HEAT PUMP SYSTEMS WITH ROOF TILE COLLECTOR

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Abstract: In historic cities, like scenic UNESCO Cultural World Heritages, and for buildings, protected as ancient monuments, the application of Solar Panels and insulation measures is mostly restricted or not possible due to the architectural structure oft he surface and the general presentation of the protected area. Such city areas are typically closely overbuilt and also the application of ground source probes or wood boilers are not allowed. In order to keep the possibility to use renewable energy, a special heat collecting system has been developed: the “roof tile collector”. The special designed roof tiles are of copper material and have a good capacity to collect the ambient heat from sun absorption, air, rain water and air humidity.
The “roof tile collector” brings the collected heat (or cold) through a circulating working fluid to the heat pump, which provides the required temperature for the heating or cooling circuit. The heat pump works principally like a brine/water ground source heat pump. Adequate to the special conditions of the primary side “roof tile collector” the heat pump, the system components and the electronic controller have to be carefully adapted. The presentation shows the special construction of the used roof tiles and how to use them as a collector, the specific system design, the adapted heat pump parameters and the results in temperature profiles, coefficient of performance and seasonal performance factors of the pilot installation. Good practice is shown by installations in Switzerland and Germany. The “roof tile collector system” is a proven new alternative for heat pump application, especially under restricted architectural conditions.

Key Words: heat pumps, historic city, roof tile collector, protected building, restricted architectural conditions

1 INTRODUCTION

2 SPECIAL SYSTEM COMPONENTS

2.1 Construction Of The Roof Tile

The roof tiles are manufactured with a special brass alloy containing small amounts of manganese and iron as alloy components. This alloy, marketed as architectural bronze for decades by Swissmetal Industries, has a self healing, a self cleaning and a self darkening surface. The mechanical dimensions and the weight are identical to the original clay tiles. The installation and the utilization of the ATMOVA tiles are fully compatible with both historic and current practice of roofers and roof constructions. At the rear side of the tile a small pipe to circulate brine and to collect ambient heat is fixed, see Figure 1. The heat transfer pipes of the tiles get fixed with the neighboring tile. A certain number of tiles can be prefixed before mounting on the roof. In Figures 2 and 3 real Roof Tile collector application is shown.

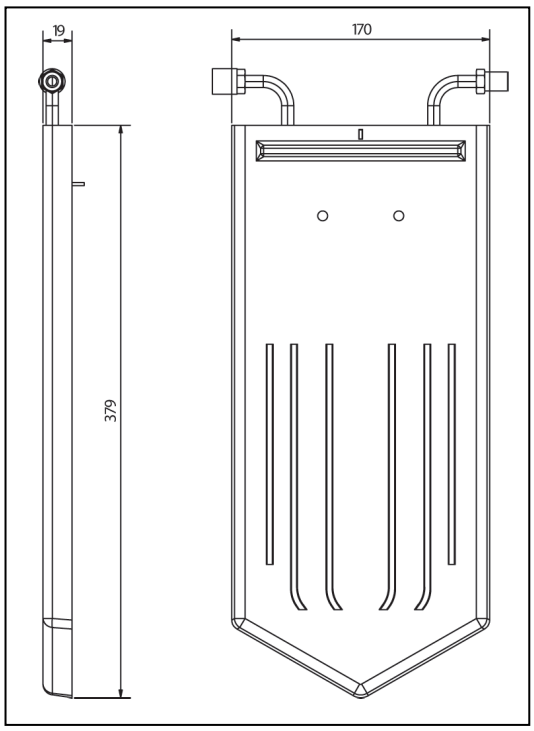


Fig. 1: Roof Tile design for historic building



Fig. 2: Detailed view of Roof Tile collector



Fig. 3 Application of Roof Tile collector on historic building in Luzern down town

2.2 Roof Tile Collector Specifications

As unglazed collector the stagnation temperature of a Roof Tile collector is +77°C. The heat flow is normally 300-500 Watt peak per square meter of aperture, comparable with a common solar collector. In addition to the performance as a unglazed solar collector two additional physical phenomena are being exploited by means of extracting ambient temperature as heat flow with a specific heat pump (similar to air source heat pump configurations): convection and condensation.
The roof tile collector passed the reliability test for solar collectors according to EN 12975-2:2006 in 2010.
The combined phenomena of heat absorption as solar collector during summer, convection with wind and rain as well as condensation including icing yields results in an annual energy harvest amount of around 800 kWh per square meter in our regions. The brine circulation is frost protected at -30 °C.

2.3. Heat Pump Specifications

The Heat Pump for the Roof Tile collector is a special tuned brine/water heat pump, type Viessmann/SATAG for very low brine temperature and high temperature lift. The heat pump has to run till outdoor temperature of -20 °C and deliver at least +60 °C flow temperature. The brine water heat pump is equipped with a special refrigerant circuit with EVI (enhanced vapor injection) for a temperature lift of 75 K or more see Figure 4 and the description in [1], [2], [3].

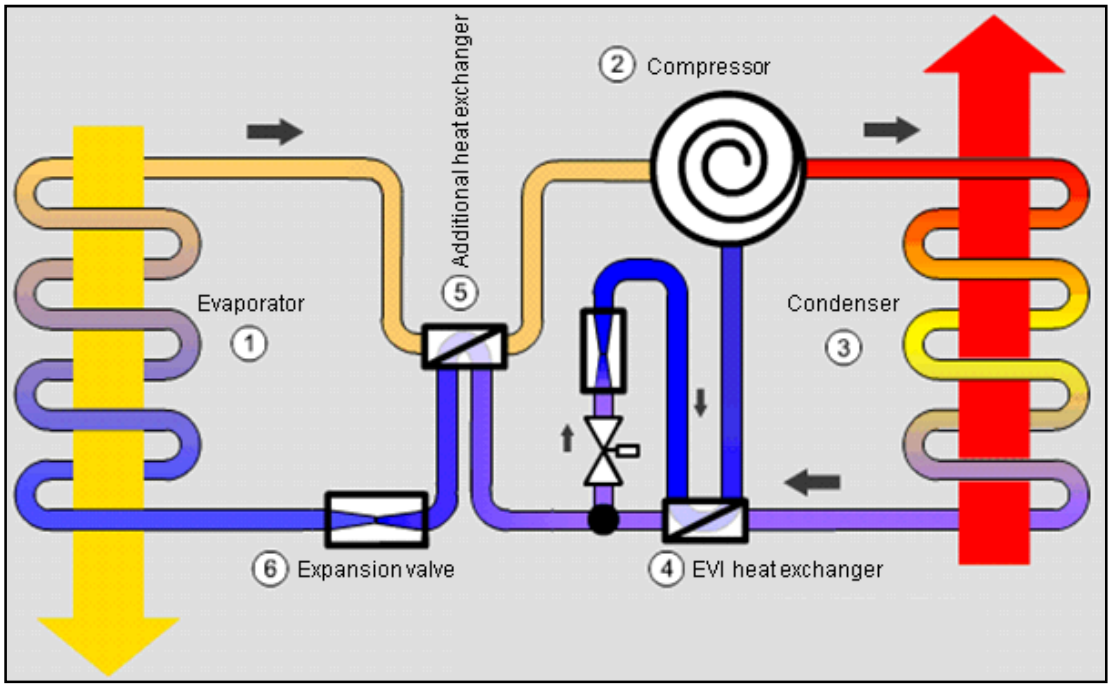


Figure 4: special refrigerant circuit with EVI (System Viessmann/SATAG)

2.4. Specific PLC System Controller

For the System Control all over the year and for the different system conditions a PLC is necessary. We applied a Saia PLC.

2.5. Other Hydraulic System components

The hydraulic system is a sort of Hybrid system and needs different heat exchangers, circulation pumps, switch valves and buffer- and domestic hot water tanks as shown in the system diagram later.

3 SPECIFIC SYSTEM DESIGN

The heat source described above as unglazed metallic roof tiles can work basically in two different operating modes: as a solar collector or as a heat exchanger with the ambient air.
A specific control unit and software algorithms in the control unit identify the weather conditions and choose the most appropriate operating modes (whether the heat pump is required or not), set valves and pumps in the hydraulic and electrical circuits to connect or disconnect the heat pump to the source.
The main service modes are the following:

- Direct load of the buffer tank by roof tile collector
- Charge of the domestic hot water tank from buffer tank
- Space heating with the heat pump
- Charge of the domestic hot water tank by the heat pump
- Deicing of the roof tile collector with heat of the buffer tank
- Charge of buffer tank with second heating device

Out of this a concept diagram for the heat pump with the roof tile collector was designed as shown in Figure 5.

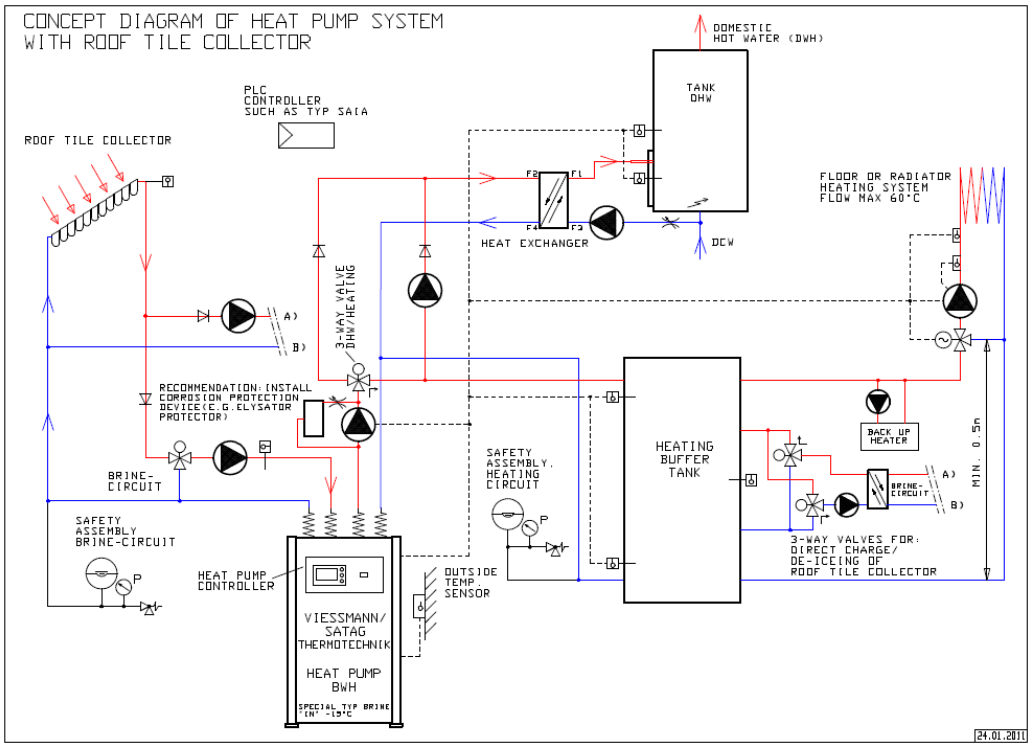


Figure 5: Concept diagram of a heat pump system with roof tile system

3.1 Climatic key parameters

3.1.1 Solar Radiation

As unglazed solar collector and in “solar mode” we obtain 700 Watts peak per m2 at a safe temperature below 77 degrees centigrade. The more sunshine, the better the aperture being exposed to the sun, the better the solar performance. Note that during summer time the heating requirements are reduced to warm water. With a typical active surface of 18 m2 for a single family house we can obtain a heat flow exceeding 12kW which is still 25% higher than the heat flow from the heat pump in such a configuration.

3.1.2 Air temperature

The annual average air temperature close to ground level compares with the ground temperature between zero and 100 meters: They are identical (e.g. Switzerland 8.8 degrees Celsius at an altitude of 300 meters above sea level).
While the temperature in the ground can be defined as constant, the air temperature is varying much more. This variation in the “air source” temperature requires special measures to make it suitable for a heat pump.

3.1.3 Air humidity

Air humidity is contributing to condensation if the system is used in “winter mode” i.e. in heat pump mode. In Switzerland we find temperature and humidity combinations such that for 70% of the time (annual view) condensation effects do occur with up to 150 Watts of heat flow per m2 of surface. At temperatures around zero +/- 5 degrees centigrade condensation becomes icing. Ice may build up to 1 cm per day and requires appropriate de-icing mechanisms (no electrical heating to de-ice).

3.1.4 Rain

In the heat pump mode raindrops do deliver a heat flow mechanism based on convection. The water temperature of the rain drops heat up the roof tiles that are a thermal interface to the environment (and a heat source for the heat pump).

3.1.5 Wind

Similar to the rain situation a strong wind corresponds with a better heat flow between the air and the metallic roof surface. Depending on wind speed and temperature differences between the air and the roof surface a heat flow up to several 100 Watts per m2 takes place.
With no wind, no sun, no humidity and in heat pump mode the roof surface gets cooled below ambient air. The air which is close enough to the roof surface gets cooled down, gets a higher specific weight and flows top down as induced convection mode. The heat pump lowest possible source temperature limit determines the minimal heat flow in this worst case operating mode. Weather statistics tell us that these worst case conditions do not occur often in our regions.

3.1.6 Snow

There are two kinds of snow. Dry snow at very cold temperatures and wet snow at temperatures around the freezing point of water. The latter is handled the same as ice and

requires appropriate de-snowing / de-icing methods. Snow is the only non-desirable weather condition for the whole system.

In general: Roof Tile collector positions with many hours of sunshine in wintertime are preferable.

3.2 Influence on Heat Pump System Design

The system design for the heat pump system has to consider broad temperature range for both cycles, the primary side (outside temperature) and the heating circulation of old, often not well insulated historic houses (high flow temperature). An acceptable COP should be result even at low source temperatures. The thermodynamic stability with varying temperatures on the source side must be granted. The roof tile collector asks for lowest volume flow requirements for heat carrying fluid (100 l/h*m2).

3.3 Influence on Heat Pump service parameters

The system compares best with a ground source heat pump in air source operating mode. The hermetically closed heat pump is operated in “safe operating area” conditions, the amount of power cycles is minimized, the minimum operating time rules are respected. A minimum of 1500 hours is the annual operating time of the heat pump. We do not expect any accelerated wear, reduced life time or reduced reliability. Reducing the source operating temperature below the standard -5 °C rating requires careful thermal insulation and the use of appropriate materials for fittings, circulating pumps, sealing gaskets and heat exchangers. Field service technicians need to be trained to understand the extended operating mode conditions.

3.4 Specific System Management

The system comes together with a specific system management implemented into an industrial control system. An Internet access allows for remote access, remote data collection, remote data analysis and remote debugging. All relevant parameters like temperatures, pressures, power consumption, heat production, real time COP, valve position feedback, volume flows and status information is being measured, processed and stored. Specific software algorithms recognize weather conditions, measure heat pump parameters, analyze heat consumption profiles and choose the most appropriate operating mode (summer mode, winter mode, de-icing mode, etc.).

4 RESULTS AND EXPERIENCES

Three Roof Tile collector systems with heat pumps are tested and observed over a period of up to two years. The test system in Dornach, Switzerland is recognized as a laboratory and surveyed constantly by the technicians. In the following, results and experiences of this installation are shown.

4.1 Characteristics of System Temperatures

Figure 6 shows measurements made during two months of wintertime in Dornach, Switzerland, from Nov. 16, 2009 to January 15, 2010. The yellow line represents the solar contribution to the heat flow (all in winter mode with activated heat pump). The blue lines represent the temperatures of the source circuit while the red lines represent the flow temperature of the load side of the heat pump. This particular installation consists of a heat

pump type Viessmann/SATAG BWH110 and 26 m2 of roof surface for a nominal heat power of 13 kW. The roof is divided into 4 partial surfaces oriented towards the North, East, South and West. The installation allowed to test several operating conditions, including the loss of a partial roof surface, the solar contribution, pressure loss, power loss, component failure, any combination of component failures. The roof pitch is 45 degrees. The used roof tiles are the version as shown in chapter 2.1.

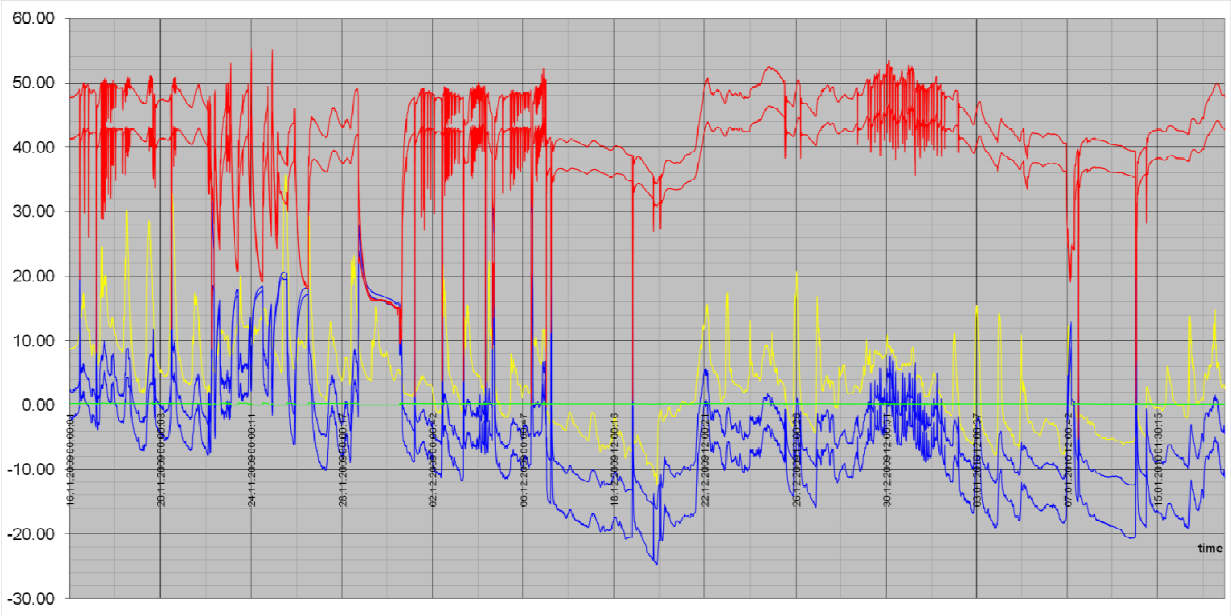


Figure 6: Temperature Diagram of test installation Dornach, 2 months

The temperatures shown above are a result of 3 types of heat flows from the source to the heat pump, electrical power driving the heat pump compressor and heat flows on the load side. The three fundamental effects absorption, convection and condensation combine in a way that the whole system can behave as a monovalent solution. In short it can be summarized that an active surface of 1 m2 is sufficient for 500 W of heat flow on the load side. Temperatures adjust to the variable heat resistance of the source side and as long as the minimum temperature on the evaporator side can be handled by the heat pump, by the circulating pump on the primary side and by the heat carrying fluid (water/glycol). The current design limits are -20 °C for the heat pump, -30 °C for the antifreeze liquid and for the primary circuit circulating pump (3-phase motor, no electronics, carefully adapted to hydraulic properties of the source).
The PLC systems shows the relevant system temperatures and main functions according to the operation mode on the screen, see Figure 7.

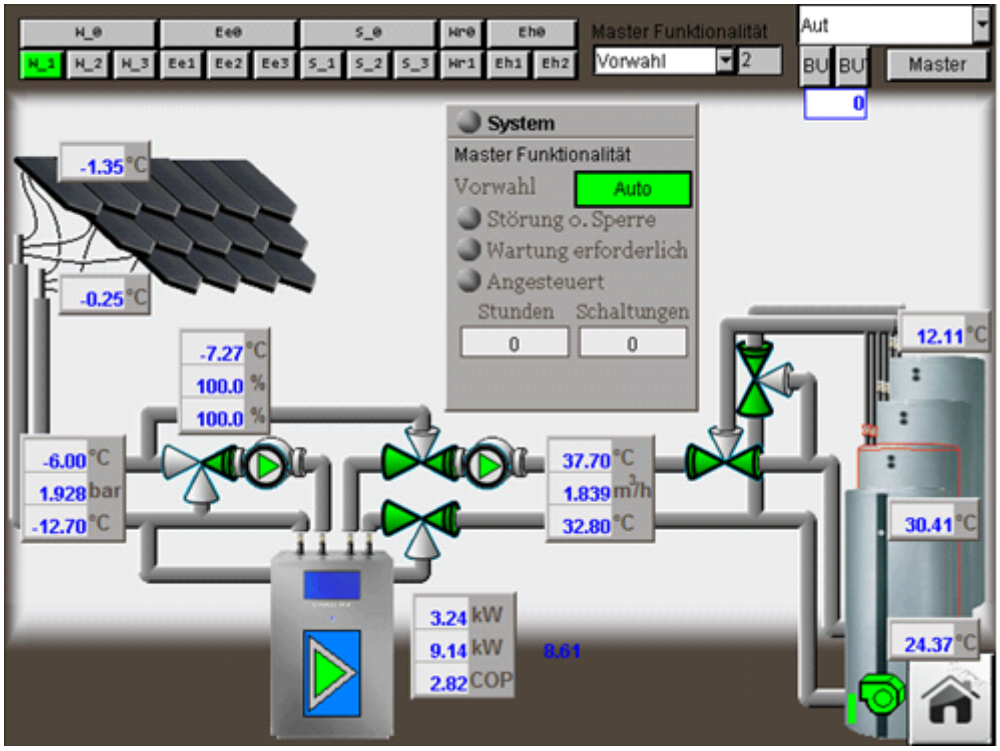


Figure 7: Running mode of the test system Dornach (System Atmova)

4.2 Influence on System response

Both 100% on-time (continuous heat pump operations) and switched (on/off) operations were tested. It takes up to 2 minutes to reach thermodynamic stability with the heat pump. Therefore the standard rule of a minimum of 15 minutes run-time and a maximum power cycle frequency of 1 per hour are implemented in the ATMOVA specific controller, sending a simple heat request signal (dry relay contact) to the heat pump. In summary the behavior of the system is close to a standard ground source heat pump behavior.

4.3 Influences on COP/SPF

The measured COP does vary between 2.0 and 4.4. The COP is as a primary function of the absolute source temperature and a secondary function of the temperature span between the sources and sinks side of the heat pump.

The yearly SPF of the test installation is 6.2. An amount of 62'000 kWh of heat were produced with 10'000 kWh of electricity. This test was done in an accelerated test environment (3 months during winter season) with an infinite load to the heat pump (up to 100% on time of the heat pump to explore steady state operations as a function of weather conditions).

The higher the consumption of heat during the summer (e.g. swimming pool) the better the overall system performance. Worst case and best case simulations forecast a SPF between 4 and 10.

Figure 8 shows the temperatures of outdoor air and of roof tile for three cold winter days Dec. 18 to 21, 2009 and the respective COP in the test installation Dornach.

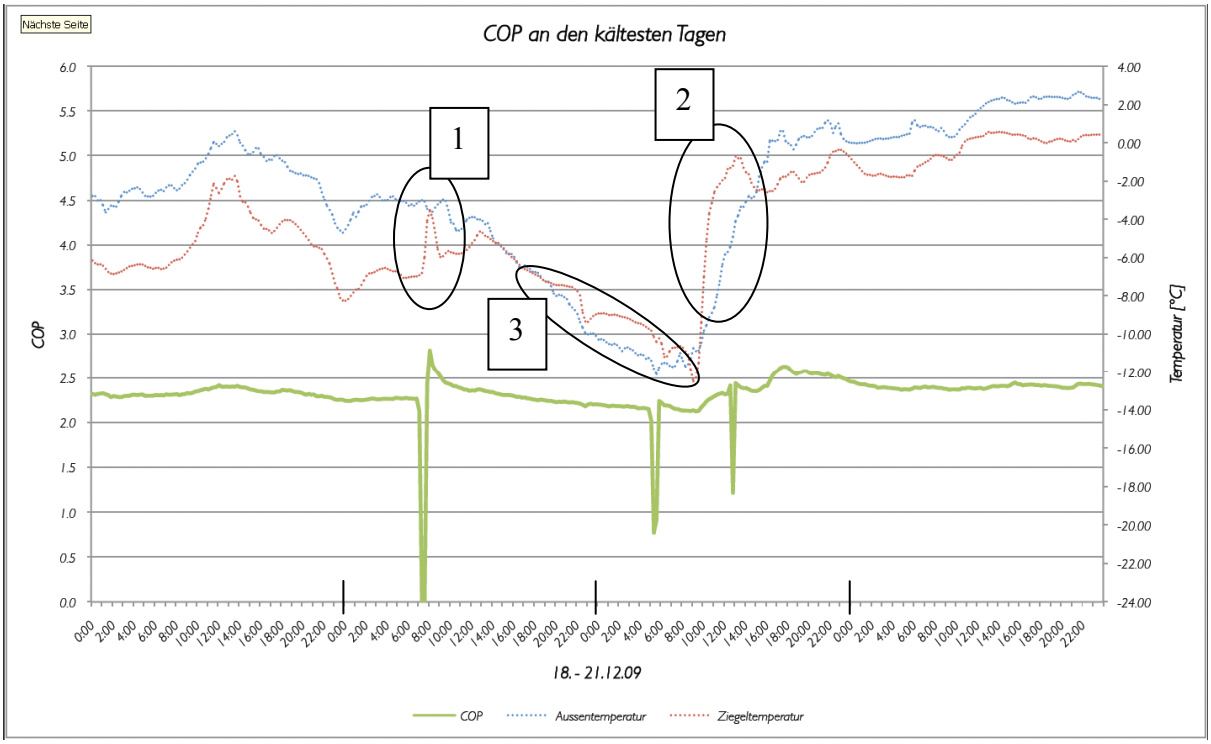


Figure 8: Temperatures and COP Dec. 18 to 21, 2009, coldest days of winter 2009.

During the runtime of the heat pump, the temperature of the roof tiles (red) is below the outdoor temperature (blue). In section 1, where the heat pump is “off”, the roof tile temperature reaches the outdoor temperature. In the morning of Dec. 20 sunshine warmed up the roof tiles to a higher level than outdoor air temperature, see section 2. In the night of Dec. 19 to 20, a manual deicing of the roof has been done in order to check the uniform brine flow through the roof tiles by means of infrared picture. That’s why the temperatures in section 3 differ. The COP’s are corresponding with the data sheet of the heat pump.

4.4 Special situations on the roof (Snow, Ice, rain)

Ice growing on the active roof tile surface is the result of condensation. The phase transition from vapor to solid state delivers a useful heat flow as long as the thickness of the ice layer remains limited to less than 10 mm. Deicing takes place with heat out of the heat storage tank, with heat that was produced with a COP of at least 2.0 or better. A roof pitch >35 degrees helps the deicing in that only a small film of liquid between the ice layer and the metallic surface needs to be created with deicing. Gravity lets slide the ice layer down the roof surface. Careful design of deicing algorithms and mechanical protection against flying ice blocks however is critical in this application.

Of all weather conditions only wet snow at temperatures around zero degrees Celsius appeared as difficult to manage (to deice). Snow is a thermal isolator and prevents the aperture to capture solar radiation and prevents normal air convection on the outer side of the roof. Since air circulation remains possible between the roof tiles inner side and the roof insulation there is no complete loss of heat flow mechanisms.
In worst case conditions snow results in source circuit temperatures falling under -15 °C.

Deicing algorithms for snow differ from pure ice. The system controller needs additional information to decide whether a deicing or a “desnowing” cycle is required.

4.5 Application historic building

In down town of Luzern a historic building of 15th century [4] is equipped since 02/2010 with this system: roof tile collector 120 m2, 3'800 tiles, each with 0.07 Litre of brine, Heat Pump Viessmann/SATAG BWH 240 with nominal capacity of 45.8 kW. 1000 Litre combi-tank with integrated 300 Litre domestic hot water tank.



Figure 9: Historic Building in Luzern with roof tile collectors system

5 CONCLUSIONS

The heat pump system with roof tiles demonstrates the feasibility of a hybrid solar collector and thermal interface to the environment. The functional integration of three functions (heating, cooling, domestic hot water) into this system requires specific hydraulics, electronics and control algorithms.

The two critical core elements are the source made of metallic roof tiles that survive at least 30'000 temperature cycles with a swing of 100K and EN12975 requirements and a wide source temperature range heat pump with a high COP at low source temperatures.

The system is an alternative, where Solar collectors and ground loop drillings are not possible or even forbidden. The application of the system for historic buildings is evident. After the pilot installations improvements for the cost effective application, especially the mounting of roof tile collector, through training of the installers are necessary.

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