INVESTIGATION OF COMBINED SOLAR THERMAL AND HEAT PUMP SYSTEMS – FIELD AND LABORATORY TESTS

Anja Loose *, Sebastian Bonk and Harald Drück
Institute for Thermodynamics and Thermal Engineering (ITW), Research and Testing Centre for Thermal Solar Systems (TZS), University of Stuttgart, Germany
* Corresponding Author, E-mail: loose@itw.uni-stuttgart.de

Abstract

The technological combination of solar thermal systems with heat pumps continues to be a highly topical subject in the market of sustainable domestic hot water and space heating concepts. The main background for this development is the expected increase of efficiency for both, the solar thermal system and the heat pump due to synergetic effects resulting from the mutual interaction of these sub-systems. Nonetheless, objective performance test methods are not yet common standard. In this context field tests with different combined solar and heat pump systems installed in single family houses in Germany are being performed by ITW within the project "WPSol". In parallel, the laboratory testing procedure CTSS[1] is being extended for the performance determination of such combined systems, focusing on the dynamic behaviour of the heat pump. TRNSYS simulations are also performed and validated by means of measured field test data. In this paper selected examples of the investigated system concepts are presented, the monitoring procedure is described and first results are discussed. Furthermore, the extension of the CTSS test procedure is introduced and the new heat pump test facility at ITW is shown.

1. Introduction

During the past years, a variety of combined solar thermal and heat pump systems with different conceptual designs have appeared on the European market, claiming that higher seasonal performance factors (SPF) of the overall systems can be achieved than with traditional, separated heating systems. However, uniform and objective criteria for the evaluation of the combined solar and heat pump systems' thermal performances are not available up to now. Because of this corresponding test and assessment procedures are needed in order to be able to determine the energetic performance and the environmental impact of combined solar thermal and heat pump systems in an objective manner.

Therefore, international efforts are currently being made, e.g. within the IEA SH&C Task 44 and HPP Annex 38 "Solar and Heat Pump Systems"[2]. In parallel, the research project "WPSol" (Performance testing and ecological assessment of combined solar thermal and heat pump systems) has been initiated by ITW in order to develop performance test methods for such combined systems [1], [2], [3]. Key activities within this project are the development of a dynamic performance test procedure for heat pumps using the new heat pump test facility established at ITW, the extension of the CTSS test method towards combined solar thermal and heat pump systems, the development of numerical models for specific components and TRNSYS simulations of complete systems, life cycle analyses for the

[1] CTSS: Component Testing – System Simulation; Standardised in EN 12977 series
[2] IEA: International Energy Agency, SH&C: Solar Heating and Cooling Programme, HPP: Heat Pump Programme

determination of ecological aspects and field tests, i.e. monitoring of combined solar thermal and heat pump systems under real operating conditions. Some of the seven systems being monitored within the project WPSol are described in the following chapter.

2. Field tests of combined solar thermal and heat pump systems

A large number of field tests of the separate technologies (i.e. solar thermal systems & heat pumps) have been performed already for heat pumps only [4], [5] and for solar thermal combi systems without heat pumps [6], [7] but not yet for the combination of solar thermal and heat pump systems. Although some of these combined systems have been monitored as single cases, a systematic study for this is still missing. Therefore field tests based on in-situ monitoring are being performed within the project WPSol as well as within Task 44/Annex 38 in order to determine the thermal performance of combined solar thermal and heat pump systems under real operating conditions.

The aim of this monitoring is on the one hand the detection of installation errors, optimisation of the operation of the entire system and controlling functions for different operation modes as well as the dimensioning of the collector field and storage size, etc. On the other hand, measured data are necessary for the validation of numerical simulation models of combined solar thermal and heat pump systems. The combined solar thermal and heat pump systems which are monitored within the project WPSol represent a broad spectrum of different concepts. Seven systems have been installed in Germany, at locations between Osnabrück in the north down to Füssen at the southern border to Austria. Five of these systems have already been equipped with measuring equipment and monitoring is running, while the remaining two systems will be installed in summer 2012. In the following, two examples of the systems under investigation are described in more detail.

2.1. Hybrid system – air/water split heat pump combined with solar thermal collectors and a condensing gas boiler

This system is composed of an air to water heat pump with split refrigerant cycle, solar thermal collectors and a condensing gas boiler providing heat for domestic hot water preparation and space heating. The integrated system controller controls the entire heating system and additionally measures and evaluates different energy flows within the system. The regenerative heating system’s modular design enables the combination of the air to water split heat pump with an additional gas boiler as hybrid system. The latter is called by the manufacturer “hybrid heat pump – a multi-heat system for energy efficient modernisation”. The hybrid heat pump system was developed especially for retro-fitting old central heating systems without the need for a building renovation at the same time; i.e. it can provide heat at a relative high flow temperature level appropriate for existing radiator systems.

The inside unit of this air to water split heat pump (the “hydraulic module”), apart from the condenser, includes the hydraulics for the integration of the condensing boiler, for storage and DHW (domestic hot water) charging and for the space heating loop. A combistore with an internal solar loop heat exchanger is operated in a stratified way by a division into three zones. The upper zone is for DHW preparation, the middle zone is used for supplying heat to the space heating loop, if solar heat is available and for defrosting of the heat pump (so called “bivalent renewable loop”) and the lower zone near the bottom is used for the input of the solar energy. In the heating mode of the heat pump the middle zone is also used as additional buffer volume during periods with low heat consumption.
A simplified hydraulic scheme of the system and the heat pump’s inside unit are depicted in Fig. 1.

The air to water split heat pump with inverter scroll compressor can modulate from 30 % - 100 % power. The heat pump is able to deliver heat to the space heating loop directly. For defrosting, thermal energy from the combistore (middle zone) is used. The heat pump keeps the delivered heat power constant via a special injection technology in the coolant circuit down to ambient temperatures of -15 °C, no electric heating element is required. Space heat is taken from the middle zone of the combistore, if the temperature in this zone is sufficient. The combistore is discharged temperature-controlled. In this way the accumulated solar heat can be used directly for space heating, thereby reducing store heat losses.

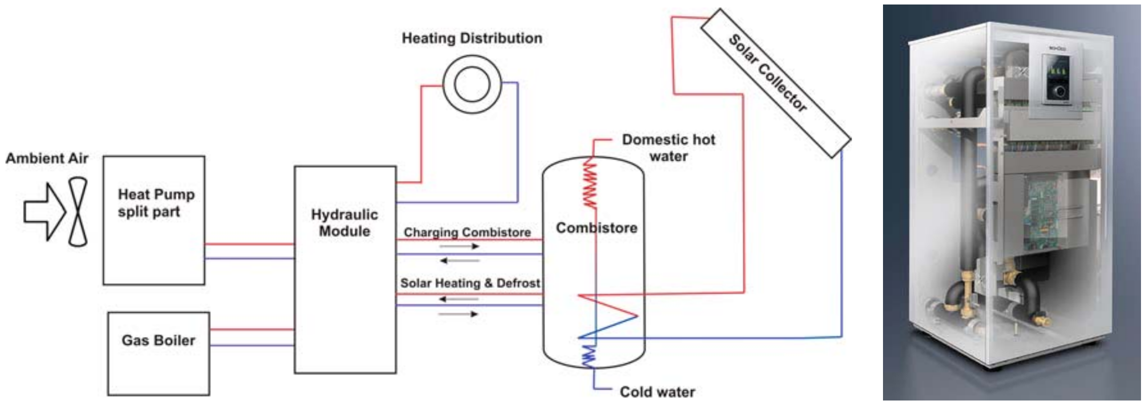

Fig. 1. Simplified hydraulic scheme and inside unit of the air/water split heat pump [Source of picture: Schüco]

2.1.1. Building description and technical data

- Single-family house, 4 persons near Osnabrück, northern Germany
- 190 m^2 heated living area, year of construction 1980, refurbishment in 2010
- Air/water split heat pump with 14 kW output, COP at A2/W35 = 3.37, refrigerant R410a
- Solar thermal system for DHW preparation and space heating;10 m² double glazed flat plate collectors and 750 l combistore
- Condensing gas boiler, 25 kW
- Design temperatures flow and return: 41 °C/31 °C (floor heating), 55 °C/42 °C (radiators), DHW tapping temp.: 45 °C
- In addition: Photovoltaic modules; approx. 2.1 kWp (not monitored)

2.1.2. Monitoring Procedure

The system is being monitored since September 2011. Data are collected once per minute with an *Ennovatis Smartbox* as data logger and transferred once per day via a GSM mobile connection to ITW. Pt 1000 temperature sensors are used for measuring ambient temperature, room temperature (boiler room), thermal stratification of combistore, temperature in primary and secondary circuit of heat pump (surface contacting sensors). The solar radiation is measured with a Si cell sensor and the ambient moisture with a hygrometer. Heat meters consisting of an ultrasonic flow meter and 2 x Pt 500 sleeve sensors each, are used for monitoring of the heat flow in each loop, including flow and return temperature and volume flow (solar loop, DHW, circulation, charging of the combistore, space heating loops, bivalent renewable loop and heat delivered by the condensing gas boiler). Electricity meters are used for the determination of the electric energy consumed by the heat pump, the hydraulic module, the solar loop pump, the two space heating loop pumps and the pump of the DHW circulation loop.

2.1.3. Results

In Fig. 2, monthly energy balances for the hybrid system are shown as heat quantities in kilowatt-hours for the months September 2011 until June 2012. The central part of each column depicts the useful energy including heat losses. This includes (from bottom to top) heat delivered to “high-temperature” space heating loop (radiators) and “low-temperature” space heating loop (floor heating system), domestic hot water preparation (DHW), DHW circulation and energy used for the defrosting of the heat pump’s evaporator. At the outer part of each column, the energy sources are shown. These are composed of the solar gains, the heat delivered by the heat pump and the heat delivered by the condensing gas boiler.

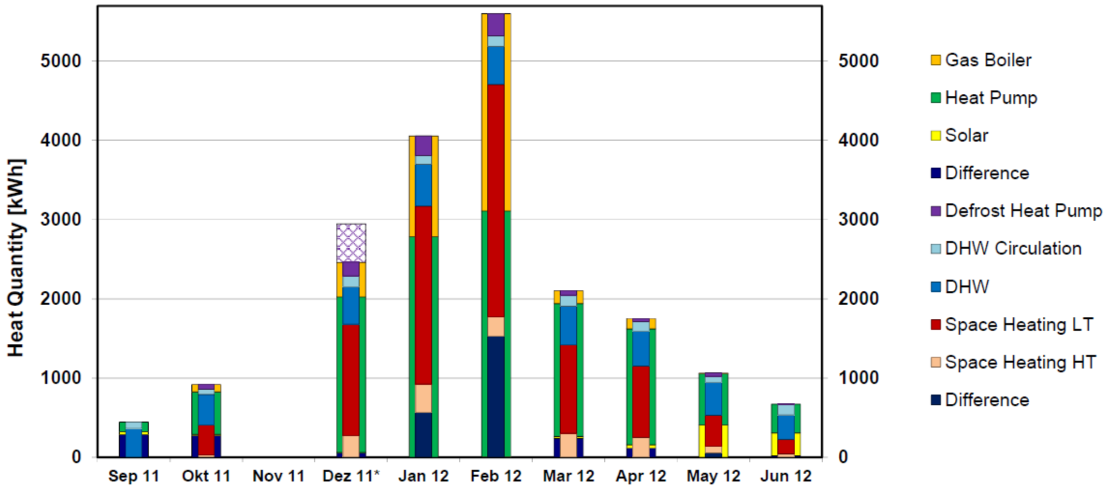

Fig. 2. Monthly energy balances of the monitored hybrid system [*data for December only from 6.12.2011, 10:00 a.m.]

It can be seen that during the winter the heat load could be covered by the combination of heat pump and condensing gas boiler. The fraction of the gas boiler is highest in February, where ambient temperatures as low as -15 °C were measured, which is rather cold for a German location. Nonetheless, the system does not work at its optimum. The solar fraction is below the expected and also the heat pump’s COP (coefficient of performance) is relatively low, with mean values around 2.0, although the maximum COP was measured in February as 5.24. This is probably due to the very complex control strategy necessary for the large variety of possible operating modes and will have to be optimised in the future.

Also, for systems like this with back-up heating other than electricity (i.e. gas), more performance figures will have to be calculated in the future for the characterisation of the system’s performance, for example the renewable energy ratio.

2.2. Solar ice store system – brine/water heat pump with different types of solar thermal collectors

This system consists of an earth buried latent heat store using water/ice as the only heat source for a brine to water heat pump. The ice store is charged with the energy delivered by solar absorbers (uncovered solar collectors) on the roof which also collect heat from the surrounding air during times with no or low solar irradiation. In addition, flat plate solar collectors are used for charging a small domestic hot water store on a higher temperature level than the ice store (c.f. Fig. 3).

This system has been developed for two reasons. On the one hand it is meant as alternative heating system for brine to water heat pumps with borehole heat exchangers at locations where borehole drilling is not possible /not allowed (e.g. due to ground water protection or other authorisations).
On the other hand it has proven to be rather difficult to supply brine to water heat pumps with solar energy. Though borehole heat exchanger systems might be regenerated with unglazed solar collectors (c.f. [8]) it is not possible to store solar energy in the ground in terms of a seasonal storage, speaking about single family houses with only one or two boreholes. Especially if an aquifer is crossing a borehole, the solar heat is removed rather quickly and cannot be recovered later on. Furthermore, flat plate collectors might be damaged by condensation from air moisture due to low return temperatures, when providing energy to the ground as additional heat sink. Another option for the integration of solar energy into a heat pump system is the direct coupling of the solar loop to the primary circuit of the heat pump without a buffer store. The problem with this approach is that especially during the space heating periods solar radiation is not always available as heat source for the heat pump.

Fig. 3. Solar thermal flat plate collectors (left side of left photo), absorbers (right side of left photo) and ice store (right picture, Source: Isocal)

The “Solar Ice Store” makes use of the traditional heat sources ground and ambient air and additionally couples solar energy into the system. The difference to other combined solar thermal and heat pump systems is in this case the ice store as a large buffer store at the primary side of the heat pump, which can store solar energy, geothermal energy and energy from the air at a low temperature level in order to act as the only heat source of the heat pump. This ice store is a concrete tank with a volume of 12 m^3 filled with water and buried into the ground. Polyethylene pipes as heat exchanger loops are wound through the store for charging and discharging (c.f. Fig. 3, right). This water or ice store, respectively, is comparable to a usual cistern, yet it is also used as latent heat store. As the brine to water heat pump extracts more and more heat from the water store, it will freeze to ice. The crystallisation enthalpy available during this process is also used for energy storage, because of which it is called an ice store. As heat transfer fluid a water/Tyfocor mixture is used (melting point -15 °C).

The ice store is charged via solar thermal energy provided by unglazed solar collectors (see Fig. 3, left), which can also use the energy of the ambient air, provided the ambient air temperature is high enough, and two flat plate collectors are used for charging a conventional small domestic hot water store. The two types of solar thermal collectors are connected in a parallel way and the system controller decides, which collector type is being operated at a time, depending on the temperatures in the collector loops, in the domestic hot water store and in the ice store.

2.2.1. Building description and technical data

- Single-family house, 1 flat, 2 persons; Year of construction: 2010
- Location: Louisendorf, Hessen, Germany
- Heated living area: 175 m^2, floor heating system
- Brine to water heat pump, COP 4.6 at B0/W35, refrigerant R410a, capacity 6 kW, scroll compressor
- 2 x 2.5 m^2 flat plate collectors and 2 x 2 m^2 IsoCal SLK absorber aperture area (i.e. 20 m^2 absorber surface for gains from air)
- 220 l DHW store, 12 m^3 IsoCal Ice store (latent heat, storage medium: water/ice)

2.2.2. Monitoring procedure

The monitoring procedure is rather the same as described above in chapter 2.1.2. The main difference is the use of turbine-type volume flow meters instead of ultrasonic ones for the three brine loops (two solar loops and primary circuit of the heat pump).

2.2.3. Results

In Fig. 4, monthly energy balances for the solar ice store system are shown as heat quantities in kilowatt-hours for the months January 2012 until June 2012. The central part of each column depicts the useful energy including heat losses. At the outer part of each column, the energy sources are seen. These are composed of solar gains from flat plate collectors to the DHW store, heat transferred from the ice store to the heat pump, electrical energy consumed by the heat pump and by the electrical heating element. In winter time geothermal heat gains can be achieved, when the temperature of the ice store is lower than the temperature of the surrounding earth.

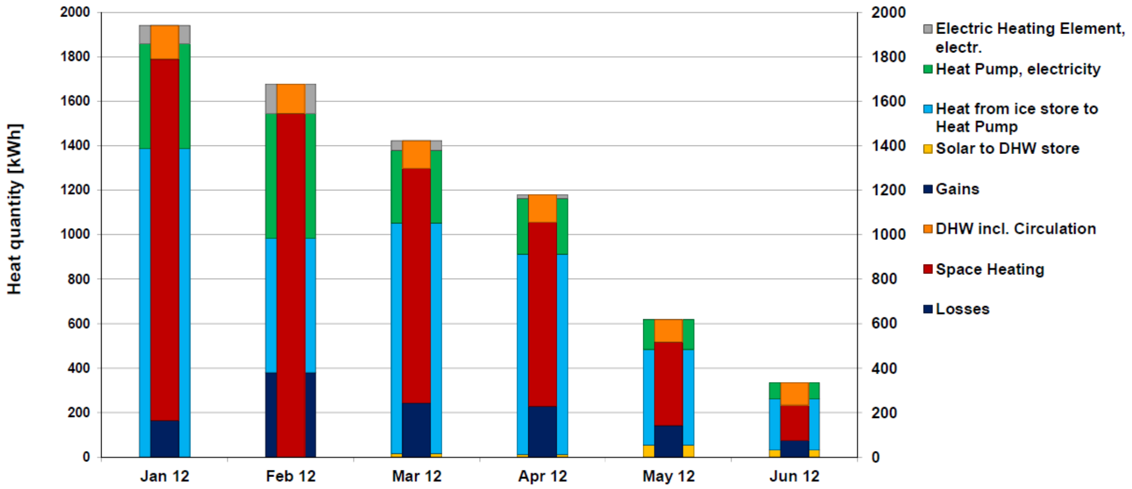

Fig. 4. Monthly energy balances of the monitored solar ice store system

The ice store has been frozen during winter time and lowest temperatures measured from the ice store were -8.1 °C (as flow temperature in the primary loop of the heat pump). The monthly COP of the heat pump as component reached mean values of 3.75, which is consistent with TRNSYS simulations of the system leading to a mean annual value of 3.9. The system reached mean fractional energy savings (f_{sav}) of around 30 % for the first half year of 2012 and the mean system seasonal performance factor (SPF) was 2.43.

3. Extension of the CTSS test procedure towards combined solar thermal and heat pump systems

Beside the field tests, corresponding performance assessment methods are being developed in order to be able to characterise the energetic performance of combined solar thermal and heat pump systems in an objective way. Such methods are not yet common standard, because of which several performance test procedures have been developed at ITW [3], [9]. For the performance characterisation of combined solar and heat pump systems, the main focus lies on a method which is based on the further development of the CTSS test method (Component Testing – System Simulation, already standardised in the EN 12977 series for domestic hot water and solar combi systems). The CTSS method uses a component oriented approach based on physical tests of the key components. The aim of the component tests is the determination of all relevant component parameters required for the detailed description of the dynamic thermal behaviour of the individual components. Therefore, laboratory test sequences and numerical models are required in order to describe the dynamic behaviour of the specific components. For heat pumps a component based model has been developed at ITW which represents the thermodynamic cycle of the refrigerant. It is based on the stationary model TYPE 265 [10] with dynamic extensions considering capacitive effects during clocked operation modes [11] as well as output-regulated behaviour of the heat pump. To adopt the model for the used refrigerant type R410a, polynomials describing the relevant thermodynamic quantities have been provided based on REFPROP data [12]. This approach of modelling has the advantage of very short computation times and therefore makes the model very adequate for parameter identification applications requiring a large number of simulations. The specific characteristic of each heat pump is described by a set of about 20 parameters. Parameters of the model are determined by means of parameter identification using measured data from several well defined test sequences performed with the heat pump on a heat pump test facility.

Fig. 5. Dynamic test facility for heat pumps at ITW

With an appropriate search algorithm the parameters are diversified until the output of the heat pump model calculated by the simulation fits to the measured output of the tested heat pump with a specific error range. This is an iterative process requiring a large number of simulation runs. The boundary conditions applied during the parameter identification are identical with the boundary conditions measured during the laboratory test. To be able to identify the model parameters with satisfactory accuracy the design of the applied test sequences is crucial. Besides a quasi-stationary sequence on the basis of EN 14511-3:2007, additional test sequences have been defined to provide information about the dynamic behaviour of the heat pump with regard to its performance. The investigation of the suitability of the introduced test sequences is currently in progress. The long term goal is an integration of the extended CTSS method into a future version of the EN 12977 series. The new test facility designed and constructed for dynamic performance tests of heat pumps at ITW is shown in Fig. 5 and has already been described in [3].

4. Conclusion

Seven combined solar thermal and heat pump systems are being monitored in a field test in Germany by ITW within the project WPSol. Two of these systems have been described in this paper, first a hybrid system with an air/water split heat pump and second a so called “solar ice store system” with a brine/water heat pump. Furthermore, the monitoring equipment has been described and first results have been shown. Monitoring is still on going, so final results cannot be presented yet. In parallel to the field test, a laboratory performance test method for combined solar thermal and heat pump systems is being developed. In this context it is intended to extend the so called CTSS test method already standardised in the EN 12977 series towards the combination of solar thermal systems with heat pumps, since this method is suitable to characterise the performance of systems under dynamic operating conditions in an appropriate way. Also this part of the work is on going until summer 2013. Both, field tests and the CTSS performance test method are crucial for a detailed analysis of the many different system concepts on the market, which all are operational, yet still have some optimisation potential.

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Acknowledgement

The Project WPSol is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit BMU) under grant number 0325967A. The authors gratefully thank for the support and carry the full responsibility of the content of this publication. Thank you also to our industrial project partners for their contributions.