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Experimental Investigation of a Novel Solar Cooling System Based On a Small-Scale Water/Silical Gel Adsorption Heat Pump

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Abstract

The paper presents the experimental investigation of the thermally driven "chillii® STC" heat pump for a novel solar cooling system. The system is developed for residential, commercial, and district heating/cooling applications in cooperation with CitrinSolar. The used chillii® STC is a water/silica gel adsorption heat pump of the SorTech AG with 5.5 kW cooling capacity and a compact design. For air-conditioning the heating temperatures are 75/67°C (heat source: solar, district heat, CHP unit), at cooling water temperatures of 27/32°C (wet cooling tower) and cold water temperatures of 18/15°C for cooled ceilings. The dimensions (length x depth x height) are 0.795 x 1.10 x 1.19 m and the operation weight is approximately 180 kg. The current experimental results of the first solar cooling installation at CitrinSolar office building showed cooling capacities in a range between 1.2 and 5.5 kW at heating temperatures of 57°C up to 80°C and different evaporator temperatures. The introduced test stand at SolarNext for testing heat pumps with cooling capacities up to 20 kW shows the possibility of testing the behaviour of heat pumps in any condition.

Introduction

Thermal cooling and heating by solar or waste heat could be lead to a clear reduction of the energy consumption and the CO_2 emissions. An assumption for thermal heat pumps is above all a very high solar fraction or betters a complete solar heating system, because low COPs lead rapidly to higher primary energy consumptions, if an additional heating system has to be used. For an economical operation of solar cooling systems the additional investment costs for the thermal heat pump technology have to be further reduced, which is expected at higher piece numbers. The market of solar cooling is still small: today in Europe approximately 8 to 9 MW of cooling capacity are installed. These are about 100 up to 120 solar cooling systems, which use solar thermal collectors for the solar air-conditioning of buildings. Most of the systems are realized in Germany and Spain. The IEA SHC Task 38, Solar Air-conditioning and Refrigeration, determined that approximately 11% of the installed systems are absorption heat pumps.

1. Heat pump chillii® STC

1.1 Functional description

The enclosed adsorption technique in general is based on temperature-dependent refrigerant adsorption capacity of certain solids. The refrigerant is adsorbed at the surface of a cooled solid at a low level of pressure and then desorbed and compressed by heating the solid. In the case of heat pump chillii® STC, developed and produced by the German company SorTech AG (Núnez et al., 2004), water as refrigerant and currently silica gel as adsorption medium are employed.

There are three external circuits of water at different temperature levels, high (HT, heating), medium (MT, recooling) and low (LT, cold) temperature, connected to secondary-medium-side of the heat exchangers in the heat pump. The working process can be described in following phases:

- During the adsorption phase vaporous water as refrigerant gets aspired out of the evaporator by the high adsorption capacity of the cooled solid. At the large effective surface of silica gel located in between fins of a finned-tube heat exchanger vapour is adsorbed. The thereby released latent and evaporation heat is received by a cooling water circuit, which in heating mode of the heat pump is the circuit for useful heat.
- In the following desorption phase heating water is passing through the same heat exchanger. Getting warmer the adsorption capacity of the solid

decreases, vapour pressure increases and the vapour flows into the now connected, cooled condenser. There again latent heat during condensation is received by the cooling water circuit.

- Condensed water is led to the evaporator via a u-shaped-tube as hydrostatic expansion valve to separate the different levels of pressure. During evaporation the cold water circuit of the heat pump passing through the evaporator provides the evaporation heat and thereby gets cooled.

To run this process continuously, it is necessary having at least two of these adsorption-desorption-modules alternating. A hydraulic switching unit connects the two desorber/adsorber modules once to the medium and once to the high temperature circuit.

There respectively is a short-term intermediate phase of heat transfer between the phases of adsorption and desorption. Then heat out of the former desorption-module is transferred into the former adsorption-module. The duration of the phases and with it of the whole cycle is between 5 and 30 minutes, depending on the required heating or cooling capacity. **Figure 1** shows the periodical characteristic of the temperatures shifting in every circuit connected to the heat pump. Depending on the employed storage sizes or load dimensions also the returns into the heat pump show this periodical behaviour.

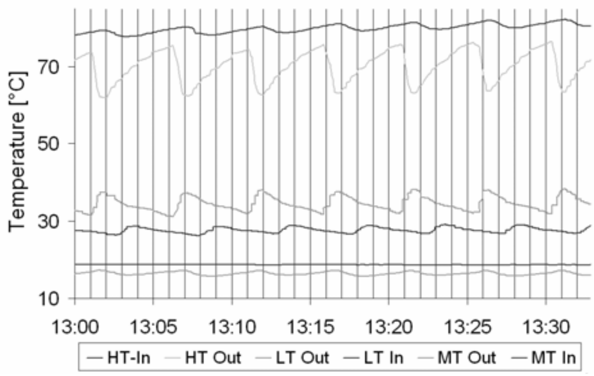

Figure 1 Periodical course of temperatures in the three external circuits passing through the heat pump

Providing signals for the valves of the hydraulic switching unit, an internal control unit makes sure proper operation of each module. A schematic view of the heat pump is shown in **Figure 2**. There are flapping return valves connecting the two adsorption modules with the condenser and evaporator cases. As there is no need of internal mechanical pumps the only moving parts in the whole heat pump are two pairs of three-pass-valves in the switching unit. All heat exchangers are assembled into one single vacuum tight container forming a sealed unit. This box is thermally insulated and then connected to the surroundings only by the hydraulic piping and an evacuation valve.

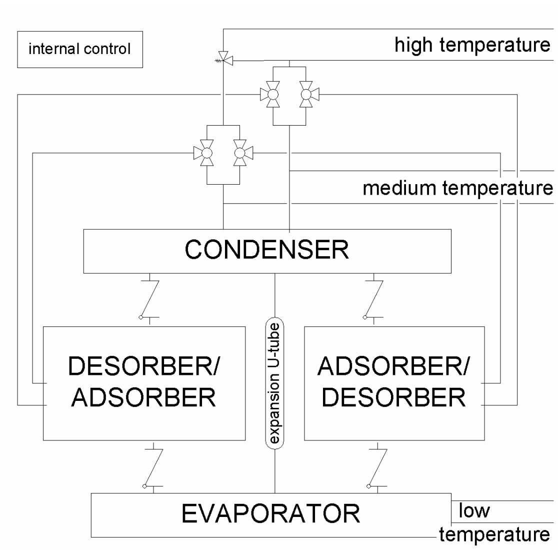

Figure 2 Schematic plan of the chillii® STC adsorption heat pump including the hydraulic switching unit

1.2 Design values of the heat pump

Since the desorption of the adsorbed water and the generation of pressure for condensation purposes using silica gel as adsorbent is already achieved at low heating temperature of 65°C to 90°C (SorTech, 2007), this technology is especially suitable for the application of solar energy. However the modules are designed such, that other sorption materials may prospectively be used as well. Design temperatures of the recooling circuit are 20°C to 35°C at the machine inlet and accordingly 25°C to 40°C at the outlet. In cooling mode of the chiller this waste heat has to be dejected through any kind of recooling device (wet cooling tower or dry cooler), while in heating mode water at this temperature level may be distributed in wall or floor heating installations. Chilled water of 6°C to 20°C can be used in fan coils or cooling ceilings as well as in central air conditioning units in cooling mode. In heating mode there should be some kind of low temperature heat source like a ground heat exchanger.

In the following some specific figures of operation of the heat pump chillii® STC6 in cooling mode will be presented. For heating temperatures of 90/83°C cold water temperatures of 12/7°C for fan coils can be achieved. In this case temperatures in the recooling circuit are set 27/32°C (wet cooling tower). At the same recooling temperature producing 18/15°C cold water temperature for cooling ceilings leads to a COP of 0.53; the nominal cooling capacity is 5.5 kW. This is valid for heating temperatures of 75/67°C. Descending to lower recooling temperatures makes operation of the chiller much more effective.

1.3 chillii®STC6 - the basic component in solar cooling systems

The very compact design of the chillii® STC adsorption heat pump (**Figure 3**), with outer dimensions (length x depth x height) of 0.795 x 1.10 x 1.19 m and an operation weight of approximately 180 kg, as well as low necessary heating temperatures greatly benefits the employment of the chillii® STC adsorption heat pump as chiller within solar cooling systems.

Figure 3 Heat pump chillii® STC6 (source: SorTech)

The required area of solar collectors would be about 20 m² for the chiller, storages of about 1,000 l for heating and 500 l for cold water help to buffer during shorter cloudy periods. The necessary temperature level of 65°C to 75°C can be provided by common flat plate collectors. Thus in many cases a solar cooling system based on this chiller will offer an effective capacity utilisation of abundant summery heat provided by solar thermal plants for heating support.

2. Solar cooling installation

First experiences with the chillii® STC6 are being gained at CitrinSolar GmbH Headquarter in Moosburg, Germany (**Figure 4**). The adsorption chiller is used for air conditioning of the offices and training classrooms. The distribution of the cold is realized by both fan coils as well as with connection to the ventilation system.

Figure 4 CitrinSolar GmbH office building

For simultaneous operation the driving energy is provided by twelve CS100 flat plate collectors (approx. 18 m²). In order to ensure high solar fraction further collectors can be connected achieving an overall collector surface of up to 90 m². The surplus thermal heat is transferred in to storage tanks with an overall volume of 7,500 l. A further storage tank of 1,000 l capacity is integrated into the cooling cycle (**Figure 5**) thus enabling to preserve a specific quantity of cooling energy and cope with power peaks exceeding the nominal load of the chiller.

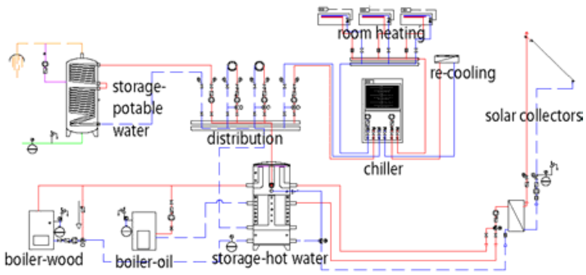

Figure 5 Simplified schematic view of the solar heating and cooling plant at CitrinSolar, Germany

One of the main reasons to operate solar driven chillers is the reduction of primary energy. Therefore, great emphasize is put on a high electrical coefficient (COP_{el}) and the resulting high coefficient related to the applied primary energy (COP_{PE}). In order to comply with the demands the proportion of fossil fuels as driving energy has to be limited. Under economical point of view a high solar fraction will also be realized specially with respect to the trivalent usage of solar energy. In this combination solar heat is used for water heating, supporting heating and solar cooling spread over the year.

The electrical power consumption of the chiller which will, of course, call for primary energy usage is mainly generated by auxiliary units. The adsorption chiller itself requires only few watts. Hence reductions need to be made especially with respect to the heat exchanger. A large dimensioned dry cooler is applied, whose fan can be infinitely adjusted depending on fluid temperature and some further factors.

3. Experimental results

So far it can be stated that the chillii® STC6 is most suitable for the operation with solar heat. At heating temperatures at about 75ºC the nominal cooling capacity of 5 kW is achieved (**Figure 6**). The reached cooling capacities are 1.2 to 5.5 kW at heating temperatures of 57°C up to 80°C and different cold temperatures. The average COP is 0.5. With heating temperatures up to 90ºC the nominal cooling capacity is even exceeded. The possibility of the adsorption chiller to still produce cold at a heating temperature of 55ºC is a most essential advantage compared with an absorption chiller. With this kind of flexibility the chillii® STC6 will assert its position under practical operation.

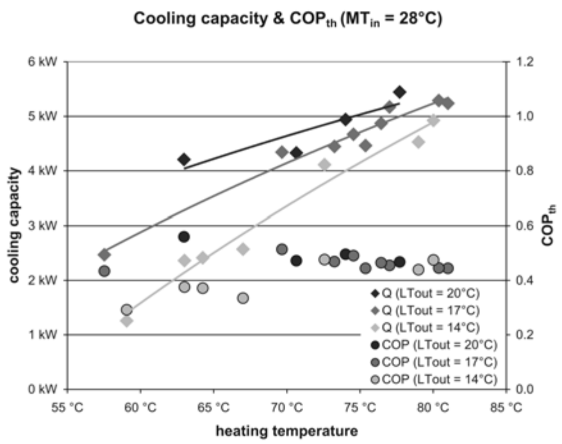

Figure 6 Measured cooling capacities and COP versus heating temperature

The control developed ensures also easy electrical connection with the complete plant (**Figure 7**). Nearly all cold consumers independent from model and manufacturer brand can be operated by the unit and will be in a position to put forward their cold requirements. With a control tuned for a specific object, even the usage of waste heat can be controlled individually and will thereby, for example, allow for the heating of swimming pool water. With this particular strategy the chillii® STC6 can be integrated into existing periphery at minimum efforts and will replace conventional chillers. Ease of use and low maintenance operation form a most convenient basis for the use of the chillii® STC6 in office buildings and, in the near future, in private households.

Figure 7 chillii®STC6 with cold storage tank, control and measurement devices

4. Advanced test equipment for heat pumps

There will be an experimental rig at SolarNext in Rimsting/Germany for testing heat pumps / chillers with cooling capacities up to 20 kW under various controlled conditions. Therefore inlet temperatures and flow rates of all of the three external circuits passing the heat pump can be adjusted independently from each other over a wide range. This provides the possibility of testing the behaviour of heat pumps in any condition. Absolute temperatures, temperature difference between inlet and outlet of every heat exchanger may be varied as well as every state of part load operation can be simulated.

The setup facilitates simultaneous testing of recooling components nearly independently from current chiller testing conditions as the circuits are indirectly in contact through a buffer storage but may as well be run almost stand alone. Current recooling devices are one dry cooling tower and alternatively for lower re-cooling temperatures one hybrid cooling tower, both using ec-ventilators.

Heating with up to 150°C hot water in the high temperature circuit is provided by an electric heater, whose output temperature spontaneously adapts to externally set values. The power output of this tempering device adds up to 40 kW.

One part of the necessary heat sink for the medium temperature circuit, which constitutes heat rejection in cooling mode and useful heat in heating mode of the heat pump, will be a buffering storage. This flown through component of the medium temperature circuit gets cooled via an internal heat exchanger by cold water produced in the chiller.

Residual waste heat will be dissipated in any kind of recooling device or, in case of need, may be transferred to fresh water through an external plate heat exchanger. Flow rate in the heat pump is adjusted by a continuously variable two pass valve. A three pass valve is able to alloy the intended temperature for the machine inlet, as reflux temperature from storage and re-cooling components basically is kept slightly lower than the desired value.

Analogue procedure using two continuously variable valves is applied for keeping temperature and flow rate of the return of cold water into the chiller exactly at externally chosen values. Therefore produced cold water is reheated via the above mentioned heat exchanger inside the storage to a temperature level something above targeted reflux temperature. A schematic view of the test rig is shown in Figure 8.

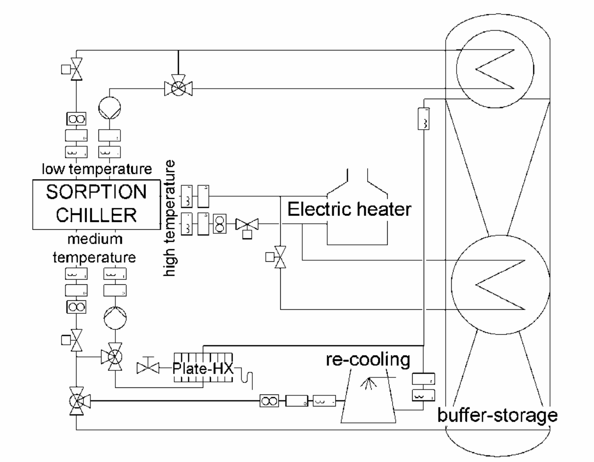

Figure 8 Hydraulic plan of the experimental rig installed at SolarNext

Cold and medium temperature circuits flow is generated by external pumps, the hot water flow by an integrated pump in the electric heating device. All pumps work without external regulation, as the flow rate is adjusted by valves.

While testing heat pumps within this station simultaneously recooling systems like wet or dry cooling towers can be operated and researched. The whole waste heat, respectively useful heat in heating mode, produced by the heat pump is then available for testing capacities and performance of these re-cooling facilities. In this case the storage will be heated by the electric heater via a second internal heat exchanger, maintaining the possibility to adjust the inlet temperature of the evaporator independently.

Measurement of flow rates and temperatures of interest are done having numerous adapted sensors in every circuit. Pressure losses over the internal heat exchangers as part of the chiller and cooling tower investigation are measured by pressure sensors located at all machine inlets and outlets.

There is data acquisition with direct feedback for the controlled process variables. Data for operation modes like the simulation of solar based heating in the course of day, taking into consideration the effects on recooling and cooling demand corresponding to specific weather data files, may be externally given and all measurement values accordingly recorded.

Ambient conditions like outside temperature only have marginal influence on the potential of the testing rig, but do not at all affect preconditions or results of measurements of the chillers performance. Thus this experimental setup provides a year round testing facility for all kind of small size heat pumps. The ability to simulate all user-defined conditions renders research of the potential of chillers especially within solar cooling systems possible.

Conclusion

A small-scale water/silica gel adsorption heat pump with nominal 5.5 kW cooling capacity, the chillii® STC6, is presented for a novel solar cooling system. Up to now the results of the first installed solar cooling installation at CitrinSolar office building showed cooling capacities in a range of 1.2 to 5.5 kW at heating temperatures of 57°C up to 80°C and different cold outlet temperatures of 14, 17 and 20°C, respectively. Advanced test equipment for heat pumps at SolarNext for testing heat pumps/chillers with cooling capacities up to 20 kW is introduced.

Nomenclature

CHP =combined heat and power unit
COP = coefficient of performance [-]
COP_{el} = coefficient of performance for electrical [-]
COP_{PE} = coefficient of performance for primary energy [-]
COP_{th} = coefficient of performance for thermal [-]
HT = high (heating) temperature [°C]
LT = low (cold) temperature [°C]
MT = medium (recooling) temperature [°C]

Literature Cited

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