EXPERIMENTAL INVESTIGATION OF THE EFFECT OF ZEOLITE COATING THICKNESS ON THE PERFORMANCE OF A NOVEL ZEOLITE-WATER ADSORPTION HEAT PUMP MODULE

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ABSTRACT

A novel zeolite-water adsorption heat pump module comprising an adsorber, an evaporator and a condenser heat exchanger as well as a module non-return valve in a hermetically sealed vessel is introduced. The investigated adsorber heat exchanger is an extruded aluminum finned-tube heat exchanger coated with AQSOA-Z02 zeolite of Mitsubishi Plastics Incorporation (MPI). The effect of the zeolite layer thickness (300 and 500 µm) on the performance of the heat pump module has been experimentally investigated under different operating conditions related to floor heating systems in Middle Europe.

A coefficient of performance (COP) of 1.18 has been measured with the 300 µm coated adsorber at a return temperature of 35 °C, increasing to 1.23 at a return temperature of 25 °C. With the 500 µm coated adsorber, the measured COPs have been enhanced to 1.27 and 1.35, respectively. This enhancement has been attributed to the increase of the ratio between zeolite and heat exchanger heat capacities.

KEYWORDS

Adsorption heat pump, zeolite-water, AQSOA-Z02, gas-fired heating

INTRODUCTION

The increased efforts to reduce CO_2-emissions and the continuous increase in fossil energy prices have led to more strong legislations concerning energy utilization efficiency in the household heating sector in Germany. According to the so called "EEWärmegesetz, 2008" or the Renewable Energy Heating Law for enhancing the share of renewable energy in household heating applications in Germany, all heating appliances to be installed in new buildings should have a minimum primary energy efficiency of 120%. Consequently, more efficient and environment friendly gas heating appliances will have a quite high market penetration chance compared to conventional technologies provided that they can be introduced into the market with a moderate cost to efficiency enhancement ratio leading to a reasonable pay-back time.

In recent years, adsorption heat pump/refrigeration systems have drawn considerable attention due to their lower environmental impact over conventional vapour compression heat pumps since these systems use ozone non-depleting working substances. Moreover, gas-fired adsorption heat pumps have a remarkable energy saving potential compared to gas-condensing boilers, which represents the state of the art of gas fired heating appliances.

Over the last three decades, several regenerative adsorption heat pump cycles have been proposed and analyzed. Meunier, 1986 as well as Douss and Meunier, 1989 have introduced and analyzed the solid adsorption cascading cycle in which they applied an active carbon-methanol pair topped by a zeolite water system. In this cascading cycle, traditional NaX and A type zeolites were applied at a desorption temperature as high as 300 °C. In a commercial gas-fired adsorption heat pump system, the realization of this desorption temperature level has been proven to be unfeasible.

An alternative heat recovery concept to the cascading cycle; namely, the two bed direct heat recovery cycle has been introduced and thoroughly investigated (Miles and Shelton, 1992; Douss, et al., 1988; Saha et al., 1995a & 1995b; Boelmann et al., 1995; Chua et al., 1999 as well as Wang and Chua, 2007). The heat transfer loops of the two sorption beds are short-circuited together at the end of each adsorption/desorption phase in order to exhibit a direct heat recovery from the hot bed being cooled (previously worked as a desorber) to the bed being heated (previously worked as an adsorber). Accordingly the recovered heat could be saved and a considerable enhancement of the coefficient of Performance (COP) could be achieved. According to this cycle, each adsorption bed has to be equipped with a circulating pump. The temperature of the heat transfer fluid being circulated by both pumps changes in each half cycle between desorption and adsorption end temperatures. In order to achieve a high seasonal performance of gas-fired adsorption heat pumps with a high degree of hydrothermal durability, zeolite NaY could be applied. The main drawback of this zeolite is the need to desorption temperatures of up to 150 °C, in order to achieve reasonable COPs. This high temperature requirement puts a severe durability for the required two circulation pumps and implies an almost knock out criteria for utilizing the direct heat recovery concept in such a development.

Another regenerative adsorption heat pump cycle is represented by the so called two-bed regenerative thermal wave cycle introduced by Tchernev and Emerson, 1988. According to this cycle, the two adsorption beds are connected in series with the heat source and heating net heat exchangers. The heat recovery between the two adsorption beds is realized by reversing the flow direction of the bed heat transfer fluid at the end of each adsorption/desorption working phase. One of the main technical advantages of this cycle is the need to only one circulating pump for the bed heat transfer fluid loop. Moreover, this pump could be located close to the heating net heat exchanger, exhibiting the medium cycle temperature and the lowest temperature changes compared to the two circulating pumps required for the two heat transfer fluid loops of two bed direct heat recovery cycle (Lang et al., 2002 and 2003 as well as Dawoud et al., 2003). This leads to a long time durability of the thermal wave heat pump.

The main drawback of the above mentioned regenerative adsorption heat pump cycles compared to single stage intermittent adsorption heat pumps is the quite high complexity to efficiency enhancement ratio. In other words, the incremental increase in the heating appliance complexity, and consequently in its cost, compared to the efficiency enhancement is quite high.

The main challenges are thus to integrate a periodically operating heat pump cycle into a heating appliance serving a continuous heat demand, achieving an incremental enhancement of gas utilization efficiency and minimizing the increase in the system complexity and cost compared to condensing boiler technology. In this work, we are introducing a novel zeolite-water adsorption heat pump module to be integrated in an innovative heating appliance as an effective contribution to rationally utilize natural gas and to reduce the CO_2-emmisions in the field of heating and hot water production in one and two family houses compared to gas condensing boilers. Besides, first experimental results concerning the effect of the zeolite coating thickness on the performance of the adsorption heat pump module are introduced.

THE NOVEL ADSORPTION HEAT PUMP MODULE

Figure 1 depicts a schematic of the novel zeolite water adsorption heat pump module developed by Dawoud and Bornmann, 2009. The module composes three heat exchangers integrated in one hermetically sealed stainless steel vessel. On the top of the vessel the adsorber/desorber heat exchanger is located. The condenser is constructed as a concentric cylinder integrated in the vessel's wall in the top section. In the lower part of the vessel, the evaporator is placed. Between the top and lower parts of the heat pump module a module non-return valve comprising a ball and a concave plate having a central opening and a seat for the ball is located.

Figure 1.a illustrates the heat pump module in the desorption phase, during which the adsorber/desorber heat exchanger is to be connected to the heat source (e.g. gas-fired heating cell). The desorbed water vapor out of zeolite results first in closing the non-return valve (pressing the ball in its seat on the concave plate). The water vapor pressure increases further in the module's upper room until it exceeds the saturation pressure corresponding to the heating water inlet temperature into the condenser (temperature of the heating circuit return flow). From this time on, water vapor is condensed on the internal condenser wall, falls down and collected around the ball as depicted in Figure (1.a).

This desorption phase continues until the condenser heating power (measured as the product of the heating water mass flow rate and the temperature difference over the condenser heat exchanger) falls below a certain limit (here 200 W). This implies that the desorption-condensation phase is to be ended and that an adsorption-evaporation phase is to be triggered.

During the desorption phase, the ball valve is closed by the higher pressure dominating in the condenser room and by the ball's own weight. At the beginning of the adsorption phase, depicted in Figure 1.b, the pressure decreases in the condenser room because the previously dried zeolite is now cooled down and be capable of adsorbing water vapor from the condenser room. In the heating system, this is realized by connecting the heating circuit return flow with the adsorber heat exchanger inlet (Dawoud and Stricker, 2008). As soon as the pressure difference between evaporator and condenser rooms becomes equal to the opening pressure (caused by the ball's own weight), the ball valve is opened. The condensed water, which is accumulated around the ball during the desorption-condensation phase, is then discharged into the evaporator room. From that point on, water vapor is evaporated upon receiving the heat of evaporation from the ambient heat source and is adsorbed by the zeolite resulting in the release of the heat of adsorption, which is then transferred to the heating circuit as a useful heat.

The hydraulic integration of the introduced heat pump module into the gas-fired heating system can be read in detail in Dawoud and Stricker, 2008.

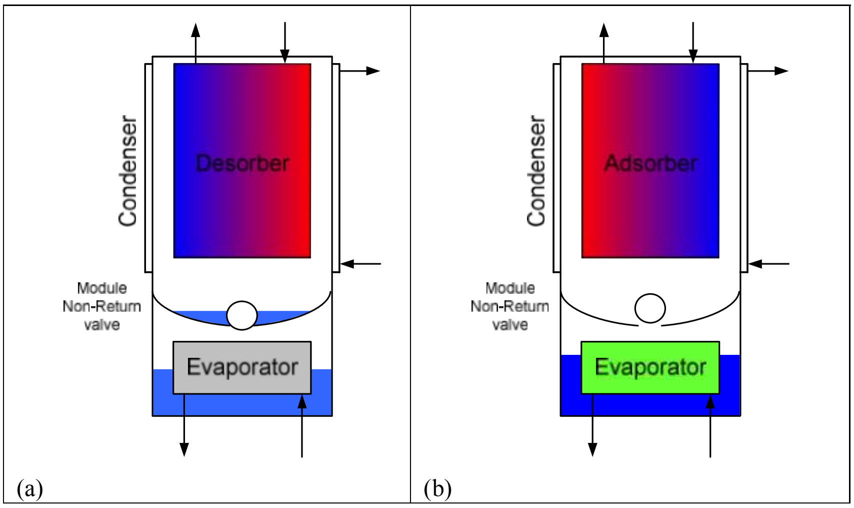

Figure 1. Schematic of the adsorption heat pump module; a) during the desorption-condensation phase and b) during the adsorption-evaporation phase

THE ADSORBER HEAT EXCHANGER

Figure 2 illustrates the investigated extruded aluminum finned tube adsorber heat exchanger. The longitudinal fins have been directly coated with Mitsubishi zeolite AQSOA-Z02 (Kakiuchi et al., 2003 as well as 2005a and 2005b) with two different zeolite layer thicknesses; namely 300 and 500 µm.

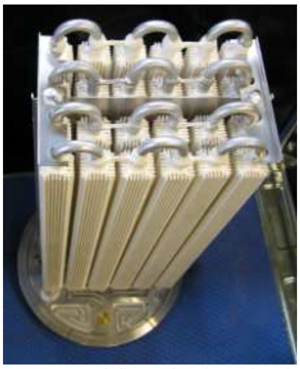

Figure 2: Coated finned-tube adsorber heat exchanger

Table 1 presents the main design parameters of two coated adsorber heat exchangers.

Table 1: Key data of the extruded finned tube adsorber heat exchangers

Abbrivation	S300	S500
Zeolite layer thickness [µm]	300	500
Dimensions lxwbxh [mm]	205x138x545	
Mass without Zeolite [kg]	6.56	
Zeolite Mass [kg]	1.50	2.56
Heat Capacity Ratio Adsorber heat exchanger / Zeolite [-]	10.14	5.96

EXPERIMENTAL PROCEDURE

During the experiments, the influence of the zeolite layer thickness on both coefficient of Performance (COP) and mean Heating Power (MHP) of the heat pump module have been investigated. The evaporator inlet temperature has been adjusted to 5 and 10 °C and the heating net return temperature to 25, 30 and 35 °C, corresponding to a floor heating system incorporating a ground heat source in middle Europe. The return temperature is equal to the inlet temperature into the condenser and adsorber heat exchangers during the desorption and adsorption phases, respectively. The desorption temperature has been varied between 90 and 100 °C.

For the evaluation of the heat pump module, the coefficient of performance (COP) is defined according to Equation (1) as the ratio between the heat gained out of both condenser and the adsorber heat exchanger during the adsorption phase and the heat taken by the adsorber heat exchanger during the desorption phase in one complete heat pump cycle.

$$COP = \frac{Q_{Con} + Q_{Ads}}{Q_{Des}} \tag{1}$$

Whereas the power input/output to/from the adsorber heat exchanger and that obtained from the condenser are defined by equations 2-4.

$$\dot{Q}_{Des} = \dot{m}_{HC} \cdot c_{p\_HC} \cdot \Delta T_{Des} \tag{2}$$

$$\dot{Q}_{Ads} = \dot{m}_{HC} \cdot c_{p\_HC} \cdot \Delta T_{Ads} \tag{3}$$

$$\dot{Q}_{Con} = \dot{m}_{HC} \cdot c_{p\_HC} \cdot \Delta T_{Con} \tag{4}$$

The Mean heating power (MHP) of the heat pump module is defined as the integral of the heating power obtained out of the condenser and the adsorber heat exchanger during the adsorption phase over the cycle time divided by the cycle time according to equation 5.

$$MHP = \frac{1}{t_C} \cdot \int_0^{t_C} (\dot{Q}_{Con} + \dot{Q}_{Ads}).dt \qquad (5)$$

Temperature difference measurements have been carried out using PT-100 pairs having an absolute accuracy in measuring temperature difference of less than ±0.1 K. The measurement of the volume flow rate of the heating circuit heat transfer fluid (water) is accomplished with an magnetic inductive flow meter having a maximum error of ±0.06% of the measured value. The uncertainty analysis showed a maximum relative error in COP measurements of ± 1.4% and in the MHP of ±1% from the measured value.

RESULTS AND DISCUSSION

At the beginning, the effect of the desorption temperature on COP and MHP of the adsorption heat pump module with the 300 µm coated adsorber (S300) at different return temperatures and at an evaporator inlet temperature of 10 °C has been experimentally investigated. The desorption temperature has been varied between 90 and 100 °C. Figures 3 and 4 illustrate the obtained results on COP and MHP, respectively.

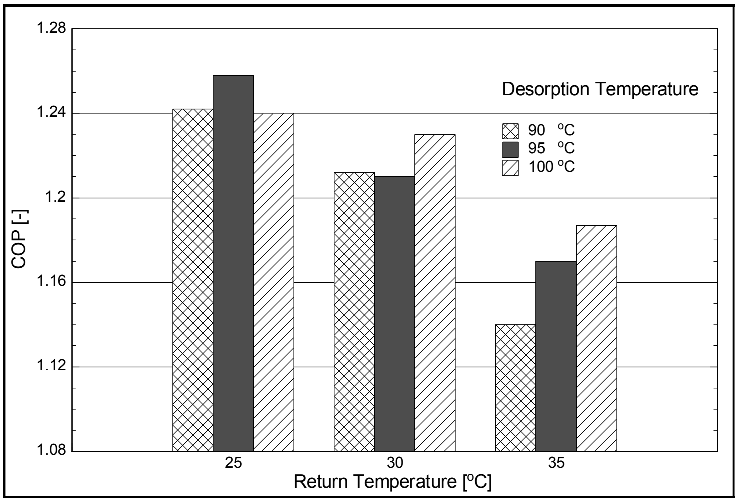

Figure 3. Measured COPs of the S300 adsorber at different return and desorption temperatures at an evaporator inlet temperature of 10 °C

It is evident from Figure 3 that increasing the return temperature results in decreasing the COP for each investigated desorption temperature. This is to be attributed to the decrease in the degassing ratio (difference between the zeolite water loading at the end of the adsorption and desorption phases). The effect of the desorption temperature on COP is rather different depending on the return temperature. At the return temperature of 25 °C, COP attains a maximum at 95 °C, whereas, within the tested desorption temperature range, the COP increases continuously with the desorption temperature at the return temperatures of 30 and 35 °C. It is also a common practice that at fixed evaporator and return temperature, the COP attains a maximum at the so called optimum desorption temperature. This is the desorption temperature, at which the differential water loading change against desorption temperature attains its maximum. In other words, the 95°C is the optimum desorption temperature at the return flow of 25°C and the evaporator inlet temperature of 10 °C. At the return temperature of 30 and 35 °C the optimum value seems to be equal to or higher than 100°C. In the further investigations, the desorption temperature is fixed to 100 °C.

As the sensible heat added to the adsorber heat exchanger increases with the desorption temperature, the MHP increases with the desorption temperature for all tested return temperatures as depicted in Figure 4. As explained before, the difference in the zeolite water loading upon adsorption and desorption decreases with increasing the return temperature. As this differential water loading is directly proportional to the condenser heating power, the MHP of the adsorption heat pump module decreases with increasing the return temperature.

Figure 5 presents the influence of the evaporator inlet temperature on the COP of the heat pump module with the 300 µm coated adsorber at a desorption temperature of 100 °C.

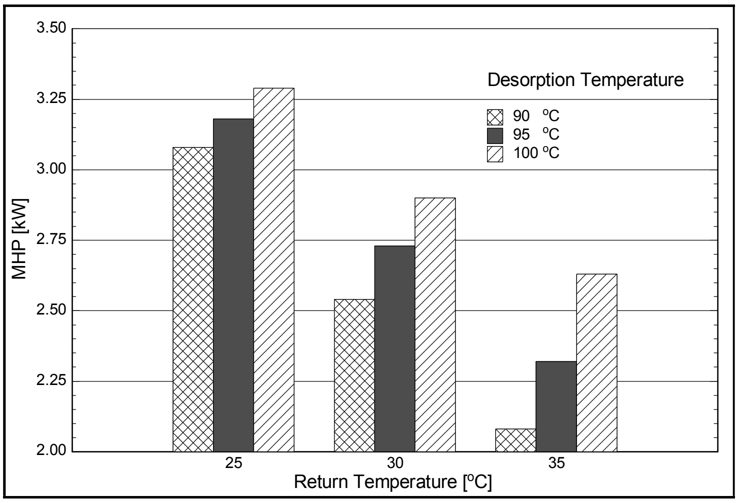

Figure 4. Measured MHPs of the S300 adsorber at different return and desorption temperatures at an evaporator inlet temperature of 10 °C

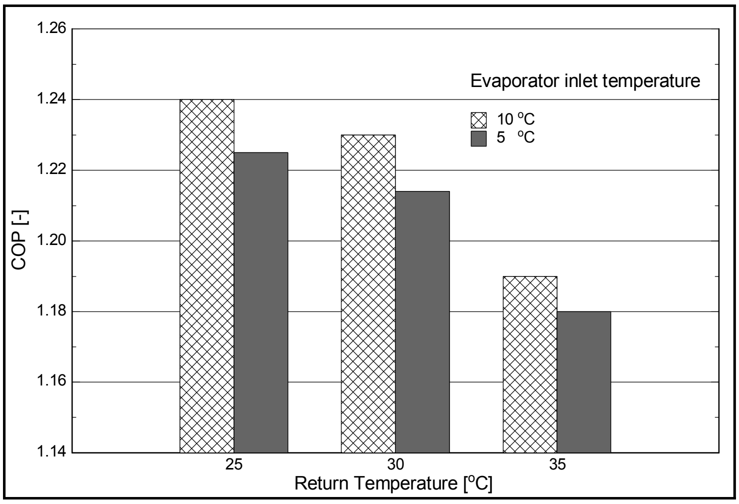

Figure 5. Effect of the evaporator inlet temperature on COP of the S300 adsorber at different return temperatures and a desorber inlet of temperature of 100 °C

Decreasing the evaporator temperature at fixed return and desorption temperatures results also in decreasing the differential zeolite water loading upon adsorption and desorption, which has its direct influence on decreasing the COP as illustrated in Figure 5. The measured decrement in COP lies in the order of less than 1.5% by decreasing the evaporator inlet temperature from 10 to 5°C, which is quite low compared to other zeolite-water pairs. This seems to be a unique feature of the utilized AQSOA-Z02 zeolite coating.

The effect of the zeolite coating thickness on COP and MHP of the tested heat pump module is depicted in Figures 6 and 7, respectively. In both Figures the evaporator inlet and desorption temperatures, have been fixed to 10 and 100 °C, respectively. The measured COP with 300 µm zeolite layer thickness on the extruded finned tube heat exchanger amounts to 1.18 at a return temperature of 35 °C, increasing to 1.23 at a return temperature of 25 °C. With enhancing the zeolite layer thickness from 300 to 500 µm, the measured COPs increase to 1.27 and 1.35, respectively. This remarkable enhancement could be referred to the obvious decrease in the heat capacity ratio between the adsorber heat exchanger and zeolite as given in Table 1 upon increasing the zeolite layer thickness.

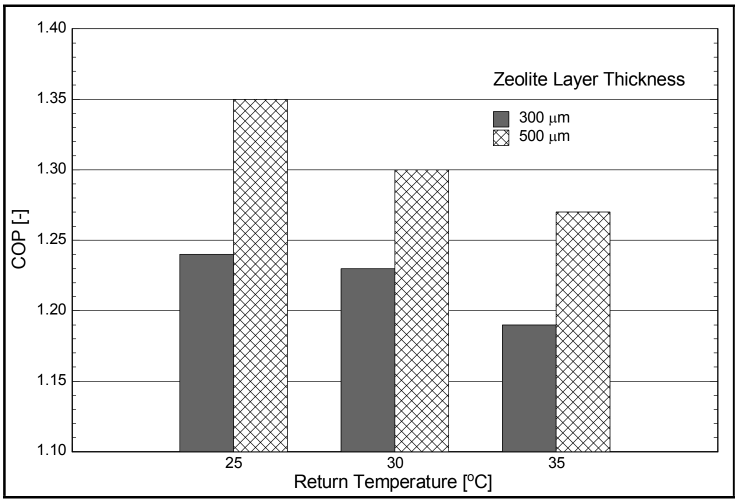

Figure 6. Effect of zeolite layer thickness on COP at different return temperatures and at an evaporator and desorber inlet temperatures of 10 and 100 °C

However, increasing the zeolite layer thickness results in enhacing the heat and mass transfer resistances through the zeolite layer, which implies increasing the time requirement for approaching the same degree of equilibrium in the utilized zeolite mass. This results in increasing the cycle time, leading to decreasing the thermal power output from the zeolite heat pump module. This becomes evidence from Figure 7 comparing the MHP measured with the 500 µm adsorber (S500) with that of the 300 µm adsorber (S300).

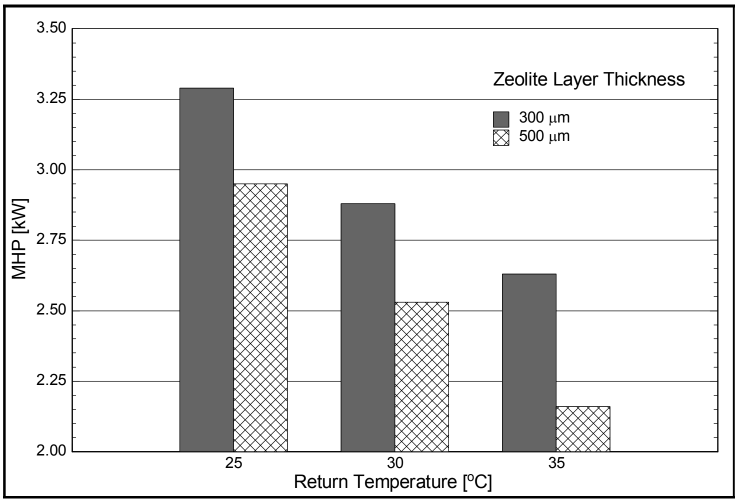

Figure 7. Effect of zeolite layer thickness on MHP at different return temperatures and at an evaporator and desorber inlet temperatures of 10 and 100 °C

The MHP reduction due to the zeolite layer thickness increase becomes more dominant at higher return temperatures, as the driving force for the mass transfer (differential zeolite water loading upon adsorption and desorption) becomes less. Nevertheless, the measured specific heating power of the introduced adsorption heat pump module varies between 820 and 2200 W per kg of zeolite, which can be considered as a major improvement in the adsorption heat pump development. The state of the art with loose pellets on a finned tube adsorber heat exchanger (Lang et al., 2003 and Gad El-Rab et al., 2009) realizes at most one fourth of the measured specific heating powers in this work.

CONCLUSION

A novel zeolite-water adsorption heat pump module comprising an adsorber, an evaporator and a condenser heat exchanger as well as a module non-return valve in a hermetically sealed vessel has been introduced. In this heat pump module, an extruded aluminum finned-tube heat exchanger coated with AQSOA-Z02 zeolite of Mitsubishi Plastics Incorporation has been experimentally investigated. At a return temperature of 25 °C, the measured COP of the heat pump module increases from 1.23 to 1.35 by increasing the zeolite layer thickness from 300 to 500 µm. An enhancement in COP of 0.09 (from 1.18 to 1.27) has been measured at a return temperature of 35 °C. This enhancement has been referred to the increase of the ratio between zeolite and heat exchanger heat capacities. The enhancement in COP due to increasing the zeolite layer thickness is accompanied with a decrease in the mean heating power of the heat pump module. However, the measured specific heating power of 820 to 2200 W per kg of coated zeolite can be considered as a great enhancement compared to applying zeolite in form of loose pellets between the fins of a finned tube heat exchanger.

NOMENCLATURE

Symbol	Meaning	Unit
COP	Coefficient of performance	[-]
c_P	Specific heat capacity (at constant pressure)	[kJ/(kgK)]
$\dot{m}$	Mass flow rate	[kg/s]
MHP	Mean heating power	[kW]
Q	Heat amount	[kJ]
$\dot{Q}$	Heat flow	[kW]
ΔT	Temperature difference	[K]
t	Time	[s]
t_{hc}	Half cycle time	[s]
Subscripts		
Ads	Adsorber	
C	Cycle	
Con	Condenser	
Des	Desorber	
HC	Heat transfer fluid of the heating circuit	

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