

DEVELOPMENT OF AN ADSORPTION CHILLER AND HEAT PUMP FOR DOMESTIC HEATING AND AIR-CONDITIONING APPLICATIONS

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ABSTRACT

The scope of this paper is to present the development of a prototype of a small adsorption heat pump working on the adsorption pair silica gel - water. The development of this prototype with remarkable high power densities has been carried out during the last year and is a result of continued joint work on adsorption heat transformation systems carried out at SorTech AG and the Fraunhofer Institute.

Keywords: adsorption, chiller, heat pump, silica gel, solar cooling

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INTRODUCTION

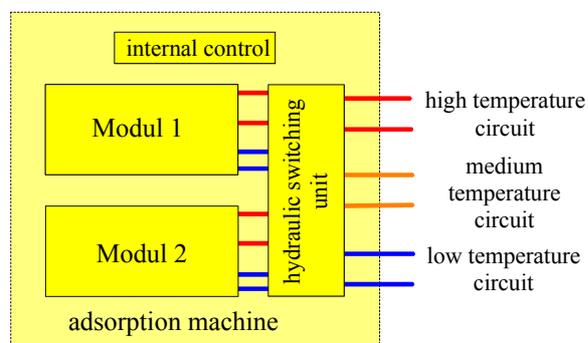
With the aim to reduce the amount of primary energy used for domestic heating purposes the introduction of heat driven heat pumps can provide a significant improvement in fossil fuel utilisation. Furthermore, if the design of the heat pump allows the additional use of its cooling properties, year round operation becomes possible using waste or solar heat in summer in order to provide cooling for air conditioning applications. Combining such a thermally driven heat pump / chiller with a combined heat and power system a tri-generation system for heat, cold and power is made available. But up to now no small power heat pumping system with such characteristics is available on the market although an increased demand is currently observed.

The results presented in this contribution are results obtained with the first and second prototype that has been constructed and tested in the last six months. Therefore they should be considered as preliminary results. The present machine has still a high potential for improvement and optimisation in the near future.

THE DEVELOPED HEAT PUMP PROTOTYPE

Description of the Heat Pump

The developed system consists of two identical modules. Each module contains a heat exchanger for the adsorption material and a second heat exchanger for evaporation and condensation of the process water. Both heat exchangers are assembled into one single vacuum tight container forming a sealed unit that is connected to the surroundings only by hydraulic piping. At the present stage of development the adsorption heat exchanger is filled with silica gel as adsorbent. But the



design of the reactor is such, that also other sorption materials could be used.

Both modules are interconnected through a hydraulic switching unit. This hydraulic unit connects both modules to the heat source and

sink and allows their operation in a quasi-continuous mode. An internal control unit ensures proper operation of each module providing the switching signals for the valves in the hydraulic unit switching between the different internal phases of the heat pump. In figure 1 a schematic of the heat pump is presented.

Figure 1. Schematic of the heat pump. The main components are: two modules, the hydraulic switching unit and the control unit.

The dimensions of both modules together without the hydraulic switching unit are 355mm x 520mm x 1360mm. The total weight of both modules is 258 kg. Each module is filled with about 35 kg of silica gel.

Operation

The two modules are designed in order to be operated with hot water at temperatures of 75°C-95°C. Design heating temperatures of 35°C to 40°C which are delivered in heating mode are suitable for low temperature heating systems such as wall or floor heating installations. For cooling application this is the temperature level of the heat rejection. In the cooling operation chilled water of 10°C to 15°C is produced in an almost continuous mode. Further on these three temperature levels are denoted T_{high} , T_{medium} and T_{low} . According to the type of operation the heat pump can be connected to different heat sources and sinks. Table 1 gives some possible connections.

Hydraulic circuit	Cooling application	Heating application
High temperature heat source (T_{high})	Driving heat source; e.g. solar system	Driving heat source, e.g. gas furnace
Medium temperature heat sink (T_{medium})	Heat rejection; e.g. dry or wet cooling tower; ground coupled heat exchanger	Useful heat, heating system
Low temperature heat source (T_{low})	Useful cooling, chilled water circuit	Low temperature heat source; e.g. ground heat exchanger

Table 1. Sources for the three temperature levels for heating and cooling applications of the sorption system

The two modules of the heat pump are operated in a periodic and phase-shifted mode. While one module is in its adsorbing phase the other module is being desorbed. This results in four consecutive operation phases of the four heat exchangers. The four phases are summarised in table 2. The duration of each phase and therefore the duration of the whole cycle depends on the required heating or cooling power. For the results presented here it is in the order of 15 to 30 minutes. During the phases of internal heat recovery no heating or cooling power is provided to the external circuits. These phases have a duration of about 30 to 60 seconds.

Phase	Ads. 1	Ads. 2	Evap./Cond. 1	Evap./Cond. 2
1	Desorption	Adsorption	Condensation	Evaporation
2	Heat transfer to Ads. 2	Heat exchange with Ads. 1	Heat transfer to Evap/Cond. 2	Heat exchange with Evap/Cond. 1
3	Adsorption	Desorption	Evaporation	Condensation
4	Heat exchange with Ads. 2	Heat transfer to Ads. 1	Heat exchange with Evap/Cond. 2	Heat transfer to Evap/Cond. 1

Table 2. Operation phases of the heat exchangers in the modules of the heat pump.

Measurements

The first tests of the system were carried out at the test facilities for heat driven heat pumps and chillers installed at SorTech AG. Different values of the driving temperature, the medium temperature and the low temperature were tested and the performance characteristics were obtained.

Measurements for the following operation conditions were carried out:

- Driving temperature T_{high} for desorption: 75°C, 85°C and 95°C. T_{high} is the *inlet* temperature of the reactor during the desorption phase
- Medium temperature T_{medium} : 25°C, 30°C and 35°C. T_{medium} is the *inlet* temperature to the reactor during the adsorption phase. For condensation it is the *inlet* temperature to the condenser.

- Low temperature: T_{low} to 10°C to 20°C.
 T_{low} is the *outlet* temperature of the evaporator.

All temperatures are measured in the pipes of heat exchangers, i.e. at inlet or outlet position to the heat pump.

In table 3 the nominal volume flows used during the tests are presented. These values are preliminary values and further tests with different volume flows will be carried out.

Circuit	Volume flow [l/h]
Low temperature	1600
Medium temperature	3200
High temperature	1600

Table 3. Volume flows in the three hydraulic circuits.

With these volume flows cooling powers P_{low} from 3 to 7 kW and heating powers P_{medium} from 8 to 22 kW are achieved. During one cycle the instant power of the three circuits is not constant as it can be seen in the temperature curves presented in figures 2 to 4. Therefore the mean power over the whole cycle has to be calculated. It is obtained by the exchanged heat at each temperature level during the cycle divided by the duration of the complete cycle:

$$P_{high} = \frac{Q_{high\ temperature}}{t_{cycle}}$$

$$P_{medium} = \frac{Q_{medium\ temperature}}{t_{cycle}}$$

$$P_{low} = \frac{Q_{low\ temperature}}{t_{cycle}}$$

The duration of the cycle t_{cycle} is the time necessary in order to complete the whole cycle consisting of the phases 1 to 4 of table 2.

The measured powers P_{low} were limited by the available power of the low temperature heat source. In the experiments presented in this contribution the power P_{low} was set to a nominal value and the resulting power of the other circuits was measured. The volume flows were kept fixed in all circuits. Lower volume flows as in table 3 are possible, but it has still to be studied how the reduced volume flows affect the power of the heat pump.

For the evaluation of the heat pump the cooling and heating COP have been calculated. The $COP_{cooling}$ of the machine is determined by the mean power in the high temperature and low temperature hydraulic circuits:

$$COP_{cooling} = \frac{P_{low}}{P_{high}}$$

The $COP_{heating}$ for heating applications is determined by the mean power in the medium temperature and the high temperature hydraulic circuits:

$$COP_{heating} = \frac{P_{medium}}{P_{high}}$$

In order to take into account all the different temperatures that are involved in the operation conditions of the machine a new parameter, namely the reduced temperature $T_{reduced}$ is defined. The reduced temperature $T_{reduced}$ is the fraction between the temperature difference between reactor and evaporator / condenser during the adsorption and the desorption phase. It gives an idea of the ratio of the ‘gained’ temperature difference (“temperature lift”) to the ‘driving’ temperature difference (“temperature drive”).

$$T_{reduced} = \frac{T_{medium} - T_{low}}{T_{high} - T_{medium}}$$

Figures 2 to 4 show an example of the temperatures in the hydraulic circuits.

In figure 2 a diagram of the temperatures in the inlet and outlet pipes of the reactors during the different cycle phases are presented. The value T_{A1_VL} is the inlet temperatures of the reactor 1, the value T_{A1_RL} is the outlet temperature. Corresponding temperatures of the reactor 2 are labelled with A2. In figure 3 the corresponding temperatures of the evaporator/condensers are shown. The two evaporator/condenser are labelled VK1 and VK2, respectively. In the application these values correspond to the temperature of the low temperature heat source in the heating mode and to the temperature of the produced cold water in the chilling mode. In figure 4 the temperatures in the medium temperature circuit are plotted. In the cooling mode this is the temperature of heat rejection and in the

heating mode the temperature of the heating system.

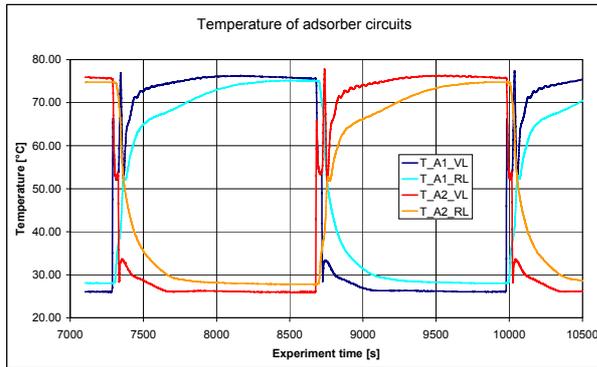


Figure 2. Diagram of the inlet (VL) and outlet (RL) temperatures of the two reactors in the four phases of the cycle.

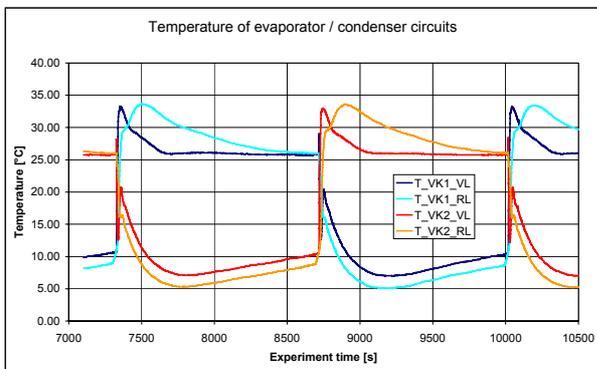


Figure 3. Diagram of the inlet (VL) and outlet (RL) temperature of the two evaporators/condensers in the four phases of the cycle.

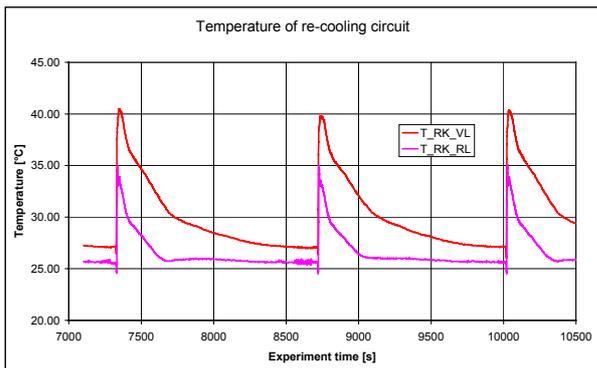


Figure 4. Diagram of the inlet (VL) and outlet (RL) temperatures in the medium temperature circuit during one whole cycle (cooling of adsorber and condenser).

In figure 2 it can be seen that each adsorber is going through a desorption and an adsorption phase. Between these phases a short heat recovery phase in which heat from the desorbed reactor is transferred to the adsorbed

reactor can be observed. The evaporator/condenser part in each module switches from condensing mode to evaporation mode during one cycle. The diagram of the medium temperature circuit shows the final result at the medium temperature level: in this circuit the heat from the adsorber in the desorbing phase and the heat from the condenser during condensation is combined and rejected together to the medium temperature heat sink.

In figure 5 the resulting heating and cooling powers for these operation conditions are presented. During most of the cycle the cooling power P_{low} is constant at about 3.5 kW. The heating power P_{medium} shows stronger variations between peak values above 25 kW at the beginning and about 5 kW at the end of each half-cycle. The reason for a constant cooling and non-constant heating power is to be found in the operation mode: the machine was operated with a constant cooling demand and the cycle evolved according to this constraint.

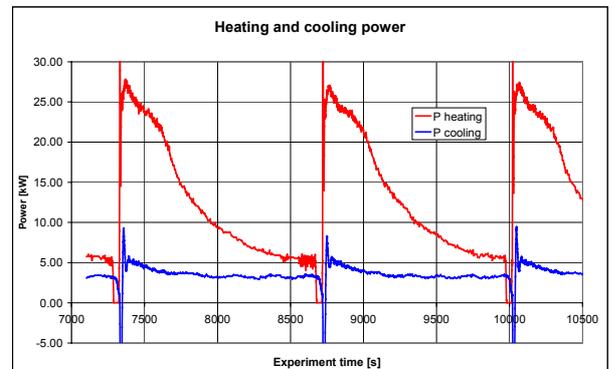


Figure 5. Heating and cooling power during one typical cycle. The machine was operated with a constant cooling demand.

The duration of the adsorption and desorption phase is an important optimisation parameter and is defined in the control procedure of the machine. The longer the adsorption phase is extended, the more water is adsorbed in the reactor. The adsorbent gets closer to the equilibrium loading at the given heat rejection temperature. This measure increases the COP of the machine. On the other hand it reduces the average power over the cycle as at the end of each adsorption phase, the process gets increasingly ineffective and only low powers

can be extracted. Therefore choosing the best cycle time is one of the important parameters for the control of the unit.

Results for COP and power

In the following the results for the COP and the power are presented as function of the reduced temperature. All the results were obtained for a nominal cooling power of 3.5 kW. In figure 6 the heating and cooling COP for different high, medium and low temperatures is presented. In figure 7 the corresponding results for the mean heating and cooling power are shown.

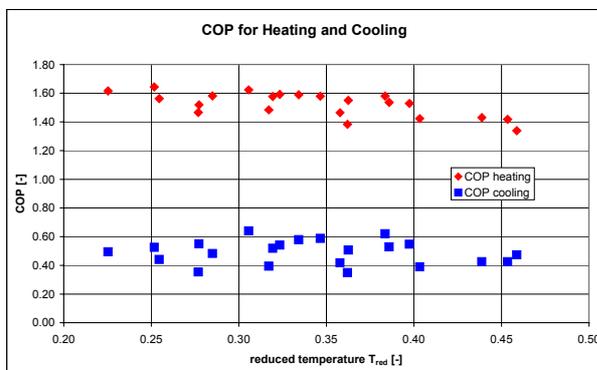


Figure 6. Heating and cooling COP as a function of the reduced temperature.

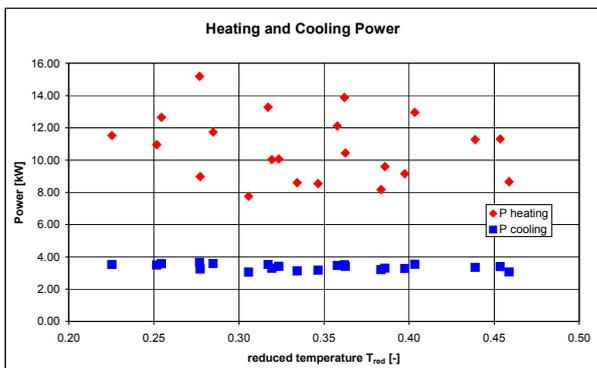


Figure 7. Mean heating and cooling power of the adsorption chiller as a function of the reduced temperature.

With the presented operation conditions of figure 6 and 7 an average $COP_{cooling}$ of around 0.5 and $COP_{heating}$ of 1.5 can be expected. At a constant cooling power P_{low} of 3.5 kW average heating powers P_{medium} of between 8 and 16 kW have been achieved. The exact results depend on the particular operation temperatures of the machine, but stay

remarkably constant over a wide range of values of the reduced temperature.

In figure 8 the improvements achieved during the development of the second prototype can be observed. In the diagram the results for the power density of the first prototype (labelled SWP2) at two nominal cooling powers and the results for the second prototype (labelled SWP3) at a nominal power of 3.5 kW is presented. It can be seen, that at the same cooling power output of 3.5 kW the new prototype achieves higher values of the reduced temperature. Higher reduced temperatures mean, that higher ‘temperature lifts’ are achieved with lower ‘temperature drives’. This indicates a better performance. The same is the case for the COP as can be seen in figure 9. The design of both prototypes is identical with only small improvements in their construction. The improvements are mainly due to an optimised control of the machine.

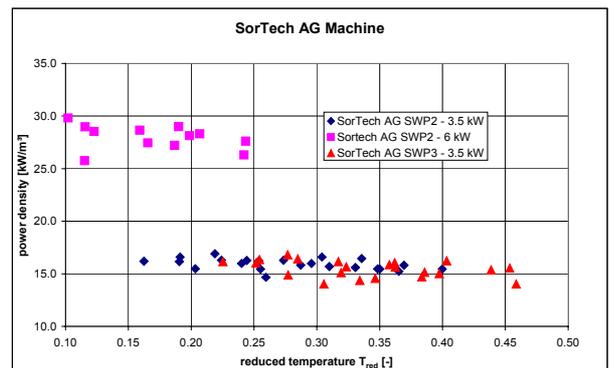


Figure 8. Improvement in the reduced temperature for two SorTech prototypes at the same cooling power output. SWP2 is the first, SWP3 the second prototype.

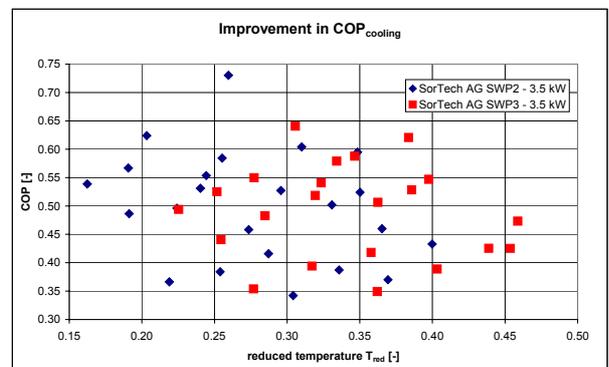


Figure 9. $COP_{cooling}$ for the two tested SorTech prototypes. The second prototype SWP3

shows the same range of COP values as SWP2 but at higher reduced temperatures.

Finally a comparison of the COP values and power densities of the SorTech machine with the manufacturer data of some comparable commercially available machines is presented.

The Nishiyodo NAK 20/70 machine is an adsorption chiller working with the adsorption pair silica gel – water and is available with cooling powers starting from 70kW. It has two periodic working adsorbers with one condenser and one evaporator connected to the reactors via self-activated vacuum valves. The presented data are manufacturers data [Nishiyodo].

The Yasaki WFC-SC10 machine is a small, 36 kW adsorption chiller working with the adsorption pair LiBr-Water. The presented data are manufacturers data [Yazaki].

In figure 10 the comparison of the cooling COP_{cooling}, and in figure 11 the comparison of the power density is presented. The power density is calculated by dividing the nominal power by the volume of the machine.

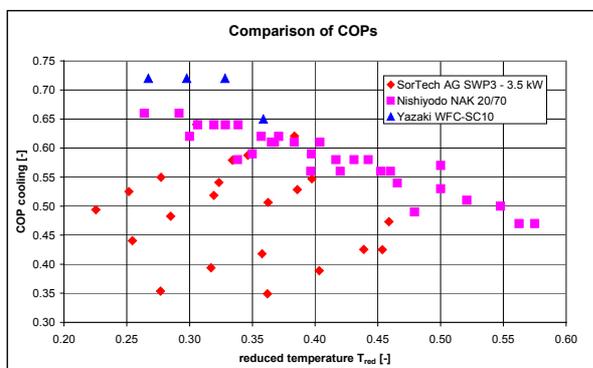


Figure 10 COP_{cooling} of the small power SorTech adsorption chiller compared to the results of commercially available chillers.

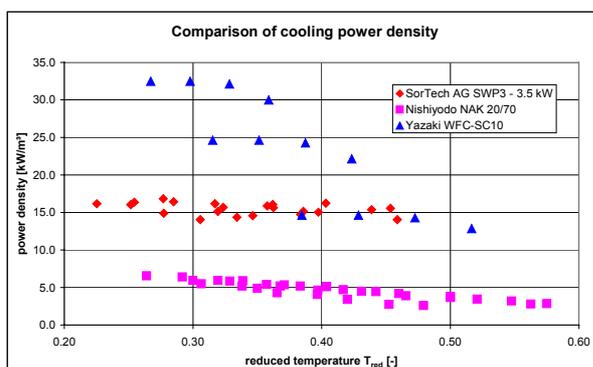


Figure 11. Cooling power density for the SorTech, Nishiyodo and Yazaki machines over the reduced temperature.

It can be seen, that the SorTech machine in its present development and optimization stage, shows COPs that are close to the values of the commercial machines. Nevertheless, the COPs are much more scattered than in the two other machines and the reached reduced temperatures are somewhat lower. These results are due to the fact, that in the SorTech machine the evaporator and condenser is integrated into one unit reducing therefore the COP_{cooling} value. On the other hand, with this design the machine gains compactness and simplicity as no internal valves are necessary. The results for the power density supports this fact. Here, the SorTech machine shows higher values than the NAK 20/70 adsorption machine. Nevertheless, both adsorption machines have lower densities than the Yazaki adsorption chiller.

CONCLUSIONS

The preliminary results of the first two prototypes of an adsorption chiller and heat pump shows a promising development. With the tested prototypes heating coefficient of performance of more than 1.5 and cooling COPs for air-conditioning purposes (12°C – 15°C) of 0.5 have been achieved. The machine is being developed for the market of small capacity chillers with nominal cooling powers in the range of 3 to 8 kW and nominal heating powers of up to 16 kW.

Using silica gel as adsorbent driving temperatures of 75°C are sufficient to operate the machine, but the developed design also allows the use of other adsorbents like zeolites if higher driving temperatures are available. A reliably working control procedure has been developed and implemented in the machine. Work will be continued in order to improve the operation and reliability of the prototype.

NOMENCLATURE

T_{high} : driving temperature for the heat pump (high temperature source), inlet temperature to the heat pump.

T_{medium} : re-cooling (cooling application) or heating temperature (heating application). Inlet temperature to the heat pump, temperature of the medium temperature sink.

T_{low} : cooling temperature. Outlet temperature of the heat pump, low temperature level.

T_{reduced} : reduced temperature

P_{high} : mean driving (desorption) power

P_{medium} : mean power at the medium temperature level.

P_{low} : mean cooling power.

t_{cycle} : cycle duration (phases 1 to 4)

$\text{COP}_{\text{cooling}}$: Coefficient of Performance for cooling

$\text{COP}_{\text{heating}}$: Coefficient of Performance for heating

A1: Adsorber 1

A2: Adsorber 2

VK1: Evaporator/condenser 1

VK2: Evaporator/condenser 2

RK: Re-cooling circuit

VL: inlet temperature

RL: outlet temperature

ACKNOWLEDGEMENTS

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