

PERFORMANCE INVESTIGATION ON MASS RECOVERY THREE-BED ADSORPTION CYCLE

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ABSTRACT

Design of a novel, three-bed, advanced adsorption chiller employing mass recovery scheme, which is driven by low temperature heat source is introduced and the performance of the proposed chiller is evaluated numerically. The innovative chiller is driven by exploiting renewable energy sources or waste heat of temperature between 60 and 90°C with a coolant at 30°C for air-conditioning purposes. Silica gel/water is taken as adsorbent/adsorbate pair for the present chiller. The performance of the proposed chiller is evaluated by numerical means. The three-bed adsorption chiller comprises with three adsorber/desorber heat exchanger, one evaporator and one condenser. When first two beds are in mass recovery process, isolating from both evaporator and condenser, the third bed is connected with evaporator to enhance cooling effect. The cycle simulation calculation indicates that the COP value of the three-bed adsorption chiller with mass recovery is 0.66 with a driven heat source temperature at 80°C in combination with coolant inlet and chilled water inlet temperatures at 30°C and 14°C, respectively.

Keywords: Adsorption chiller, Renewable energy source, Mass recovery.

1. INTRODUCTION

There is a strong tendency toward the development of new technologies to solve the global environmental problems, such as the destruction of atmospheric ozone layer and global warming. Refrigeration/heat pump system, specially the vapor/compressor cycle, is one of the technologies, which is responsible for ozone layer destruction, as they use HCFCs, HFCs and their mixtures. Moreover, the increase usages of the vapor compressor driven refrigeration devices will make us more dependent on the primary energy resources. In contrast, it is necessary to reduce the primary energy consumption and to introduce renewable energy for the sustainable development in the global energy sector. Therefore, refrigeration technologists are extremely investigating to originate or to develop an alternative to vapor compressor refrigeration devices. Thermally driven, sorption technology is one of the possible alternatives. In the moment, absorption (liquid-vapor) cycle is most promising technology. However, the adsorption (solid-vapor) cycle have a distinct advantage over other systems in their ability to be driven by heat of relatively low, near-environmental temperatures, so that heat source (waste or solar heat) below 100°C can be

recovered, which is highly desirable (Kashiwagi et al. [1]). Many advanced cycles have been proposed to improve the system performance. Meunier [2] investigated the system performance of cascaded adsorption cycles in which an active/methanol cycle is topped by zeolite/water cycle. To improve the COP value, Shelton et al. [3] proposed a thermal wave regenerative adsorption heat pump system. In a similar effort, Critoph [4] proposed a forced convection adsorption cycle. Pons and Poyelle [5] investigated the effect of mass recovery process in conventional two bed adsorption cycle to improve the cooling power. Later, Wang [6] showed that mass recovery process is very effective for the high evaporating pressure lift as well as for the low regenerating temperature. Alam et al. [7] analyzed four-bed mass recovery cycle with silica gel/water pair employing a new strategy to improve the cooling effect. Recently, Saha et al. [8] analyzed a dual-mode, multi-bed adsorption chiller to improve the heat recovery efficiency and Khan et al. [9] studied two-stage adsorption chiller using re-heat parametrically to utilize low-temperature waste heat as heat source.

Most of the advanced cycles in adsorption refrigeration/heat pump are proposed to achieve high

COP (coefficient of performance) and/or SCP (specific cooling power) values. Few cycles, however, are proposed to utilize relatively low temperature heat source. Saha et al. [10] proposed and investigated a two-stage chiller and the required driving heat source temperature of the two-stage chiller was validated by experiment. The silica gel/water based two-stage chiller can exploit heat source of temperature around 60°C along with a coolant at 30°C. However, the COP of the two-stage chiller is low. Moreover, both the COP and cooling capacity of the two-stage chiller are sensitive to the driving heat source temperature. Recently, Saha et al. [11] proposed and analyzed a non-regenerative, three-bed silica gel/water based adsorption chiller without mass recovery. The three-bed cycle improves waste heat recovery efficiency about 35% in comparison with that of the conventional two-bed adsorption system for the same external conditions.

The objectives of the present study is to utilize near environmental temperature waste or renewable heat sources between 50 and 70°C with a cooling source of 30°C. So, a cycle simulation computer program of the three-bed chiller with mass recovery scheme is developed to improve the cooling effect. In the two-bed mass recovery cycle when, two beds are in mass recovery process, no beds are connected with the evaporator. But in the present treatment, when two beds are in mass recovery process, another bed (3rd bed) is connected with the evaporator, which improves cooling power as of the continuous evaporation. Numerical results are analyzed in terms of SCP and COP by varying heat transfer fluid (hot and cooling water) inlet temperatures and adsorption/desorption cycle time.

2. WORKING PRINCIPLE OF THE THREE-BED CHILLER WITH MASS RECOVERY SCHEME

The schematic diagram and time allocation of the three-bed mass recovery chiller are shown in Fig. 1 and Table 1, respectively. The three-bed mass recovery chiller comprises with three sorption elements (adsorber/desorber heat exchangers), a condenser, an evaporator, and metallic tubes for hot, cooling and chilled water flows as shown in Fig. 1. The design criteria of the three-bed mass recovery chiller are almost similar to that of the three-bed chiller without mass recovery which is proposed and developed by Saha et al. [11]. However, in the proposed design, it needs extra piping, which connects two beds during mass recovery. The configuration of beds in the three bed chiller with mass recovery were taken as uniform in size.

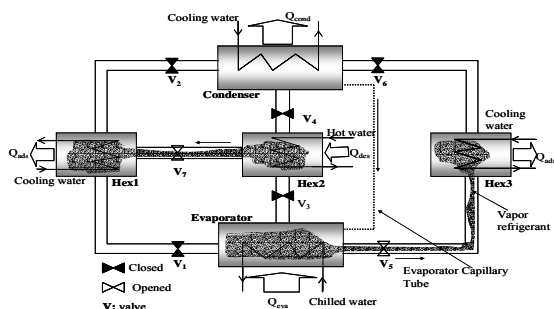


Fig 1. Schematic of the three bed chiller with mass recovery

Table 1: Operational strategy of three bed chiller with mass recovery.

Mode	A	B	C	D	E	F	G	H	I	J	K	L
Hex1	Pre-heating	Pre-cooling	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption
Hex2	Pre-heating	Pre-cooling	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption
Hex3	Pre-heating	Pre-cooling	Pre-heating	Pre-cooling	Pre-heating	Pre-cooling	Pre-heating	Pre-cooling	Pre-heating	Pre-cooling	Pre-heating	Pre-cooling

Desorption
 Mass recovery with heating
 Pre-cooling
 Adsorption
 Mass recovery with cooling
 Pre-heating

Operational strategy of the proposed chiller (see Table 1), however, is completely different from the operational strategy of a three beds without mass recovery scheme. In proposed design, when two beds (*Hex1* and *Hex2*) are in mass recovery process, at the same time another bed (*Hex3*) is connected to an evaporator to get more cooling effect and continue the evaporation. The chiller can be operated in different strategies. However, only one strategy has been considered in the present study. To complete a full cycle, the chiller needs 12 modes, namely A, B, C, D, E, F, G, H, I, J, K and L as can be seen from Table 1.

In mode A, *Hex1* (at the end position of adsorption-evaporation process) and *Hex2* (at the end position of desorption-condensation process) are connected with each other continuing cooling water and hot water, respectively that can be classified as two-bed mass recovery process. When the concentration levels of both beds *Hex1* and *Hex2* reach in nearly equilibrium levels, then warm up process will start, called mode B (pre-heating or pre-cooling). In mode B, *Hex1* is heated up by hot water, and *Hex2* is cooled down by cooling water. When the pressure of *Hex1* and *Hex2* are nearly equal to the pressure of condenser and evaporator, respectively then *Hex1* and *Hex2* are connected to condenser and evaporator, respectively. This connection will continue to modes C, D, E, and F for both *Hex1* and *Hex2*. In mode C, D, E, and F, *Hex1* works as desorber and *Hex2* works as adsorber. In the adsorption-evaporation process, refrigerant (water) in evaporator is evaporated at evaporation temperature, T_{eva} , and seized heat, Q_{eva} from chilled water. The evaporated vapor is adsorbed by adsorbent (silica gel), at which cooling water removes the adsorption heat, Q_{ads} . The desorption-condensation process takes place at condenser pressure (P_{cond}). The desorber (*Hex1*) is heated up to temperature (T_{des}) by heat input Q_{des} , provided by the driving heat source. The resulting refrigerant is cooled down by temperature (T_{cond}) in the condenser by the cooling water, which removes condensation heat, Q_{cond} .

In modes A, B, and C, *Hex3* is connected to the evaporator. Mode D is the warming process for *Hex3* (pre-heating process), after mode D, *Hex3* works as desorber connecting with condenser, called mode E. Mode F is the pre-cooling process for *Hex3*.

The mode G is same as mode A. In these modes, *Hex2* (at the end position of adsorption-evaporation process) and *Hex1* (at the end position of desorption-condensation process) are connected with each other continuing cooling water and hot water respectively. When the concentration levels of both beds *Hex2* and *Hex1* reach in nearly equilibrium levels, then warm up process will start, called mode H. In mode H, *Hex2* is heated up by hot water, and *Hex1* is cooled down by cooling water. When the pressure of *Hex2* and *Hex1* are nearly equal to the pressure of condenser and evaporator respectively, then *Hex1* and *Hex2* are connected to the condenser and the evaporator respectively. This connection will continue to modes I, J, K, and L for *Hex1* and *Hex2*. In mode I, J, K, and L, *Hex2* works as desorber and *Hex1* works as adsorber. For *Hex3*, modes G, H, I, J, K, and L are same as modes A, B, C, D, E, and F, respectively. Mode L is the last process, after this mode, all beds return to their initial mode (mode A).

3. MATHEMATICAL FORMALISM

The heat transfer and energy balance equations for the adsorbent beds can be described as follows:

$$T_{w,out} = T_{hex} + (T_{w,in} - T_{hex}) \exp\left(-\frac{UA_{hex}}{\dot{m}_w c_w}\right) \quad (1)$$

$$\frac{d}{dt} \left\{ W_s (C_{ps} + C_{pw} q) + (W_{khex} C_{pcu} + W_{fhex} C_{pAl}) T_{hex} \right\} = W_s Q_{st} \frac{dq}{dt} + \dot{m}_w C_{pw} (T_{w,in} - T_{w,out}) - \delta W_s C_{pw} \left\{ \gamma (T_{hex} - T_{eva}) + (1 - \gamma) (T_{hex} - T_{wv}) \right\} \frac{dq}{dt} \quad (2)$$

where, δ is either 0 or 1 depending whether the adsorbent bed is working as a desorber or an adsorber and γ is either 1 or 0 depending on whether the adsorbent bed is connected with the evaporator or another adsorbent bed.

The heat transfer and energy balance equations for the evaporator can be described as:

$$T_{chill,out} = T_{eva} + (T_{chill,in} - T_{eva}) \exp\left(-\frac{UA_{eva}}{\dot{m}_{chill} c_{chill}}\right) \quad (3)$$

$$\frac{d}{dt} \left\{ W_{eva,w} C_w + W_{eva,hex} C_{eva,hex} \right\} T_{eva} = -LW_s \frac{dq_{ads}}{dt} - W_s C_w (T_{con} - T_{eva}) \frac{dq_{des}}{dt} + \dot{m}_{chill} C_{chill} (T_{chill,in} - T_{chill,out}) \quad (4)$$

The heat transfer and energy balance equations for the condenser can be written as:

$$T_{cond,out} = T_{cond} + (T_{cw,in} - T_{cond}) \exp\left(-\frac{UA_{cond}}{\dot{m}_{cw} c_w}\right) \quad (5)$$

$$\frac{d}{dt} \left\{ W_{cw,w} C_w + W_{cond,hex} C_{cond,hex} \right\} T_{cond} = -LW_s \frac{dq_{des}}{dt} - W_s C_w (T_{des} - T_{cond}) \frac{dq_{des}}{dt} + \dot{m}_{cw} C_w (T_{cw,in} - T_{cw,out}) \quad (6)$$

The mass balance for the refrigerant can be expressed as:

$$\frac{dW_{eva,w}}{dt} = -W_s \left(\frac{dq_{des-cond}}{dt} + \frac{dq_{eva-ads}}{dt} \right) \quad (7)$$

where, the subscripts *des-cond* and *eva-ads* stand for the refrigerant vapor flow from desorber to condenser and evaporator to adsorber, respectively. The silica gel/water property model is similar to the model used by Saha et al. [11].

4. MEASUREMENT OF SYSTEM PERFORMANCE

The performance of a three-bed adsorption chiller with mass recovery is mainly characterized by SCP, which is defined as cooling capacity per kg silica gel, and COP, and can be measured by the following equations: Specific Cooling Power (SCP) =

$$\dot{m}_{chill} C_w \int_0^{t_{cycle}} (T_{chill,in} - T_{chill,out}) dt / W_{s,chiller} \cdot t_{cycle}$$

here, $W_{s,chiller}$ stands for the total mass of silica gel in the chiller.

Coefficient of Performance (COP) =

$$\dot{m}_{chill} C_w \int_0^{t_{cycle}} (T_{chill,in} - T_{chill,out}) dt / \dot{m}_{hot} C_w \int_0^{t_{cycle}} (T_{hot,in} - T_{hot,out}) dt$$

5. RESULTS AND DISCUSSION

In the present analysis, the system of differential equations (1)-(7) are solved by finite difference approximation with time step of one second. In the numerical solution of the differential equations, successive substitutions of the newly calculated values were used, with the iterative loop repeating the calculations until the convergence test is satisfied. The convergence factor is taken as 0.001 for all parameters. The base line parameters and standard operating conditions for the chiller operation are listed in Table 2 and Table 3, respectively.

Table 2: Baseline Parameters

Values Adopted in Simulation		
Symbol	Value	Unit
A_{hex}	1.45	m^2
A_{eva}	0.665	m^2
A_{cond}	0.998	m^2
C_{ps}	924	J / kg. K
C_{pw}	4.18E+3	J / kg. K
$C_{p,chill}$	4.20E+3	J / kg. K
$C_{p,cu}$	386	J / kg. K
$C_{p,Al}$	905	J / kg. K
L	2.50E+6	J / kg
Q_{st}	2.80E+6	J / kg
U_{ads}	1380	$W / m^2 \cdot K$
U_{des}	1540	$W / m^2 \cdot K$
U_{eva}	3550	$W / m^2 \cdot K$
U_{cond}	4070	$W / m^2 \cdot K$
W_s	14	kg
W_{khex}	12.67	kg
W_{fhex}	5.33	kg
W_{cw}	5	kg
$W_{eva,w}$	25	kg

Table 3: Standard operating condition

	Temp.(°C)	Flow rate (kg/s)
Hot water	60 - 90	0.4
Cooling water	30	0.74(= 0.4 ads +0.34 cond)
Chilled water	14	0.11
Cycle time	1800s = (730 + 140 + 30)s×2 (ads/des + mr + ph/pc)	

ads/des = adsorption/desorption,
mr = mass recovery, ph/pc = pre-heating/cooling

A novel three-bed adsorption chiller with mass recovery scheme is proposed and cycle simulation computer program is developed to analyze the performance of the innovative chiller. Therefore, it is important to operate the chiller with renewable energy or waste heat of temperature below 100°C as the driving heat source. In this context, hot water temperature range is taken between 60 and 90°C.

Figure 2 shows inlet and outlet temperature profiles of hot, cooling and chilled water with hot, cooling and chilled water inlet temperatures are 80, 30, and 14°C. After 400 s, the hot water outlet temperature approaches the respective inlet temperature (80°C). But the cooling water outlet temperature from the adsorber after 400 s is still 1°C higher than its respective inlet temperature. The reason for this is the increasing amount of refrigerant requiring cooling at the end of adsorption process, in contrast to the desorption process, where little refrigerant remains to be heated. The delivered chilled water temperature, however, continues below the inlet temperature, showing the continuation of cooling energy production, which is highly desirable. Figures 3 and 4 show heat source temperature variation on SCP and COP, respectively. SCP rises from 16 to 96 W/kg as the hot water inlet temperature is increased from 50 to 90°C with a cooling water inlet temperature of 30°C. This is because the amount of refrigerant circulated increases, due to increased refrigerant desorption with higher driving source temperature. With hot water temperature variation, the simulated COP values peak between 70 and 85°C. The optimum COP value is 0.66 for hot water inlet temperature at 80°C along with the coolant and chilled water inlet temperature are at 30 and 14°C, respectively. The delivered chilled water temperature is 6°C for this operation condition. Figure 5 and 6 show the effect of cooling water inlet temperatures on SCP and COP. In the present simulation, cooling water mass flow rate into adsorber is taken as 0.4 kg/s, while for the condenser the coolant mass flow rate is taken as 0.34 kg/s. The SCP increases steadily as the cooling water inlet temperature is lowered from 40 to 20°C. This is due to the fact that lower adsorption temperatures result in larger amounts of refrigerant being adsorbed and desorbed during each cycle. The simulated COP values also increase with lower cooling water inlet temperature. For the three bed chiller the COP value reaches 0.74 with 80°C driving source temperature in combination with a coolant inlet

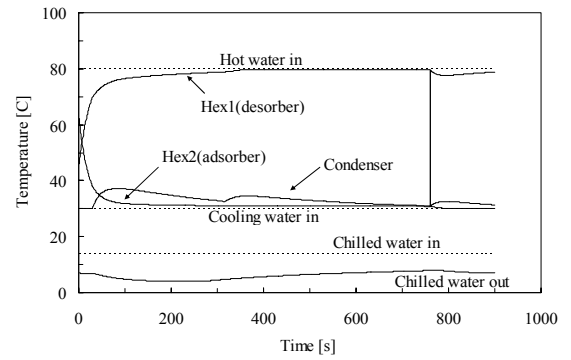


Fig 2. Temperature history of three bed chiller with mass recovery.

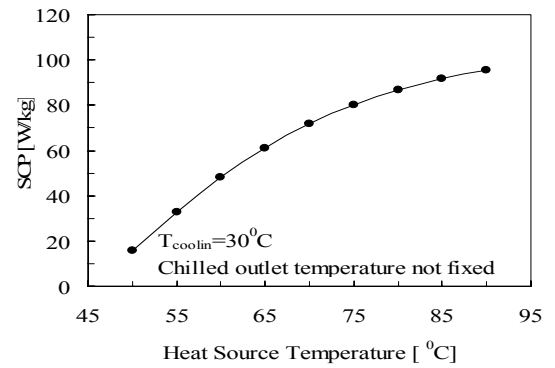


Fig 3. The effect of heat source temperature on SCP.

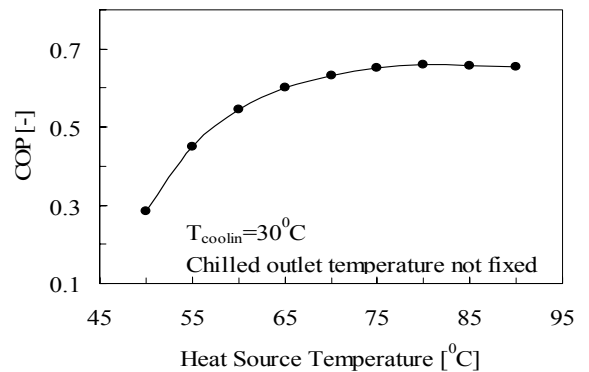


Fig 4. The effect of heat source temperature on COP.

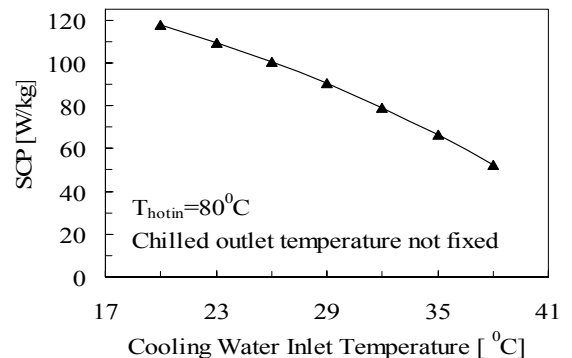


Fig 5. The effect of cooling water inlet temperature on SCP.

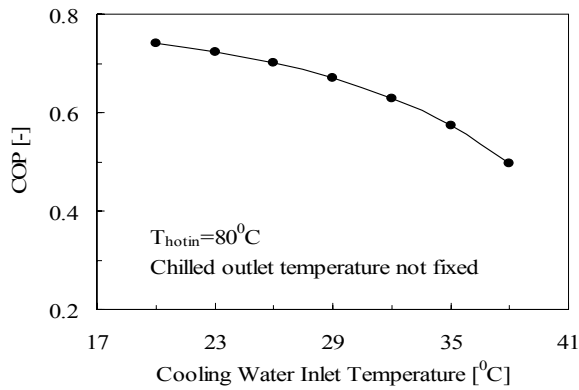


Fig 6. The effect of cooling water inlet temperature on COP.

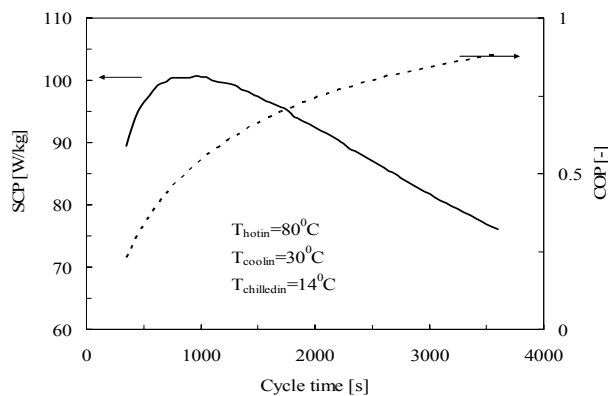


Fig 7. Cycle time effect on SCP and COP.

temperature of 20°C. SCP and COP variations with adsorption/desorption cycle time are depicted in Fig. 7. The sensible heating/cooling time is kept constant 30 s. The highest SCP values are obtained for cycle time between 750 and 1100 s. When cycle times are shorter than 750 s, there is not enough time for adsorption or desorption, so SCP decreases abruptly. On the other hand, when cycle times are greater than 1100 s, SCP decreases gradually as the adsorbent approaches to its equilibrium condition. COP increases uniformly with longer cycle times (see Fig. 7), this is because of the lower consumption of driving heat with longer adsorption/desorption cycles.

6. CONCLUSIONS

A novel three-bed chiller with mass recovery scheme is proposed and the performances are evaluated by numerical technique. There is an increasing need for energy efficiency and requirement for the system driven with low temperature heat source. For the utilization of the demand, multi-bed mass recovery cycle with silica gel/water pair is presented and the effects of operating conditions are investigated. The following concluding remarks can be drawn from the present analysis.

(i) The main feature of the proposed chiller is the ability to be driven by relatively low temperature heat source.

The chiller can utilize the fluctuated heat source temperature between 50 and 90°C to produce effective cooling.

(ii) Specific cooling capacity of the proposed chiller is increased as heat source temperature is increased from 50 to 90°C and cooling water inlet temperature is decreased from 40 to 20°C.

(iii) The optimum COP value (0.66) is obtained for hot water inlet temperature at 80°C in combination with the coolant and chilled water inlet temperatures are 30 and 14°C, respectively. The delivered chilled water temperature is obtained at 6°C.

(iv) Adsorption/desorption cycle time is very sensitive to the heat source temperature. The highest SCP values are obtained for cycle time between 750 and 1100 s in the present study.

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8. NOMENCLATURE

Symbol	Meaning	Unit
A	area	(m ²)
C _p	specific heat	(Jkg ⁻¹ K ⁻¹)
L	latent heat of vaporization	(Jkg ⁻¹)
\dot{m}	mass flow rate	(kgs ⁻¹)
P _s	saturated vapor pressure	(Pa)
Q _{st}	isosteric heat of adsorption	(Jkg ⁻¹)
q	concentration	(kg refrigerant/kg adsorbent)
q*	concentration at equilibrium	(kg refrigerant/kg adsorbent)
T	temperature	(K)
t	time	(s)
U	Overall heat transfer coefficient	(Wm ⁻² K ⁻¹)
W	weight	(Kg)
<i>Subscripts</i>		
<i>ads</i>	adsorber or adsorption	
<i>cond</i>	condenser	
<i>chill</i>	chilled water	
<i>cw</i>	cooling water	
<i>des</i>	desorber or desorption	
<i>eva</i>	evaporator	
<i>hex</i>	heat exchanger	
<i>hw</i>	hot water	
<i>in</i>	inlet	
<i>out</i>	outlet	
<i>s</i>	silica gel	
<i>w</i>	water	
<i>wv</i>	water vapor	