Measurement results of a hybrid adsorption-compression heat pump based on a roots compressor and silica gel-water sorption cycle

Michel van der Pal
Anton Wemmers
Simon Smeding
Jakobert Veldhuis

This paper will be presented at the ISHPC conference 2011, April 5-7 2011, Padua, Italy

ECN-M--11-029 MARCH 2011

MEASUREMENT RESULTS OF A HYBRID ADSORPTION-COMPRESSION HEAT PUMP BASED ON A ROOTS COMPRESSOR AND SILICA GEL-WATER SORPTION CYCLE

Michel van der Pal[a], *Anton Wemmers*[a], *Simon Smeding*[a], *Jakobert Veldhuis*[a]

[a] Energy research Centre of the Netherlands (ECN), P.O. Box 1, 1755 ZG, Petten,
vanderpal@ecn.nl

ABSTRACT

Thermally driven sorption systems can provide significant energy savings, especially in industrial applications. The driving temperature for operation of such systems limits the operating window and can be a barrier for market-introduction. By adding a work-driven compressor, the heat-driven cycle can be made with waste heat at lower temperatures. In this paper such heat pumps, using both the work potential from waste heat and work from a compressor, will be referred to as hybrid heat pumps.

ECN has a long history on sorption heat pump research, including both silica gel-water as well as ammonia-salt sorption systems, and has recently started the development of a hybrid heat pump. The final goal is to develop a hybrid heat pump for upgrading lower (<100°C) temperature industrial waste heat to above pinch temperatures. This heat pump will likely be based on the adsorption and desorption of ammonia on ammonia-salts and combine the continuous process of the compressor with the batch operated sorption reactors. The compressor for these heat pumps will typically run at a low pressure ratio (<3), to achieve high energy efficiency, and at relatively high volume-flows (>1000 m^3/hr).

The first tests on a hybrid heat pump are, however, conducted on a silica gel-water system that has been thoroughly tested earlier, in combination with a roots compressor. This paper will present the results of measurements on this hybrid heat pump system.

1. INTRODUCTION

In The Netherlands more than 100 PJ of heat in the refining and chemical industry is actively disposed of (see *Figure 1*). More than 20 PJ of this heat has a temperature of more than 100°C and can be used in a heat-driven heat pump to upgrade this industrial waste-heat to useful process heat, thereby reducing the industrial primary energy demand.

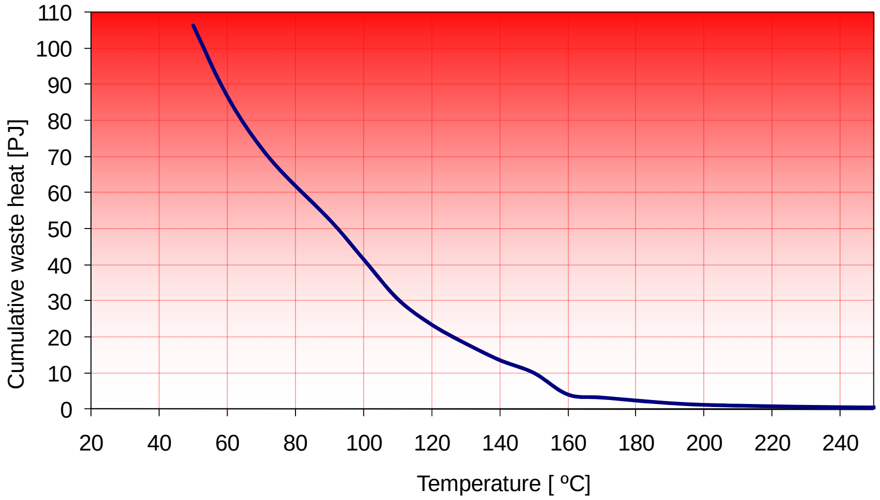

Figure 1. Cumulative waste heat in the refining and chemical industry in the Netherlands (Spoelstra et al., 2002).

After a review of potential heat pump technologies, a heat pump based on chemisorption of ammonia on salts was selected for further development at ECN. Industrial waste heat with a temperature between 100°C to 150°C can be upgraded to 180°C to 220°C to create medium-pressure steam. The sorption cycle is shown schematically in *Figure 2* with the colored arrows showing the heat flows into (at middle temperature) and out (at ambient and high temperature) of the system.

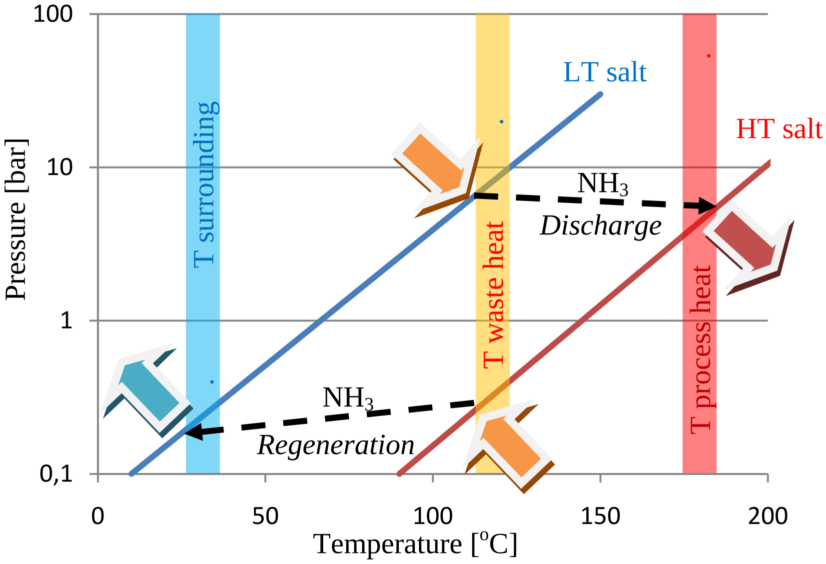

Figure 2. Schematic diagram of a heat-driven heat pump type II for upgrading (industrial) heat to a higher temperature. The blue and red line show the sorption line of respectively low and high temperature sorbent. The colored arrows show heat flows into (at middle temperature) and out (at ambient and high temperature) of the system.

The temperature lift that can be achieved using this cycle is limited by the chosen sorbents and waste heat temperature. The temperature lift decreases with decreasing waste heat temperatures. Assuming compressors can energy efficiently achieve a maximum of 50°C temperature lift and that this cycle is favored over a heat-driven cycle, the heat-driven heat pump type II requires a waste-heat temperature of more than 100°C.

By using a compressor, the operating window can be extended to lower waste heat temperatures. This is shown in *Figure 3*. The increase in pressure during the discharge phase of the cycle, allows the use of waste heat with a lower temperature. Model calculations have shown this hybrid cycle can reduce required waste-heat temperature (for a temperature lift of at least 50°C) to as low as 70°C and still yield net primary energy savings. For The Netherlands this means another 40PJ of waste heat can be reused (see *Figure 1*).

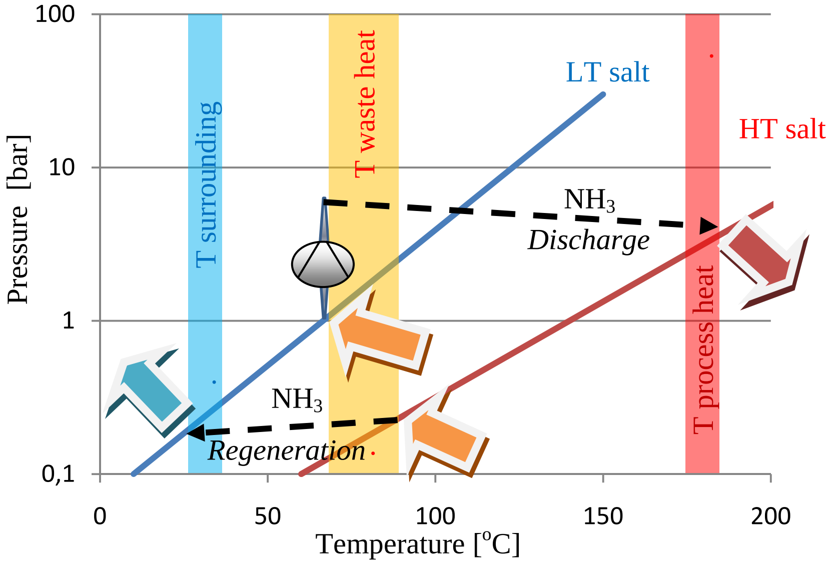

Figure 3. Schematic diagram of a hybrid compression - heat-driven heat pump for upgrading (industrial) heat to a higher temperature. The blue and red line show the sorption line of respectively low and high temperature sorbent. The colored arrows show heat flows into (at middle temperature) and out (at ambient and high temperature) of the system.

However, the combination of a batch-process (solid sorption heat pump) with the continuous operation of a compressor could result in unforeseen problems and/or lower than expected performance. To determine the effects of the hybrid operation, a combination of compressor with a reactor has been tested. Although our study (van der Pal et al., 2010) showed the ammonia-salt reactions of $CaCl_2$ and $MnCl_2$ as most energy efficient, for practical reasons a silica gel-water system was tested. This paper shows the results of these measurements.

2. MATERIALS AND METHODS

Experimental set-up

The system comprises of a condenser, evaporator and a reactor vessel. This setup has been described by De Boer et al (Boer et al., 2005). The reactor vessel contains a reactor consisting four silica gel filled Behr heat exchangers (Grisel et al., 2010). Each heat exchanger contains 1.5 kg of silica gel so the reactor contains 6 kg of silica gel in total. A heating and cooling rig is used to provide the reactor, condenser and evaporator with water at the desired temperature. During the regeneration phase of the cycle the reactor is heated to high temperature (60 to 90°C) while the condenser is kept at ambient temperature. During the discharge phase of the cycle the reactor is cooled down to ambient and the evaporator kept at desired cooling temperature. Valves with a timer are used to switch between the two phases. By measuring the temperature of the water entering and leaving the components (evaporator, condenser and reactor) and its flow rate, the amount of heat consumed or released can be calculated. Furthermore the temperature and pressures in the components are measured.

The compressor, type Falco WY1000B from Busch Ltd, is a roots-type compressor that provides a volume flow of up to 1200 m^3h^{-1}. The frequency of the compressor is controlled by a Vacon NXL frequency controller and can be varied between 0 and 60 Hz. The maximum power consumption is 3 kW electricity and is monitored with a Sineax P530 power meter. The compressor has a leak rate of less than $1 \cdot 10^{-6}$ $mbar \cdot l \cdot s^{-1}$. On the gas side of the compressor, the pressure and the temperature of the compressed gas are measured.

Measurements

The following four configurations (see *Figure 4*) were used in our measurements:

1) In configuration 1, the compressor is placed between the condesner and the evaporator. The performance of this regular compressor cycle is determined for a temperature of 10°C and 20°C on respectively the evaporator and the condenser. The frequency of the compressor was varied in 5 Hz steps between 15 and 30 Hz;
2) In configuration 2, the system contains the condenser, evaporator and the reactor. The performance of this pure heat-driven system is determined. The cycling times and temperatures on the evaporator, condenser and reactor were equal to the temperatures used in the hybrid configurations;
3) In configuration 3, all components are used. Placed between the evaporator and the reactor, the effect of the compressor on the discharge phase of the cycle is analyzed. The temperature of the evaporator and condenser are kept at respectively 12°C and 35°C whilst the reactor cycled in 2x6 minute intervals between 35°C and 85°C. The compressor frequency was set to 30Hz;
4) In configuration 4, all components are used. Placed between the reactor and the condenser, the effect of the compressor on the regeneration phase of the cycle is analyzed. The temperature of the evaporator and condenser are kept at respectively 12°C and 26°C whilst the reactor cycled in 2x6 minute intervals between 26°C and 71°C. The compressor frequency was set to 30Hz.

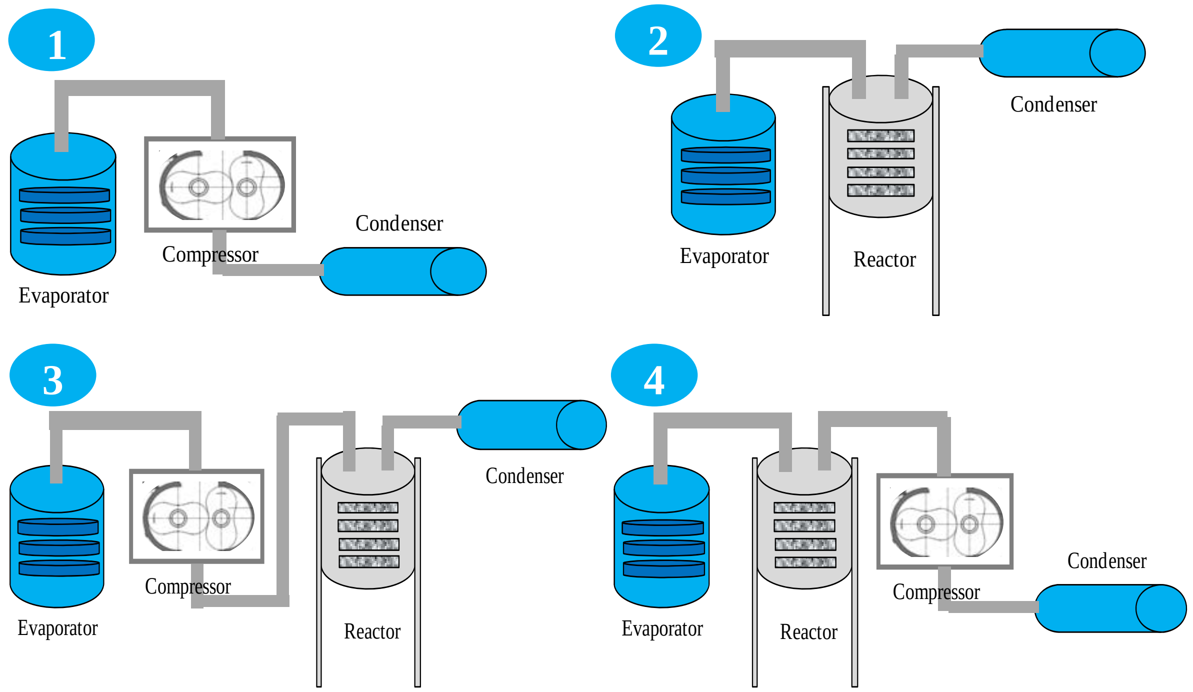

Figure 4. The four configurations for measuring system performance: 1 - continuous 'standard' compression, 2 - purely heat-driven sorption system, 3 - hybrid system with compression at low pressure and 4 – hybrid system with compression at high pressure.

3. RESULTS AND DISCUSSION

Figure 5 shows the results of the measurements with the compressor between the evaporator and condenser (configuration 1). The trends are according to expectations. The power used by the compressor increases with frequency. The increase in frequency also results in higher pressure ratios and increased condenser and chilling power. The compressed gas temperature also rises. This is due to both increased pressure ratio (= ratio pressure compressed/suction gas) as well as increased volume flow. For adiabatic process, the latter should not affect the compressed gas temperature. In practice, however, the gas loses a considerable amount of its heat before its temperature is measured. The overall electric efficiency of the compressor is low: the $COP_{electric}$ (ratio of chilling power/compressor power) is about 1.5 at 30 Hz operation. This is due to the poor properties of water vapor as refrigerant under given conditions and the type of compressor that has been used. Roots compressors are inherently energy inefficient.

Conditions:

Frequency	Hz	15	20	25	30
T cond in	°C	20.67	21.05	21.31	21.39
T evap in	°C	10.17	10.09	10.09	10.10

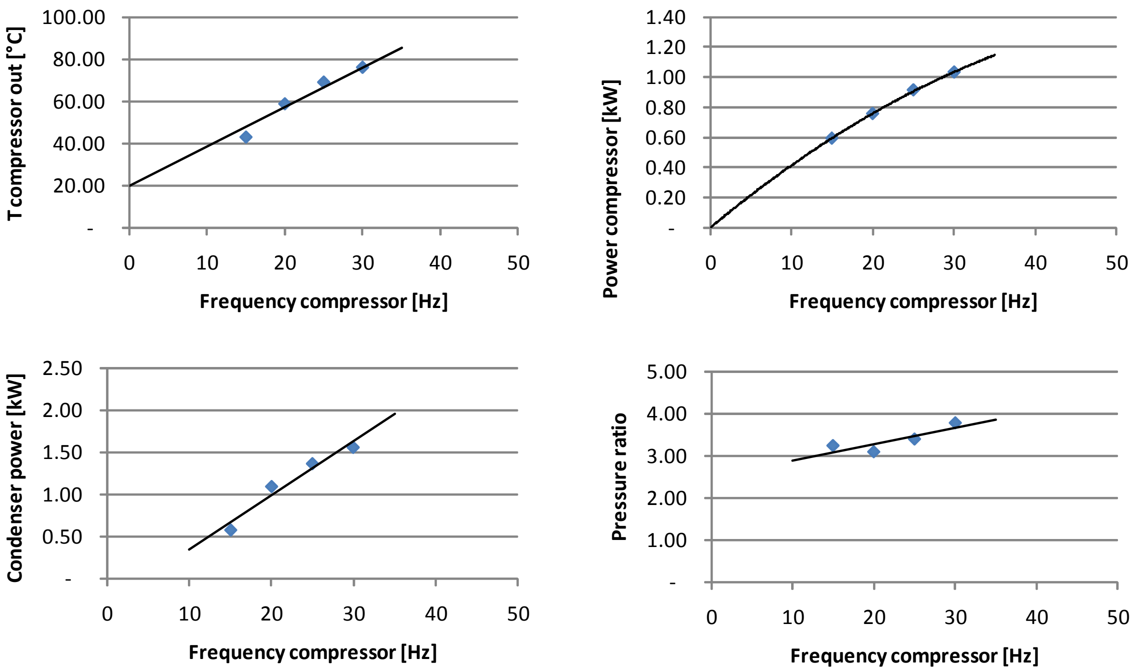

Figure 5. The compressed gas temperature, compressor power, condenser power and pressure ratio as a function of the compressor frequency for condenser and evaporator temperatures of respectively 20℃ and 10℃.

Figure 6 shows the results for configurations 2&3. The compressor has a clear effect on the performance compared to the heat-driven system: the chilling power increases from 0.7 kW to approximately 1.2 kW and the - for heat loss corrected - thermal efficiency ($COP_{thermal}$) increases from 40% to 60%. The effect of the compressor is also reflected in the pressure ratio.

Conditions:

Frequency Hz	0	30
T heating in °C	84.73	84.58
T cooling in °C	35.05	35.32
T evap in °C	12.57	11.74

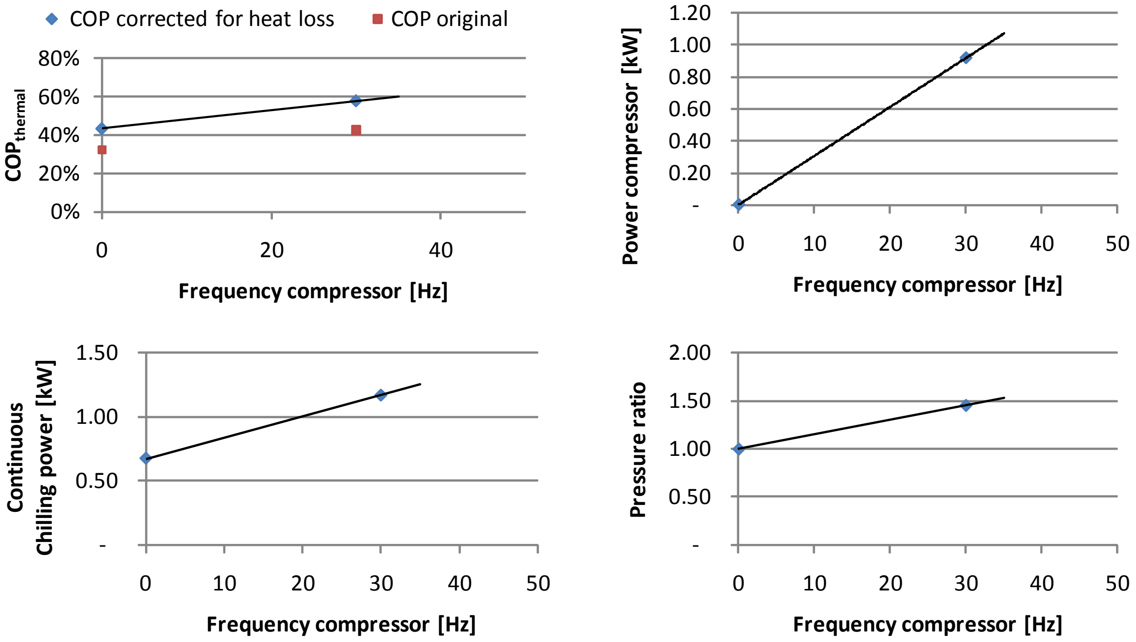

Figure 6.The thermal efficiency ($COP_{thermal}$), the compressor power, the chilling power and the pressure ratio for the heat-driven (frequency = 0 Hz) and hybrid (at frequency of 30 Hz) operation of the system where the compressor is placed between the evaporator and the reactor.

Figure 7 shows the results for configurations 2&4. The effect of the compressor seems only to be reflected in the increased pressure ratio. Despite this considerable effect on the pressure ratio, no significant effect on the chilling power is observed and there is only a slight (1%) increase in thermal efficiency. The cause for this small effect of the compressor might be found in the measured vapor pressure and the local temperature of the silica gel. These are plotted in the diagram of the isosteres of the silica gel (see *Figure 8*). The red line shows the hybrid cycle whilst the green line shows the heat-driven cycle. The presence of the compressor results in a considerable reduced pressure in the reactor during the regeneration cycle. The pressure-temperature relation at the end of the regeneration equals 12wt% for the heat-driven cycle and 4wt% for the hybrid operation. During the discharge cycle, the local temperature of the silica gel in hybrid operation remains higher than in the heat-driven cycle. As a result the temperature-pressure relation equals 20wt% for the hybrid operation compared to 28 wt% in the heat-driven cycle. This means in both cycles 16wt% of moisture is exchanged, resulting in similar chilling powers and COP values. The reduced temperature variation for the hybrid cycle could be caused by reduced thermal conductivity, either due to the reduced wt% moisture and/or the low vapor pressure.

Conditions:	Frequency Hz	0	30
	T heating in °C	71.39	71.30
	T cooling in °C	26.23	26.19
	T evap out °C	12.28	12.27

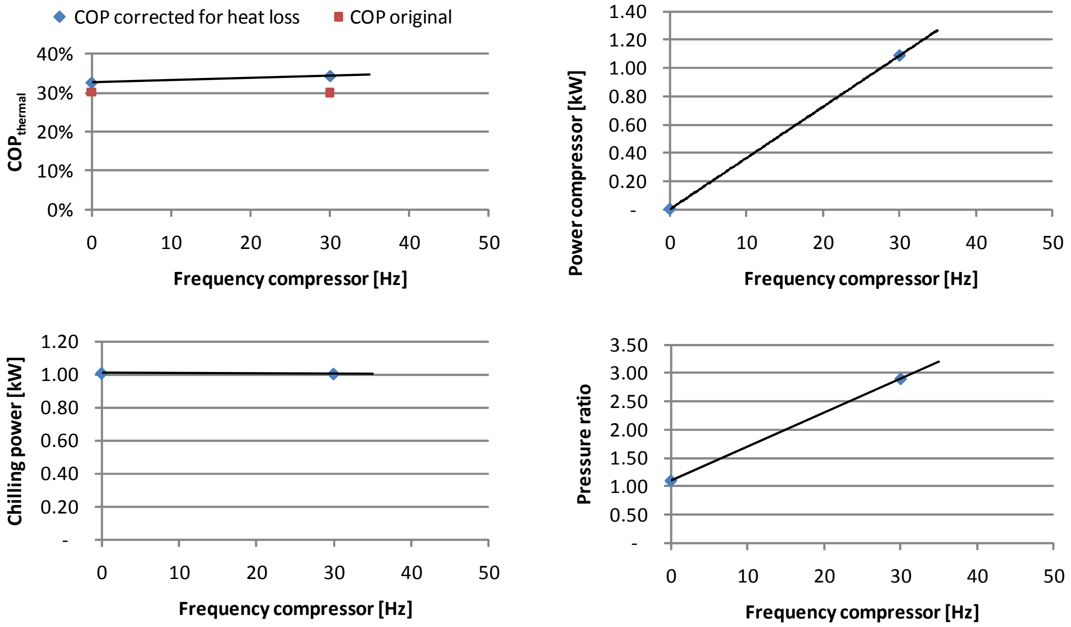

Figure 7.The thermal efficiency ($COP_{thermal}$), the compressor power, the chilling power and the pressure ratio for the heat-driven (frequency = 0 Hz) and hybrid (at frequency of 30 Hz) operation of the system where the compressor is placed between the reactor and the condenser.

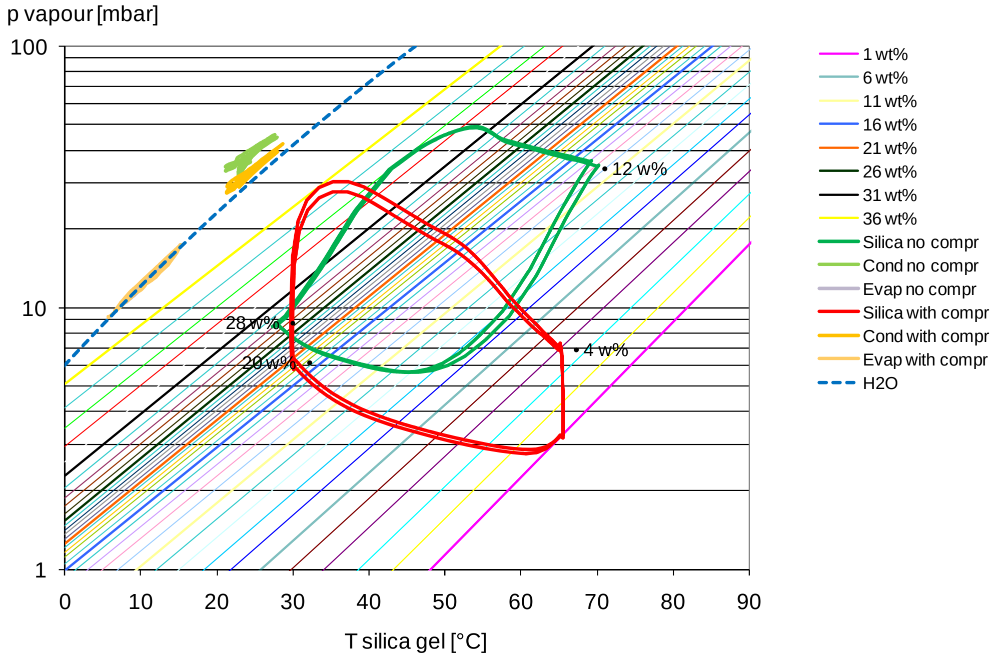

Figure 8. The pressure-temperature relation for silica gel (Restuccia et al., 1999). The green line shows the measured pressure-temperature of the silica gel for the heat-driven cycle whilst the red line shows the measured pressure and temperature of the silica gel measured during hybrid operation.

4. CONCLUSIONS AND RECOMMENDATIONS

From the measurements can be seen that the hybrid operation of the sorption-cycle can yield considerably higher chilling powers and $COP_{thermal}$ compared to the purely heat-driven cycle. However, this improvement does not necessary always occur as the results for Configuration 4 show. In this configuration, where the compressor is placed between reactor and condenser, hardly any improvement in chilling power or COP is measured. It is therefore important to consider the entire system of compressor and heat-driven components and their interaction. This could be done using model calculations.

ACKNOWLEDGEMENT

This work has been funded by AgentschapNL (Dutch agency for sustainable development and innovation) within the EOS-LT program, contract number EOSLT08026.

REFERENCE LIST

Boer, R. de, S. F. Smeding, R. J. H. Grisel (2005): *Development and testing of a sorbent filled heat exchanger for use in compact solid sorption cooling systems*. ECN-RX--05-121, 2005.

Grisel,R.J.H., S.F.Smeding, R.d.Boer, 2010, Waste Heat Driven Silica Gel/Water Adsorption Cooling in Trigeneration. *Applied Thermal Engineering,* 30 [8-9] : 1039-1046.

Restuccia, G., Yu.I. Aristov, G. Maggiot, G. Cacciola, M.M. Tokarev, 1999, *Performance of sorption system using new selective water sorbents. Proceedings of the International Sorption Heat Pump Conference, Munich, Germany, March 24-26, 1999*, pp. , ZAE Bayern: 219-223.

Spoelstra,S., W.G.Haije, J.W.Dijkstra, 2002, Techno-Economic Feasibility of High-Temperature High-Lift Chemical Heat Pumps for Upgrading Industrial Waste Heat. *Appl.Thermal Eng.*, 22 [14] : 1619-1630.

van der Pal, M., A. Wemmers, S. Smeding, K. van den Heuvel, 2010, *Study on performance of hybrid adsorption-compression type II heat pumps based on ammonia-salt adsorption. 9th International Conference on Sustainable Energy Technologies (SET 2010)*, pp. , a hybrid thermo-chemical adsorption-compression system.: CO13.