EXPERIMENTAL RESULTS AND MODEL CALCULATIONS OF A HYBRID ADSORPTION-COMPRESSION HEAT PUMP BASED ON A ROOTS COMPRESSOR AND SILICA GEL-WATER SORPTION

Michel van der Pal, Robert de Boer, Anton Wemmers, Simon Smeding, Jakobert Veldhuis, Jan-Aiso Lycklama a Nijeholt, Energy research Centre of the Netherlands (ECN)
P.O. Box 1, 1755 ZG, Petten, The Netherlands, 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 compressor, the sorption cycle can be run using lower waste heat temperatures.

ECN has recently started the development of such a hybrid heat pump. The final goal is to develop a hybrid heat pump for upgrading lower (<100ºC) temperature industrial waste heat to above pinch temperatures.

The paper presents the first measurements and model calculations of a hybrid heat pump system using a water-silica gel system combined with a Roots type compressor. From the measurements can be seen that the effect of the compressor is dependent on where in the cycle it is placed. When placed between the evaporator and the sorption reactor, it has a considerable larger effect compared to the compressor placed between the sorption reactor and the condenser. The latter hardly improves the performance compared to purely heat-driven operation. This shows the importance of studying the interaction between all components of the system. The model, which shows reasonable correlation with the measurements, could proof to be a valuable tool to determine the optimal hybrid heat pump configuration.

Keywords: sorption, heat pump, compressor, hybrid

1 INTRODUCTION

In The Netherlands more than 100 PJ of heat in the refining and chemical industry is actively disposed (Spoelstra et al. 2002). More than 40 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. After a review of potential heat pump technologies, a heat pump based on chemisorption of ammonia on solid 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 1 with the colored arrows showing the 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 determined by the chosen sorbents and waste heat temperature. The temperature lift decreases with decreasing waste heat temperatures. For a single-stage heat pump type II, a waste-heat temperature of more than 100°C is required to achieve a temperature lift of 50°C. Multi-stage heat pumps can achieve >50°C temperature lifts using lower waste heat temperatures but have poor efficiency. A 50°C temperature lift is considered the minimum temperature lift that is required for reusing waste heat. For temperature lifts smaller than 50°C, compressors form an attractive alternative, both in terms of energy efficiency and economy.

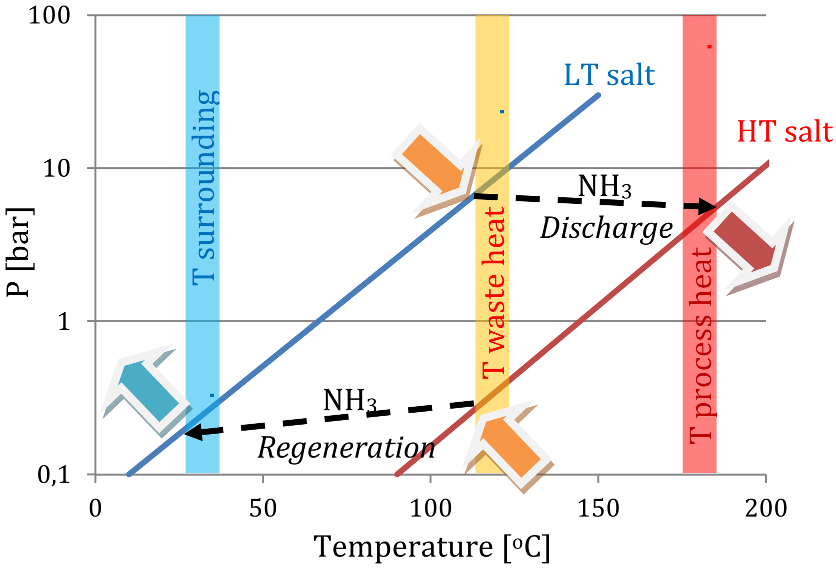

Figure 1: Schematic diagram of a heat-driven heat pump type II for upgrading (industrial) heat to a higher temperature. The blue and red lines show the sorption line of respectively low and high temperature sorbent. The colored arrows show heat flows into (at middle temperature) and out (at ambient and high temperature) of the system.

About 40 PJ of industrial waste heat in The Netherlands has a temperature between 70°C and 100°C. Extending the operating window of the sorption cycle to these lower waste heat temperatures would contribute significantly to the efficiency of the industrial energy use in The Netherlands. This extension can be achieved by adding a compression step to the cycle. This hybrid adsorption – compression cycle is schematically shown in Figure 2. 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 (van der Pal et al. 2010).

In order to make this cycle work, it is required to combine the continuous operation of the compressor with the sorption cycle. For solid sorbents, such as the ammonia salts, the latter is a batch operation. The combination of a batch-process with the continuous operation of the compressor could result in unforeseen problems and/or lower than expected performance. The objective of this study is to determine the effects of the hybrid operation, and therefore a combination of compressor with a sorption 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 water-silica gel system was tested.

Unlike ammonia-salt reactions, the adsorption of water vapor to the silica gel is a physisorption reaction. The performance of this process depends on an isosteres-field rather than the discrete transition between the adsorbed and the desorbed state that is found in chemisorption cycles. Also the temperature range the system can be operated is different than the foreseen application. Waste-heat with a maximum temperature of 90°C is used to create cooling rather than heating. This means the cycle as shown in Figure 1 is operated in reverse. In this mode, it is equal to a heat-driven cooling cycle. This paper shows the results of the measurements of the heat-driven and hybrid system based on adsorption of water vapor on silica gel. To get a better understanding of the measurements, an existing adsorption model has been adapted to describe the measurements. Also the model results are presented.

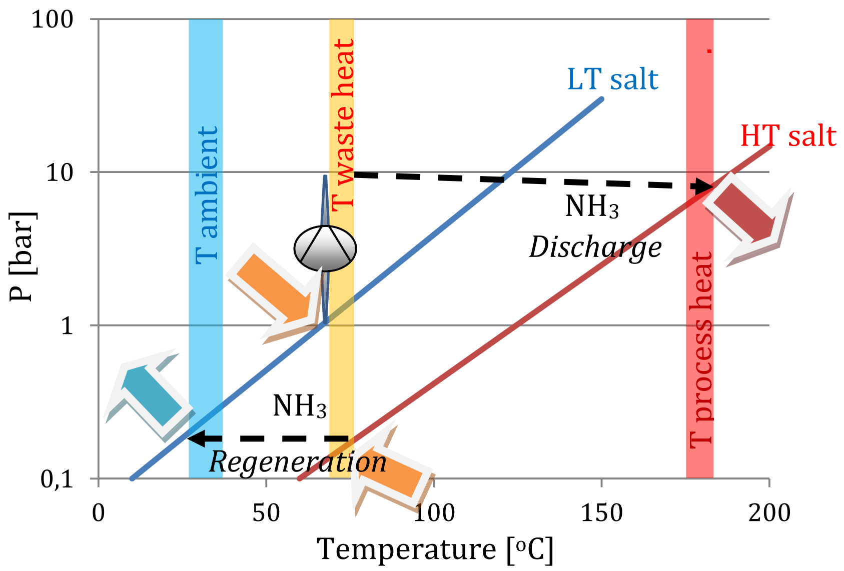

Figure 2: Schematic diagram of a hybrid adsorption - compression heat pump for upgrading (industrial) heat to a higher temperature. The blue and red lines show the sorption line of respectively low and high temperature sorbent. The colored arrows show heat flows into (at middle temperature) and out (at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

2 MATERIALS AND METHODS

2.1 Experimental set-up

The system consists of a condenser, evaporator and a reactor vessel. This setup has been described by Boer et al (Boer et al. 2005). The reactor vessel contains a sorption reactor consisting of four silica gel filled plate-fin heat exchangers (Grisel et al. 2010). Each heat exchanger contains 1.5 kg of silica gel, so the sorption reactor contains 6 kg of silica gel in total. A heating and cooling rig is used to provide the sorption reactor, condenser and evaporator with water at the desired temperature. During the regeneration phase of the cycle the sorption 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 sorption 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 sorption reactor) and its flow rate, the amount of heat consumed or released can be calculated. Furthermore the temperatures and pressures inside 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.

2.2 Measurements

The following four configurations (see Figure 3) were used in the measurements:

1) In configuration 1, the compressor is placed between the condenser 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 sorption reactor. The performance of this pure heat-driven system is determined. The conditions were identical to those in the measurements of the hybrid configurations;
3) In configuration 3, all components are used. The compressor is placed between the evaporator and the sorption reactor. Its effect on the discharge phase of the cycle is measured. The temperature of the evaporator and condenser are kept at respectively 12°C and 35°C whilst the sorption reactor cycled in 2x6 minute intervals between 35°C and 85°C. The compressor frequency was set to 30 Hz;
4) In configuration 4, all components are used. The compressor is placed between the sorption reactor and the condenser. Its effect on the regeneration phase of the cycle is measured. The temperature of the evaporator and condenser are kept at respectively 12°C and 26°C whilst the sorption reactor cycled in 2x6 minute intervals between 26°C and 71°C. The compressor frequency was set to 30Hz.

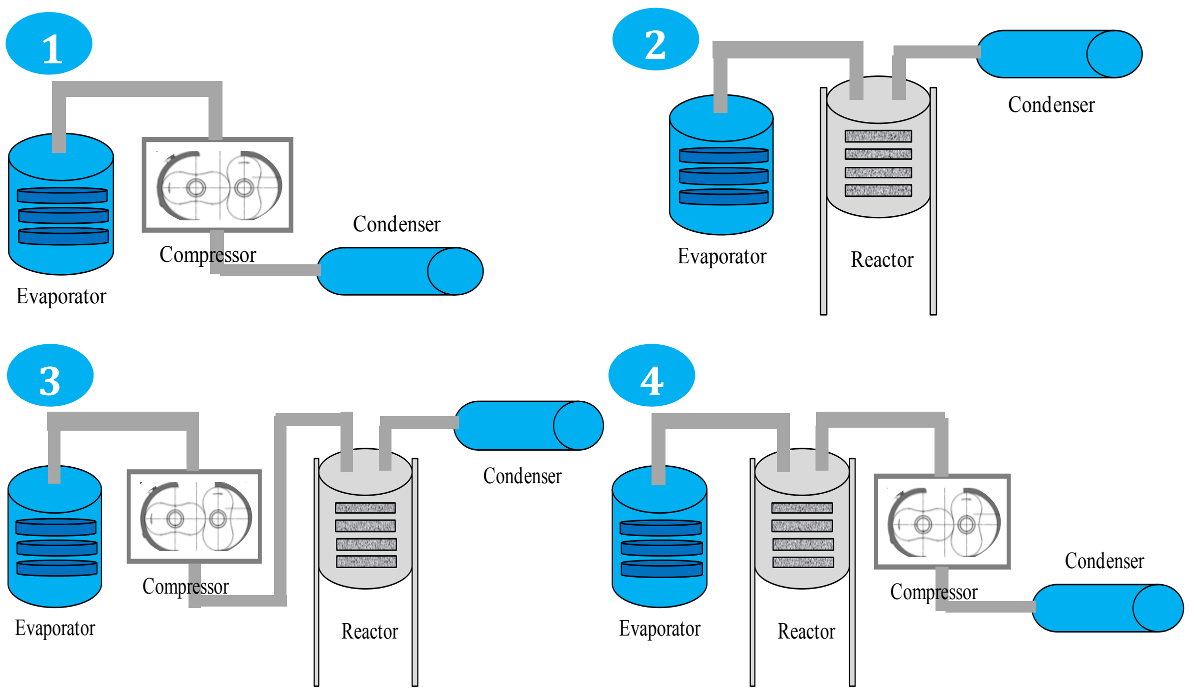

Figure 3: The four configurations for measuring system performance: 1 - continuous 'standard' compression, 2 - purely heat-driven sorption system, 3 - hybrid system with compression at low pressure and 4 – hybrid system with compression at high pressure

2.3 Model calculations

For the model calculations, an adapted version of the Matlab-Simulink model developed by the University of Valencia (Verde et al. 2010) was used. This model originally described the heat and mass transfer in a water-zeolite vapor sorption heat pump for automobile applications. The model is a transient model with (among others) the following assumptions:

- Non-equilibrium conditions with a simple kinetic model
- Zero-dimensional (i.e. uniform temperature distribution in each operating unit).
- The pressure at the sorption reactor depends on the instantaneous mass of vapor contained inside.
- The flow of water vapor between the sorption reactor, the condenser and evaporator is governed by the pressure difference between them and the position of the valves.
- The heat exchangers are characterized by their global UA value (W/K). For the sorption reactor heat exchangers, a detailed analytical study was carried out in order to estimate an adequate UA value depending on the sorbent thermal properties as well as the geometrical characteristics of the sorption reactor.

A detailed description of the model can be found here (Verde et al. 2010).

To use the model for our measurements, some changes in the model were required. These include:

- The original model used two sorption reactors to provide continuous cooling. The measurements were conducted on 1 sorption reactor. Therefore the number of active sorption reactors was reduced to one by setting the vapor flow to the second sorption reactor to zero;
- The isosteres data for zeolite were substituted with the data of the silica gel isosteres (Restuccia et al. 1999);
- The dimensions of the automobile sorption reactor were substituted with the dimensions of the sorption reactor based on the four plate-fin heat exchangers;
- The thermal masses of the sorption reactor were adapted to current system;
- The evaporator and condenser properties were adapted to current system.

To use the model for hybrid operation, some additional changes were made. The pressure step created by the compressor was used as a transient input parameter for the model calculations. Depending on the configuration, this pressure step was set between the evaporator and the sorption reactor (configuration 3) or the sorption reactor and the condenser (configuration 4). Because the pressure step was a set parameter, the flow resistance between the components was set (close to) zero. Also, the original model would directly connect the condenser and evaporator in case the pressure of the condenser is lower than in the evaporator. This option was disabled for the (hybrid) system because such shortcut was not made in the measurements.

3 RESULTS

3.1 Measurement results

Figure 4 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 discharge/suction gas) as well as increased volume flow. For an 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 likely due to the poor properties of water vapor as refrigerant under given conditions and the Roots-type compressor, which is not energy efficient.

Table 1 shows the results for hybrid operation with compressor between evaporator and sorption reactor compared to heat-driven operation. The $COP_{thermal}$ is defined as the amount of heat extracted by the evaporator divided by the amount of heating required for the regeneration of the reactor (at $T_{heating}$). The $COP_{electric}$ is defined as the amount of heat extracted by the evaporator divided by the amount of electricity consumed. The compressor has a significant effect on the performance compared to the heat-driven system. The chilling power increases from 0.7 kW to 1.2 kW and the - for heat loss corrected - thermal efficiency ($COP_{thermal}$) increases from 0.41 to 0.59.

Conditions:

Frequentie 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

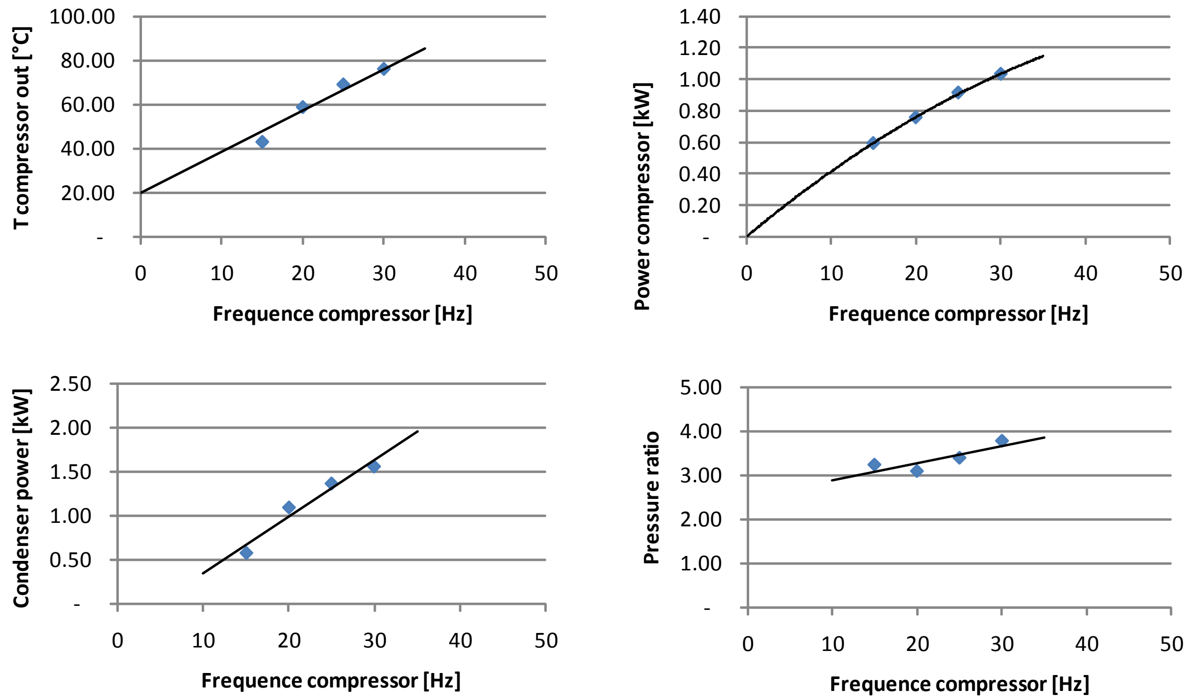

Figure 4: The compressed gas temperature, compressor power, condenser power and pressure ratio as a function of the compressor frequency for condenser and evaporator temperatures of respectively 20°C and 10°C

Table 1: Results for hybrid operation with compressor between evaporator and sorption reactor (configuration 3) compared to heat-driven operation (configuration 2).

	heat-driven	hybrid configuration 3
$T_{heating}$ (°C)	84.7	84.6
$T_{cooling}$ (°C)	35.1	35.3
$T_{evaporator}$ (°C)	12.6	11.7
pressure ratio	1.0	1.5
power compressor (kW)	0	0.9
chilling power (kW)	0.7	1.2
$COP_{thermal}$	0.41	0.59
$COP_{electric}$	na	1.3

Table 2 shows the results for hybrid operation with compressor between sorption reactor and condenser compared to heat-driven operation. The effect of the compressor seems only to be reflected in the increased pressure ratio and the compressor power. Despite this considerable effect on the pressure levels, no significant effect on the chilling power is observed and there is only a slight increase in thermal efficiency. This effect could possibly be explained by a reduced thermal conductivity of the reactor bed (van der Pal et al. 2011).

Although the performance of this system is very poor for generating cooling in terms of $COP_{thermal}$ as well as $COP_{electric}$, one needs to bear in mind that the goal of these measurements is not to create an efficient cooling system. It is a first step in the development of a hybrid heat pump for upgrading waste heat to useful process heat that will use ammonia and salts rather than water vapor and silica gel.

Table 2: Results for hybrid operation with compressor between sorption reactor and condenser (configuration 4) compared to heat-driven operation (configuration 2).

	heat-driven	hybrid configuration 4
$T_{heating}$ (°C)	71.4	71.3
$T_{cooling}$ (°C)	26.2	26.2
$T_{evaporator}$ (°C)	12.3	12.3
pressure ratio	1.0	2.9
power compressor (kW)	0	1.1
chilling power (kW)	1.0	1.0
$COP_{thermal}$	0.32	0.33
$COP_{electric}$	na	0.9

3.2 Model calculations

The measured and calculated temperatures, pressures and thermal powers for the heat-driven operation are shown in respectively Figure 5, Figure 6, and Figure 7. Figure 5 shows a good correlation between the measurements and the model calculations. Only some deviations are found around when switching between the discharge and the regeneration phase. The good correlation is somewhat deceiving: to achieve large deviations in out-going temperatures, the amount of heat released or adsorbed by the components must increase considerably.

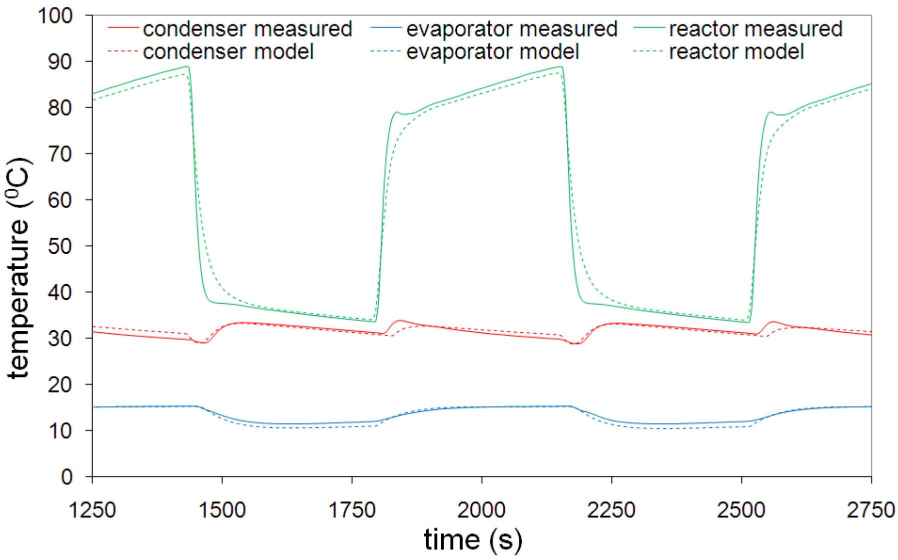

Figure 5: Heat-driven operation: the temperature from the measurement and model calculations of the condenser, evaporator and sorption reactor as a function of time

More information can be obtained from the pressure as a function of time as shown in Figure 6. For the evaporator pressure and the sorption reactor pressure during the low pressure part of the cycle, a good correlation is found between measured values and calculated values. For the pressure in the condenser and the sorption reactor during the high pressure part of the cycle, the correlation is not as good. It can also be observed that the measured pressure in the condenser increases each cycle whilst the model value remains constant. This suggests an increasing presence of non-condensables in the condenser.

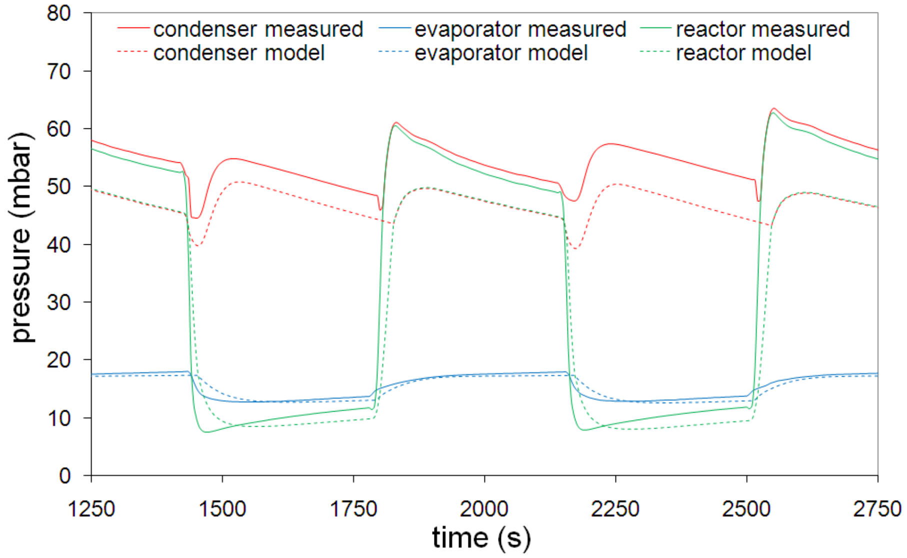

Figure 6: Heat-driven operation: the pressure from the measurement and model calculations of the condenser, evaporator and sorption reactor as a function of time

Figure 7 shows the measured and calculated thermal powers. The measured power of the sorption reactor shows a considerable quicker response compared to model calculations when switching between the discharge and regeneration phases. Also the total amount of heat input/output of the sorption reactor is per cycle considerable smaller than calculated. These effects could be caused by overestimating the thermal mass. Considering the masses of the heat exchangers, the water and the metal components were carefully determined, it is more likely the fraction of the mass varying in temperature was overestimated by the model which might be related to the uniform temperature assumption of the model. The calculated heating powers are, however, close to the measured values. The measured cooling power is somewhat smaller than calculated which could be explained by the presence of non-condensables in the system.

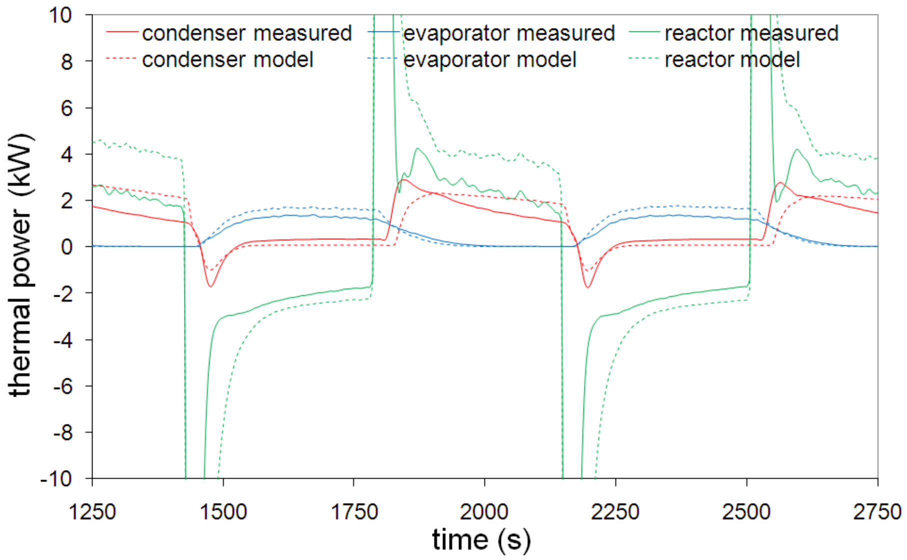

Figure 7: Heat driven operation: the thermal power, the temperature from the measurement and model calculations of the condenser, evaporator and sorption reactor as a function of time

Figure 8 shows the measured and calculated pressures of the hybrid configurations as a function of time. As can be expected, the pressure in the sorption reactor is increased when the compressor is placed between the evaporator and sorption reactor (left) and reduced when the compressor is placed between the sorption reactor and the condenser (right). The maximum pressures measured on the evaporator are higher than calculated. The condenser pressures correlate reasonably well. Because the sorption reactor pressure depends on the phase of the cycle, closely related to the evaporator or the condenser pressure (in hybrid mode increased or decreased with the measured pressure step), the measured pressure of the sorption reactor performs according to expectations for the discharge phase and shows an overshoot compared to the model during the regeneration phase.

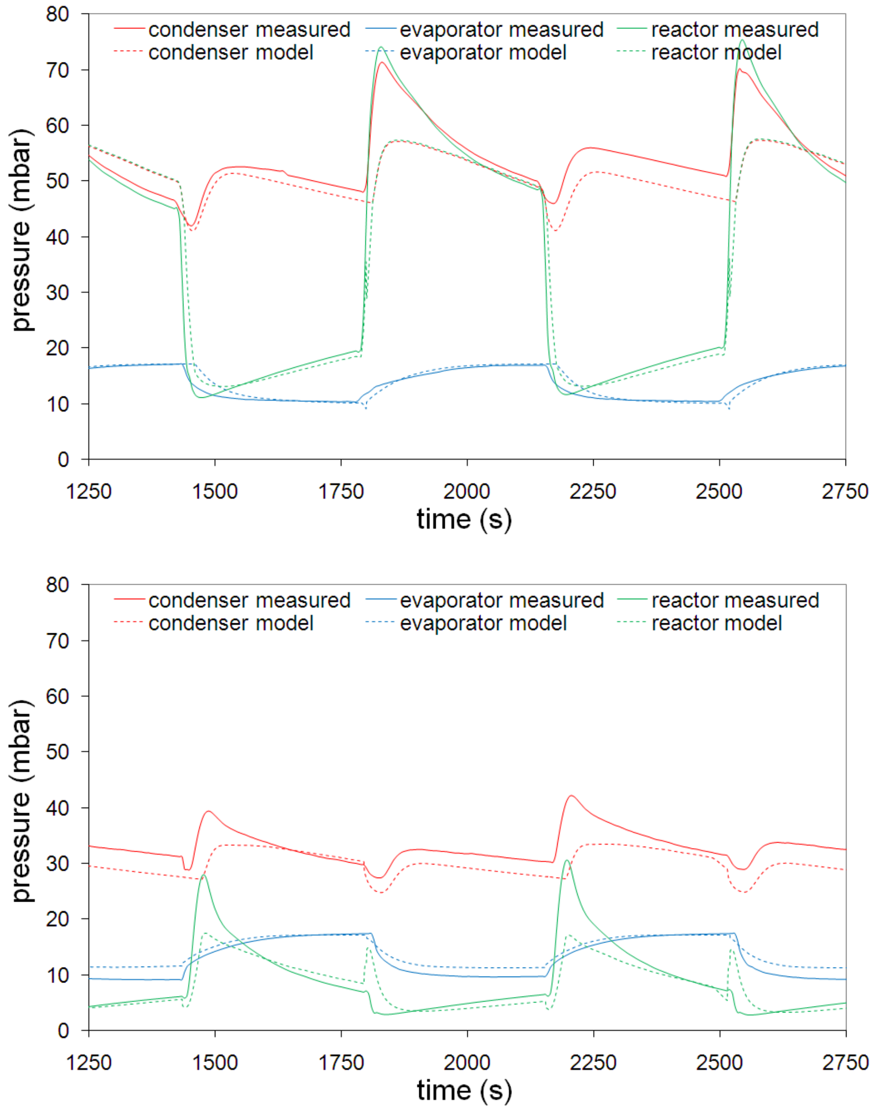

Figure 8: Measured and calculated pressures as a function of time for hybrid heat pump operation with the compressor placed between evaporator and sorption reactor (top: config 3) and placed between sorption reactor and condenser (bottom: config 4)

Figure 9 shows the measured and calculated powers of the hybrid configuration as a function of time. Similar to the heat-driven configuration, the thermal power of the sorption reactor has been somewhat overestimated. The cooling power for the hybrid operation has, similar to heat-driven configuration, been slightly overestimated. The model calculates a 58% increase in cooling power for configuration 3 which is close to measured values. For configuration 4, however, the model estimates a 28% increase in cooling power where hardly any improvement is found in the measurements.

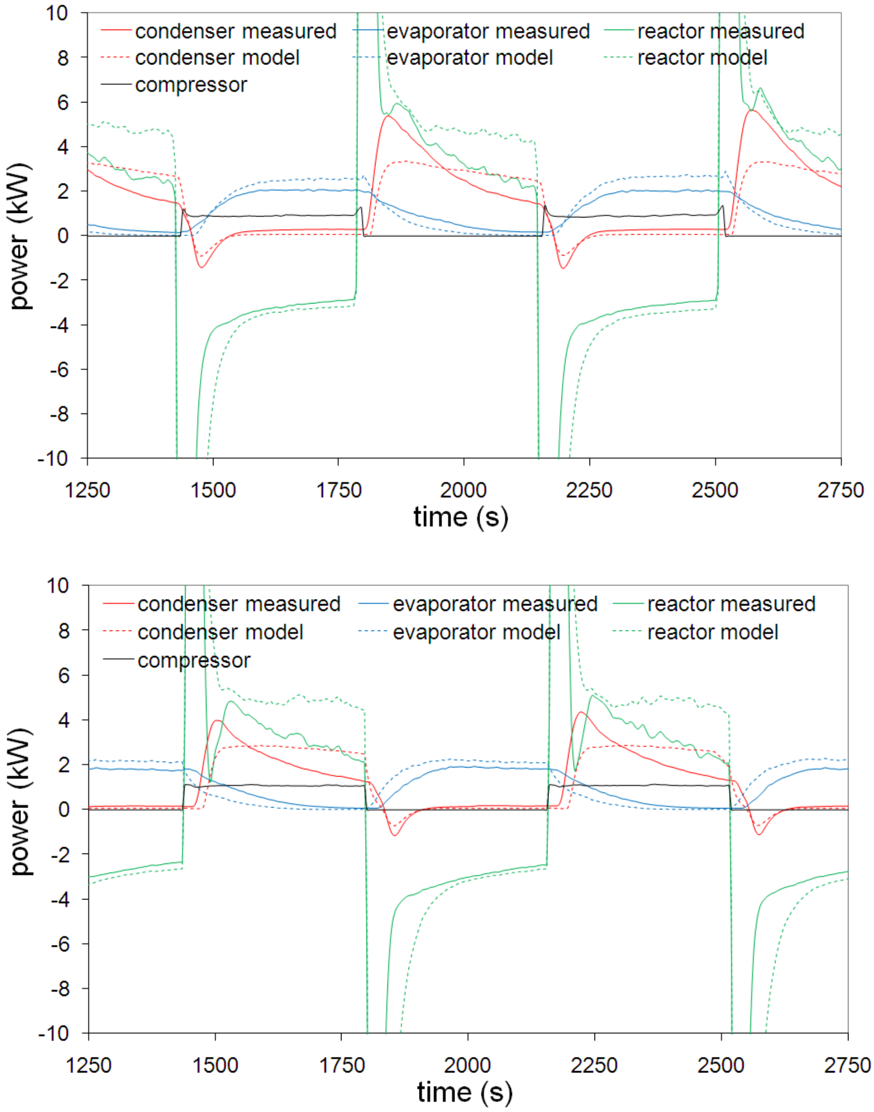

Figure 9: Measured and calculated powers as a function of time for hybrid heat pump operation with the compressor placed between evaporator and sorption reactor (top: config 3) and placed between sorption reactor and condenser (bottom: config 4)

4 CONCLUSIONS AND RECOMMENDATIONS

From the measurements and model calculations 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.

There are some differences between the measurements and the model calculations. The differences show mainly in the pressure and thermal power and are similar for both the heat-driven as well as the hybrid operation of the heat pump. These differences can (partly) be explained by differences in the amount of thermal mass and/or its temperature variation, which might be related to the uniform temperature assumption of the model. Despite the differences, the calculated evaporator (cooling) and condenser (heating) powers are close to the measured values.

A better correlation between model calculations and measurements could be obtained by tweaking the input parameters such as the thermal mass. However, to be able to use the model as a tool for accurately predicting the performance of a heat-driven and/or hybrid heat pump, it is recommended to look into the effect of the model assumptions on the calculations.

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