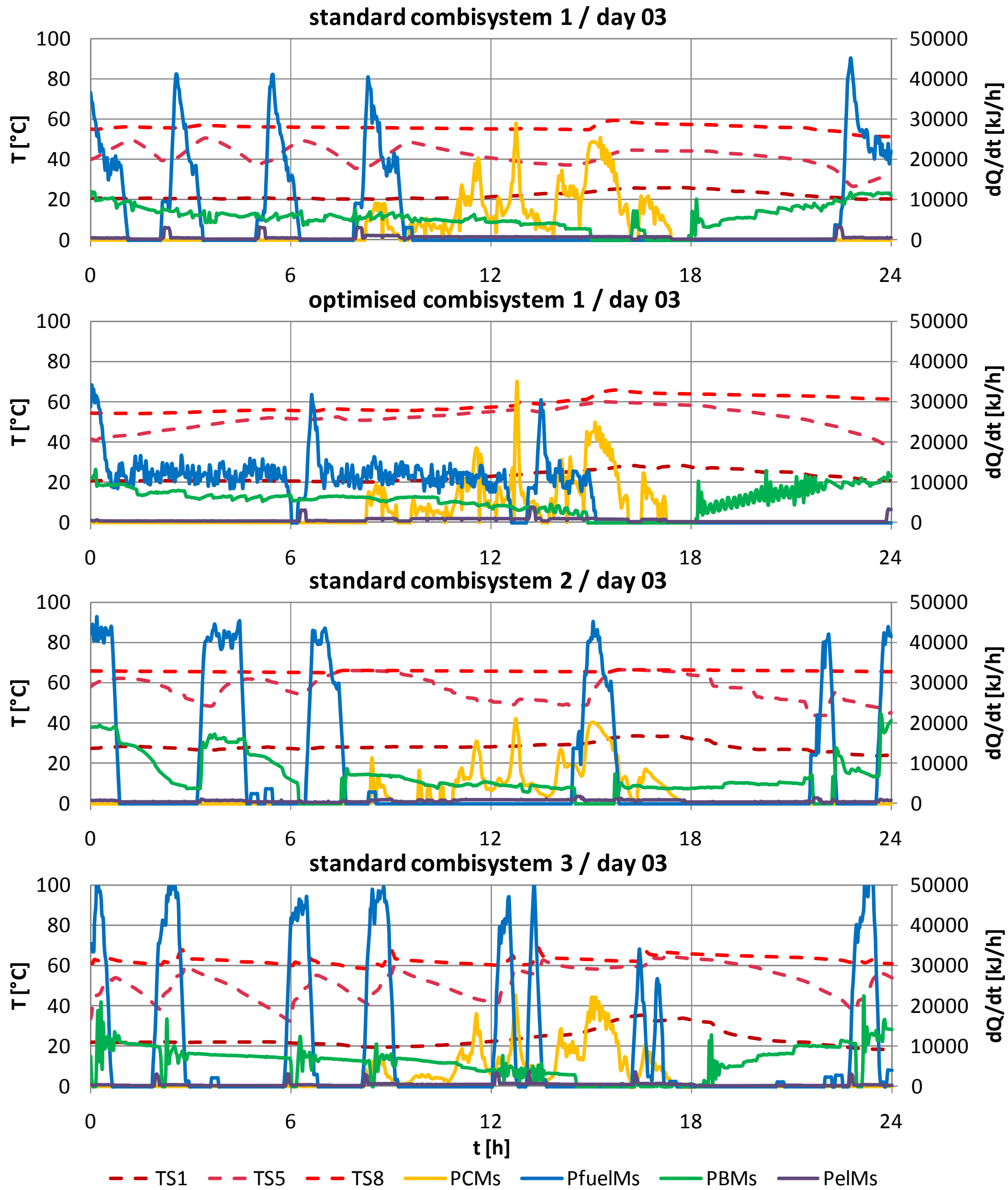

Figure 6: Course of measured values (temperatures on the left ordinate, power on the right ordinate) on the third day of the 12-day test period of the tested pellet-solar combined systems. The first two graphs show system #1 as it was installed according to the instructions of the manufactures and the results of the hydraulic optimisation. The last two graphs show results from system #2 and #3, both installed according to the instructions of the manufactures Nomenclature: T_{S1} = lower store temperature; T_{S5} = middle store temperature; T_{S8} = upper store temperature; PCM_s = lower delivered by the solar collector field; $P_{fuel}M_s$ = fuel consumption; PBM_s = building power; $P_{el}M_s$ = electric power.

The insight to the combination of wood pellet boilers and solar collectors to a single combisystem gained in the project PelletSolar were obtained through testing with the CCT method of a single system. In order to validate the generality of the conclusions a second project has been started where two more system are tested that use distinct hydraulic schemes to integrate the boiler into the system and different methods for fuel feed inside the combustion chamber. The choice of test candidates represents a wide range of common techniques of wood pellet boilers. The project is extended by measurements of the respirable dust emissions as a function of the running mode of the boiler. The results of these ongoing measurements should be integrated to the newly included simulation model which allows to calculate the annual emission load caused by the combisystem and its operation mode. Both of the systems were tested with the dynamic 12-day test. The measurements showed analogous to the previous measured pellet-solar combisystem that they are able to cover all requirements of space heating and DHW preparation in a reliable way. However, again a large potential for improvements was detected. It can be seen that all systems in the standard version operate the boiler in start-stop cycles while the enhancement introduced to system one during the project PelletSolar led to a modulation of boiler power due to the load. From an energetic point of view this mode is more desirable mainly because the consumption of parasitic energy is reduced. In addition the measurements of respirable dust indicate that the annual emission load could be reduced significantly by an optimised operation mode of the boiler.

4. CONCLUSIONS AND OUTLOOK

In this paper, the CCT method for holistic combisystem testing is described. Based on selected research projects, results of different system combinations are presented and discussed. The measurements approved that a detailed evaluation of combisystems under realistic conditions is possible.

One of the main advantages of the CCT method is the possibility to detect malfunction which are most often caused by poor interaction between the single components. It has been shown that the conventional part of auxiliary heating is most frequently affected which leads to an inappropriate operation of the boiler. Especially for wood pellet boilers the negative impacts of the intermittent boiler operation were analysed in detail. Start stop cycling of the boiler may increase the parasitic energy consumption significantly and leads to a decreased fuel efficiency (lower annual efficiency) and at the same time to increased emissions. Other common sources of error are poorly isolated piping and interfaces to the TES as well as missing heat traps or siphons.

The CCT method is well suitable and an efficient tool to support the development of (new) systems and components. An extension and adaptation for further heat sources such as heat pumps is planned for the near future. The approach is not restricted to solar heating systems. In principle, the CCT method is also feasible to check the performance and evaluate micro CHP or other concepts.

5. ACKNOWLEDGEMENTS

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