Article

High Performance Cascading Adsorption Refrigeration Cycle with Internal Heat Recovery Driven by a Low Grade Heat Source Temperature

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Abstract: This paper presents the performance of an advanced cascading adsorption cycle that utilizes a driven heat source temperature between 90–130 ºC. The cycle consists of four beds that contain silica gel as an adsorber fill. Two of the beds work in a single stage cycle that is driven by an external heat source, while the other two beds work in a mass recovery cycle that is driven by waste heat of sensible and adsorption heat of the high temperature cycle. The performances, in terms of the coefficient of performance (COP) and the specific cooling power (SCP), are compared with conventional cascading-without-mass-recovery and single-stage cycles. The paper also presents the effect of the adsorbent mass on performance. The results show that the proposed cycle with mass recovery produces as high of a COP as the COP that is produced by the conventional cascading cycle. However, it produces a lower SCP than that of the single-stage cycle.

Keywords: cascading cycle; performance; mass recovery; low temperature heat source

1. Introduction

The need for energy is constantly increasing and is leading to an increase in the price of energy; however, energy sources are getting scarce. Therefore, the search for an efficient technology has become a necessity. Heating and cooling systems are technologies that consume energy; and the demand for these systems is increasing in every aspect. Therefore, the development of a high-efficiency refrigeration and heat pump system that is driven by cogeneration of waste heat or renewable energy sources is highly desirable. Since the adsorption chillers are usually driven by heat, they can contribute to reducing the energy consumption by utilizing non-fossil fuels, such as waste heat from the cogeneration process or alternative renewable energy resources. In order to be competitive with other systems, most of the research in this field focuses on developing advanced cycles to improve chiller performance.

Silica gel–water is widely used as an adsorbent–adsorbate pair in adsorption refrigeration systems. Compared to other adsorbents, silica gel can be regenerated at a relatively low temperature that is below 100 ºC [1–4]. Silica gel also has a large capacity for the adsorption of water, which is up to 35%–40% of its dry mass [5]. In a cycle of adsorption refrigeration, the cooling power can be increased by increasing the driving heat source temperature. Another method to increase the capacity of the cooling power is to apply a mass recovery cycle.

The performance of the adsorption refrigeration cycle can be enhanced by applying a mass recovery cycle during the adsorption cycle [6–14]. The mass recovery cycle is produced by interconnecting the two beds that depressurize and pressurize after the desorption and adsorption processes, respectively. Conceptually, the pressure difference between the two beds in the beginning of the process will cause the refrigerant to flow until a pressure balance is reached between the beds. The application of a mass recovery process during the adsorption refrigeration cycle causes the span between the minimum and maximum concentration to expand. In other words, the refrigerant amount that can adsorbed/desorbed is increasing without increasing the temperature. Akahira *et al*. [6,7] determined that the mass recovery cycle provides heat to the desorber and cooling to the adsober. They also reported that the cycle produces a better performance than that of conventional mass recovery without heating and cooling. The mass recovery process produces a more effective performance if the high-pressure bed continues the heating process, while the low-pressure bed continues the cooling process. By continuing heating process, the pressure difference and the energy given by heating process will cause a more effective mass recovery process. Besides that, the adsorption heat release by cooling process will result in a more effective adsorption process.

The mass recovery cycle can improve the cooling power. However, to obtain significant improvement in the efficiency of the cycle, the internal heat recovery mechanism can be applied together with the mass recovery [12–14]. The continuous adsorption cycle can be produced by using at least two beds that work in opposite cycles at the same time. While one bed works in the heating process, the other one works in the cooling process. The internal heat recovery mainly occurs during the isosteric heating/cooling of the beds. During the internal heat recovery phase, the boiler and the bed heat exchanger are disconnected, and the fluid is pumped around to transfer heat from the hot desorbing heat exchanger to the cold adsorbing heat exchanger. The heat recovery from the hot to cold heat exchanger results in an increase in the system's performance. Recently, Uyun *et al.* [15,16]

proposed and investigated the advanced three-bed adsorption cycle to employ the heat and mass recovery cycle. They found that the performance of the cycle was superior to the performances of the three-bed single-stage and mass recovery cycles.

In order to achieve a high COP value, the cascading utilizing heat can be applied to the adsorption cycle. Generally, the cascading adsorption cycle has two different cycles, which have different adsorbent bed and desorption temperatures. The bed that works at high temperature cycles, is the top cycle, while the other bed, which works at low temperatures, is the bottom cycle. The high adsorption heat or/and condensation heat of the top cycle can be re-used as the driving force of the low cycle. Zeolite is usually used as the adsorbent of the top cycle while silica gel and active carbon are usually used as the adsorbent of the low cycle.

Zeolite works optimally at driving heat source temperatures above 150 ºC. Besides that, zeolite has a higher adsorption heat than other adsorbers, such as silica or active carbon. Therefore, most research chooses zeolite as the adsorber of the top cycle. There have been many investigations of the cascading cycle with zeolite as the adsorbent of the top cycle and active carbon as the adsorbent of the low cycle. Muenier [17] proposed a performance enhancement cycle, known as the cascading cycle, in which an adsorber zeolite/water cycle and an active carbon/methanol cycle are the top and bottom cycles, respectively. Dous and Meunier [18] experimentally investigated the performance of a cascaded cycle. Their experimental COP was 1.08.

Improvements to the cascading cycle were proposed by Liu and Leong [19], who investigated numerically a novel cascading cycle that was based on two zeolite adsorbent beds and a silica gel adsorbent bed. This cycle is simpler than that proposed by Dous and Meunier [18], since it uses only one type of refrigerant (water) and requires only one condenser and one evaporator. They concluded that the COP value of 1.3 for the cycle is more than two times that of an intermittent cycle (about 0.5). The COP value was also much higher than that of the heat and mass recovery cycle (about 0.8). However, the SCP of about 40 W/kg is much lower than those of the other two cycles. The other method of the cascading cycle was proposed by Stitou *et al.* [20]. They analyzed different cascading cycles, which couple solid gas reactions with the liquid-gas absorption process. The COP can be increased by more than 30% in comparison to the double-effect of the absorption cycles.

The cascading cycle effectively produces a high COP. However, the temperature of the top cycle of zeolite has a high driving temperature, over 150 ºC. This paper will investigate the ability to produce a high COP to improve the conventional cascading cycle, as well as to improve the cooling power of the conventional cycle in the low heat source temperature range of 90–130 ºC. Further explanation of the principle difference between the cascading cycle without mass recovery and the proposed cycle is given in the Working Principle section. In order to evaluate the improvement in performance, a comparison with the conventional single-stage adsorption refrigeration cycle will also be presented, in terms of the specific cooling power and the coefficient of performance.

2. Working Principle

Sorption refrigeration systems consist of four heat exchangers, as shown in Figure 1 and Figure 2: the desorber (generator), which exchanges heat (desorption heat, Qd) with a heating system at high temperatures (T3); a sorber, which exchanges heat with a cooling source at intermediate temperatures

(adsorption heat, Qa); a condenser, which exchanges heat with another heat sink at intermediate temperatures (condensation heat, Qc); and an evaporator, which exchanges heat with a heat source at low temperatures (evaporation heat, Qe). It can be seen from the Figure 1 that if the cycle operates at a high temperature, the waste heat from the adsorber (Qa) can be re-used to generate other cycles. This technique is the basic principle of the cascading utilizing adsorption heat, which produces a double-cooling-effect (Qe1 and Qe2) from one heat source temperature (Qd1).
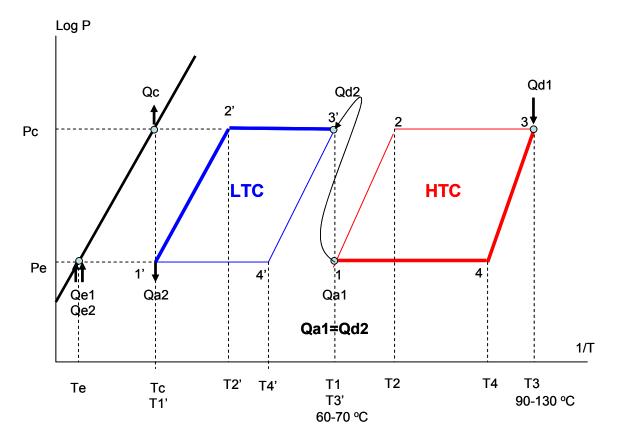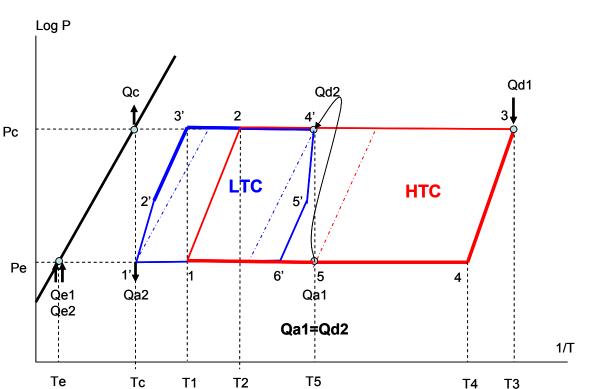
Figure 1. Ideal process of the cascading cycle without mass recovery.

The cascading adsorption cycle consists of four beds and can be divided into two cycles: the high temperature cycle (HTC) and the low temperature cycle (LTC). The two beds that contain the absorber, namely the high temperature adsorber (HTA$_1$ and HTA$_2$), are designed and used in the HTC; the beds are driven by the external heating sources. The other two beds that contain the absorber, namely the low temperature absorber (LTA$_1$ and LTA$_2$), are designed for, and used in, low heat source temperature cycles, which are driven from the waste heat of the condenser, or the adsorption heat of the HTC.

Figure 2. Ideal process of the proposed cascading cycle with mass recovery.

Figure 3 shows that the heating fluid from the external heating boiler is only connected to the HTA, while the cooling fluid from the cooling tower is only connected to the LTA. The heating fluid that is supplied from the external heating sources is circulated to the HTA by a heating pump (P1) and a cooling pump (P3). The heating fluid that circulates to the HTA is controlled by closing/opening a hot fluid valve (Vwh1-4), while the cooling fluid circulating to the LTA is controlled by closing/opening a cooling fluid valve (Vwc1-4). Pump 2 (P2) is used to circulate heat recovery fluid between the HTA and the LTA. The circulating heat recovery fluid is controlled by opening/closing the heat recovery valve (Vhr1-8). Pump 4 (P4) functions to circulate chilled water to the evaporator.

The beds are connected to the condenser during the desorption-condensation process by opening the condenser valve (Vvc1-4). While the adsorption-evaporation process occurs, the HTA and LTA are connected to the evaporator through the vapor valves of the evaporator (Vve1-4). Since the proposed cycle allows a mass recovery process in the LTC, extra valves are needed to connect to the bed. The mass recovery valves (Vm) connect LTA1 and LTA2. The sub-sections below explain the difference between the cascading adsorption cycle without mass recovery and the proposed cascading cycle with mass recovery.
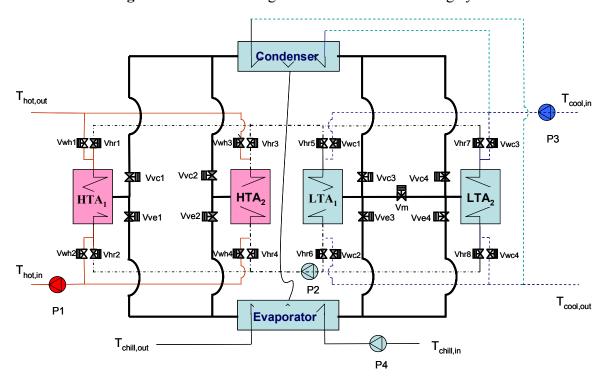
Figure 3. Schematic diagram of a four bed cascading cycle.

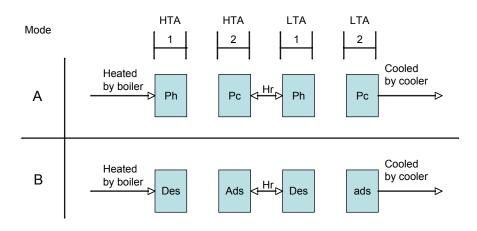*2.1. The cascading adsorption cycle without mass recovery*

The ideal processes of the cascading adsorption cycle without mass recovery conventional are presented in Figure 1. The cycle can be divided into four modes, as presented in Table 1. To complete a full cycle, the HTA and LTA pass through four steps: the pre-heating, desorption, pre-cooling and adsorption processes (Table 1). The half cycle that occurs in each adsorbent (Figure 4) can be explained as follows. In mode A, the HTA1 and LTA1 are in the pre-heating process, as shown in Figure 1 at point 1–2 and 1'–2'. At the same time, HTA2 and LTA2 are in the pre-cooling process, as shown in Figure 1 at point 3–4 and 3'–4'. In this mode, all of the heat exchangers are isolated from each other. All of the valves that connect the beds to the condenser (Vvc1-4) and the evaporator (Vve1-4) as well as the mass recovery valves (Vm) are closed. The heating system provides driving heat to HTA1 to increase the temperature; this causes the pressure of HTA1 to increase and approach the condenser pressure. Opposite to HTA1, HTA2 is in the pre-cooling process. To change the stage process from desorption to adsorption (point 3 to point 4), the HTA2 pressure should be reduced to the evaporator pressure; this reduction can be completed by decreasing the HTA2 temperature. Conventionally, reducing the HTA2 temperature can be accomplished by circulating the cooling fluid that is supplied by the cooling system. However, if the temperature of the pre-cooling is high, the potential heat loss of that process can be re-used and transferred to other beds, to increase the temperature of the other bed. For that purpose, pump 2 circulates the coolant fluid through HTA2 and LTA1 by opening valves Vhr3-6. The process causes the temperature and pressure of HTA1 to decrease to point 4, while LTA1 increases to point 2'. The pre-cooling process is also accomplished in LTA2 by releasing heat to the cooling system. Pump 3 circulates the coolant fluid through valve Vwc3,4 to decrease the temperature and pressure of LTA2 (point 4').

Mode B starts after the pressures of HTA1 and LTA1, as well as the pressures of HTA2 and LTA2, approach the condenser and evaporator pressure. In this mode, the heating and cooling process of each bed are the same as in mode A. Additionally, in this mode, HTA1 and LTA1 are in the desorption process, while HTA2 and LTA2 are in the adsorption process. The heating system provides driving heat to HTA1 for the desorption process. HTA2 produces adsorption heat during the adsorption-evaporation process that can be transferred to LTA1 as its driving force for the desorption process. Pump 3 still circulates the heat exchange fluid between HTA2 and LTA1. The heating process provides sufficient energy for releasing refrigerant from the adsorbent pores. The refrigerant then vaporizes to the condenser. By opening valve Vvc1 and valve Vvc3, the refrigerant vapor of HTA1 and LTA1, respectively, will flow to the condenser. The resulting refrigerant in the desorption process is cooled in the condenser, by circulating cooling water from the cooling system, which removes condensation heat. The desorption process of HTA1 and LTA1 takes place at the condenser pressure (Pc), as shown in Figure 2, at point 2–3 (HTA1) and point 2'–3' (LTA1). After the condensation process, the liquid refrigerant flows to the evaporator. The evaporator is connected to HTA2 and LTA2 by opening valve Vve2 and Vve4, respectively. The low adsorption heat of LTA1 that is produced during the adsorption-evaporation process is removed by supplying cooling fluid from the cooling system. The processes in the second–half are the same as in the previous half, where the position of HTA1 and LTA1 is changed to HTA2 and LTA2, respectively. Table 1 further explains the operation cycle.

Table 1. Operation scheme of the cascading cycle without mass recovery.

Mode	HTA1	HTA2	LTA1	LTA2
A	Pre-heating Ph	Pre-cooling Pc	Pre-heating Ph	Pre-cooling Pc
B	Desorption Des	Adsorption Ads	Desorption Des	Adsorption Ads
C	Pre-cooling Pc	Pre-heating Ph	Pre-cooling Pc	Pre-heating Ph
D	Adsorption Ads	Desorption Des	Adsorption Ads	Desorption Des

Figure 4. Schematic of the heat flow of the cascading cycle without mass recovery on the half cycle.

2.2. The proposed cascading adsorption cycle with mass recovery

The proposed cycle consists of four beds, which is the same as the conventional cycle that was presented in the previous sub-section. However, an extra pipe line, which includes a valve of Vm, is required between LTA1 and LTA2 for the mass recovery process. In one full cycle of the proposed cycle, the operation scheme of the cycle consists of two single-stage cycles of HTC (Figure 2, point: 1–4) and two mass recovery cycles of LTC (Figure 2, point: 1'–6'), as shown in Table 2.

The half cycle can be explained as follows. In mode A, the pre-heating and pre-cooling processes of the HTA are the same as in mode A of the cascading cycle without mass recovery (Section 2.1), where the HTA1 and HTA2 are isolated from the other heat exchanger. However, to reduce the temperature and the pressure of HTA2 in the pre-cooling process, pump2 circulates the heat exchange fluid through HTA2 and LTA1. The temperature of HTA2 decreases because sensible heat is released. The energy that is received by LTA1 causes the temperature of LTA1 to increase and the desorption process occurs.

The refrigerant vapor that is released from LTA1 flows to the condenser by the opening of valve Vvc3 and condenses in the condenser. The process is presented in Figure 2 path 3'–4'. After the condensation process, the liquid refrigerant flows to the evaporator. The adsorption-evaporation process is started by connecting the evaporator to LTA2 through valve Vv4. The refrigerant that is evaporated and captured by the evaporation heat from the low chilled water temperature is supplied to the evaporator.

The desorption process of LTA1 and the adsorption process of LTA2 continue into mode B by remaining connected to the condenser or evaporator, as described in mode A. Meanwhile, HTA1 and HTA2 are now involved in the desorption (2-3) and adsorption process (4-1), respectively. The opening/closing of the heat exchange valves are the same as in mode A. Table 2 shows, in mode B, two beds (HTA1 and LTA1) are in the desorption process, while the other two beds (HTA2 and LTA2) are in the adsorption process. The adsorption heat that is produced by HTA2 during the adsorption-evaporation process is transferred to HTA1 as a driving force for the desorption process. The refrigerant that is released during the desorption process of HTA1 and LTA1 will flow to the condenser for the condensation process. Next, the liquid refrigerant goes from the condenser to the evaporator. HTA2 and LTA2 adsorb the refrigerant in the evaporator, so that the adsorption-evaporation process will occur and produce a cooling effect.

The difference between the conventional cascading and the proposed cycle is from mode C. The LTA1 is in the end of the desorption process. The temperature, as well as the pressure of LTA1, is at a high level (Figure 2, point 4'). LTA2 is the opposite of LTA1 and is at a low level at the end of the adsorption process (Figure 2, point 1'). In this mode, LTA1 and LTA2 are connected in the mass recovery process with heating and cooling, respectively. In this process, heat is required to force the refrigerant from LTA1 to LTA2. The HTA2 supplies heat to LTA1 by a circulating heat exchange. The adsorption heat of HTA2 is transferred to LTA1 for energy input of mass recovery with heating.

In mode D, after the mass recovery process, the LTA1 and LTA2 continue to the pre-cooling (Figure 2, point 5'–6') and pre-heating processes. (Figure 2, point 2'–3'). The process is the same as in the pre-heating and pre-cooling of HTA, explained in mode A, where the beds are isolated from the
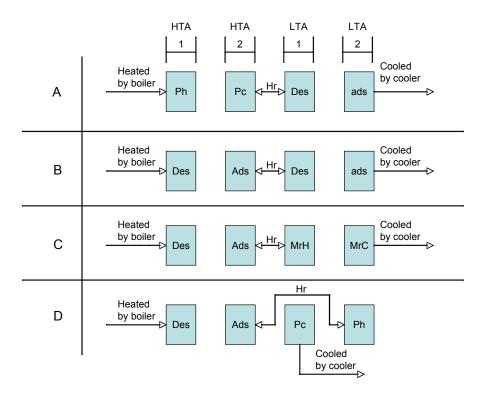
other heat exchangers. However, in mode D, the adsorption heat of HTA2 circulates to LTA2 to increase the temperature of LTA2.

The modes of E-H are the same operation cycle as modes A-D. However, the position of HTA1 and LTA1 are changed to HTA2 and LTA2, respectively. Table 2 further explains the complete operation cycle.

Table 2. Operation scheme of the proposed cascading cycle.

Cycle	HTA 1	HTA 2	LTA 1	LTA 2
A	Pre-heating Ph	Precooling Pc	Desorption Des	Adsorption Ads
B	Desorption Des	Adsorption Ads	Desorption Des	Adsorption Ads
C	Desorption Des	Adsorption Ads	Mass recovery MrH	Mass recovery MrC
D	Desorption Des	Adsorption Ads	Pre-cooling Pc	Pre-heating Ph
E	Pre-cooling Pc	Pre-heating Ph	Adsorption Ads	Desorption Des
F	Adsorption Ads	Desorption Des	Adsorption Ads	Desorption Des
G	Adsorption Ads	Desorption Des	Mass recovery MrC	Mass recovery MrH
H	Adsorption Ads	Desorption Des	Pre-heating Ph	Pre-cooling Pc

Figure 5. Schematic of heat flow of the proposed cascading cycle with mass recovery on half cycle.

3. Numerical Modeling

3.1. Adsorption model

The adsorption equilibrium model of the silica gel-water is described as a function of the temperature and pressure by the following:

$$q^* = q^*(P,T)$$

(1)

where q* is the equilibrium uptake at equilibrium, T is the temperature of the silica-gel and P is the adsorbate's partial pressure in the gas phase. The equilibrium of the silica gel-water pair is defined by a modified form of the Freundlich model (the S-B-K equation) as follows [1,22]:

$$q^* = A(T_s)\left[\frac{Ps(T_w)}{Ps(T_s)}\right]^{B(T_s)}$$

(2)

where $A(T_s) = A_0 + A_1 Ts + A_2 Ts^2 + A_3 Ts^3$ and $B(T_s) = B_0 + B_1 Ts + B_2 Ts^2 + B_3 Ts^3$.

The coefficient of $A_{0..3}$ and $B_{0..3}$ are determined by the least squares method applied to the experimental data, as discussed by Saha *et al.* [1]. $P_s(T_w)$ and $P_s(T_s)$ refer to the saturation vapor pressure at the refrigerant temperature T_w and the silica gel temperature T_s, respectively.

The adsorption rate is approached as the linear driving force equation:

$$\frac{dq}{dt} = ksap(q^* - q)$$

(3)

where overall mass transfer coefficient $(ksap)$ is given by:

$$ksap = \frac{15}{Rp^2} Ds_o \exp\left(-\frac{E_a}{RT}\right)$$

(4)

Ds_0 is the pre-exponential constant, E_a is the activation energy for surface diffusion, R is the gas constant, and T is the temperature.

3.2. The energy balance for HTA and LTA

The adsorption and desorption heat balances are described by identical equations, where the heat transfer fluid (oil) of the HTA temperature term $T_{H,in}$ and $T_{H,out}$ denotes the heat that is exchanged by the fluid upon the heat recovery process with the LTA and the hot oil temperature during the heating process. The heat transfer and the energy balance of the HTA adsorbent bed can be described as follows:

$$T_{H,out} = T_H + (T_{H,in} - T_H)\exp\left(-\frac{U_{hex}A_{hex}}{F_{H,oil}Cp_{oil}}\right)$$

(5)

$$\frac{d}{dt}\left\{\left(W_H C_H + W_H C_w q_H + W_{hex} C_{hex}\right)T_H\right\} =$$

$$W_H Q_{st,H}\frac{dq_H}{dt} - \delta_H W_H C_v\left(T_H - T_e\right)\frac{dq_H}{dt} + Q_{H,in} \tag{6}$$

where δ_H is either 0 or 1, which depends on whether the HTA is working as a desorber or an adsorber.

The heat balance of the LTA can be written as:

$$T_{L,out} = T_L + \left(T_{L,in} - T_L\right)\exp\left(-\frac{U_{hex}C_{hex}}{F_{L,oil}Cp_{oil}}\right) \tag{7}$$

$$\frac{d}{dt}\left\{\left(W_L C_L + W_L C_w q_L + W_{hex} C_{hex}\right)T_L\right\} =$$

$$W_L Q_{st,H}\frac{dq_L}{dt} - \delta_L W_L C_v\left\{\gamma_L\left(T_L - T_e\right) + \left(\gamma_L - 1\right)\left(T_L - T_v\right)\right\}\frac{dq_L}{dt} + Q_{L,in} \tag{8}$$

γ is either 1 or 0, which depends on whether the bed is connected to the evaporator or another bed (mass recovery process).

During the desorption and pre-heating processes, the HTA is heated by an external heat source. The heat input is given by:

$$Q_{H,in} = F_{H,oil}C_{oil}\left(T_{H,in} - T_{H,out}\right) \tag{9}$$

During the pre-cooling and adsorption processes, the LTA is cooled by an external cooling source. The cooling input is given by:

$$Q_{L,in} = F_{L,oil}C_{oil}\left(T_{L,in} - T_{L,out}\right) \tag{10}$$

During the heat recovery process between the HTA and LTA, the heat exchange fluid circulates between the HTA and the LTA. Hence, the inlet/outlet temperature of the HTA should be equal to the outlet/inlet temperature of the LTA. Thus, from Equation 5 and Equation 7, $T_{H,in}$ and $T_{L,in}$ can be written as:

$$T_{L,in} = T_{H,out} = T_H + \left(T_{H,in} - T_H\right)\exp\left(-NTU_H\right) \tag{11}$$

$$T_{H,in} = T_{L,out} = T_L + \left(T_{L,in} - T_L\right)\exp\left(-NTU_L\right) \tag{12}$$

By neglecting the sensible heat of the heat exchange fluid, the following is obtained:

$$Q_{L,in} = -Q_{H,in} \tag{13}$$

Using Equations 8 and 9, Equation 10 can be written as follows:

$$Q_{L,in} = -Q_{H,in}$$

$$= F_{hr}C_{oil}\left(T_H - T_L\right)\frac{\left[1 - \exp\left(-NTU_L\right)\right]\left[1 - \exp\left(-NTU_H\right)\right]}{\left[1 - \exp\left(-NTU_L\right)\exp\left(-NTU_H\right)\right]} \tag{14}$$

where F_{hr} is the mass flow rate of the heat exchange during the heat recovery process. NTU_H and NTU_L denote the number of heat transfer units of the HTA and LTA heat exchanger, respectively.

3.3. Energy balance for the condenser

In the calculation, it is assumed that the condenser can perfectly condense all of the refrigerants that are desorbed by the HTA and LTA, and that the refrigerant condensate would easily flow into the evaporator. The energy balance of the condenser can be expressed as:

$$T_{c,out} = T_c + \left(T_{c,in} - T_c\right)\exp\left(-\frac{U_{c,hex}A_{c,hex}}{F_{c,w}Cp_w}\right) \tag{15}$$

$$\frac{d}{dt}\left\{\left(W_{c,w}C_w + W_{c,hex}C_{c,hex}\right)T_c\right\} = \delta_H\left(-L - C_v\left(T_{des,H} - T_c\right)\right)W_H\frac{dq_{des,H}}{dt}$$
$$+ \delta_L\left(-L - C_v\left(T_{des,L} - T_c\right)\right)W_L\frac{dq_{des,L}}{dt} \tag{16}$$
$$+ F_c C_w\left(T_{c,in} - T_{c,out}\right)$$

where δ_H and δ_L are either 1 or 0, depending on whether the condenser is connected to the HTA / the LTA or not, respectively. The value of the overall heat transfer of the condenser $U_{C,hex}C_{C,hex}$ is assumed to be fixed by the term on the left side, which represents the sensible heat that is required by the refrigerant condensate $W_{c,w}$, as well as the heat exchanger tube of the condenser $W_{c,hex}C_{c,hex}$. On the right side, the first and second terms express the heat flow of the refrigerant vapor (v) from the desorption process of the HTA (*des,H*) and the LTA (*des,L*), respectively. The last term represents the total amount of heat that is released during the condensation process.

3.4. Energy balance for the evaporator

The energy balance for the evaporator can be expressed as:

$$T_{e,out} = T_e + \left(T_{e,in} - T_e\right)\exp\left(-\frac{U_{e,hex}A_{e,hex}}{F_{e,w}C_w}\right) \tag{17}$$

$$\frac{d}{dt}\left\{\left(W_{ew}C_w + W_{e,hex}C_{e,hex}\right)T_e\right\} =$$
$$- L\left(\gamma_H W_H\frac{dq_{ads,H}}{dt} + \gamma_L W_L\frac{dq_{ads,L}}{dt}\right) \tag{18}$$
$$- C_w\left(T_c - T_e\right)\left(\delta_H W_H\frac{dq_{des,H}}{dt} + \delta_L W_L\frac{dq_{des,L}}{dt}\right)$$
$$+ F_e C_w\left(T_{e,in} - T_{e,out}\right)$$

During the adsorption-evaporation process, the refrigerant will be adsorbed by the adsorbent, which is connected to the evaporator and is expressed by γ_H and γ_L and is equal to 1. At the same time, the evaporator receives liquid refrigerant heat from condenser and heat flow from the low temperature of

the chilled water, which is expressed in the second and third terms on the right side of Equation 15. The terms $\frac{dq_{ads,H}}{dt}$ and $\frac{dq_{des,H}}{dt}$ refer to the adsorption and desorption uptake rates of the HTA, respectively. The terms $\frac{dq_{ads,L}}{dt}$ and $\frac{dq_{ads,H}}{dt}$ refer to the adsorption and desorption uptake rates of the LTA.

3.5. Mass balance

The mass balance for the refrigerant in the evaporator can be expressed as:

$$\frac{dW_{ew}}{dt} = -\left(W_H \left(\frac{dq_{des-c,H}}{dt} + \frac{dq_{e-ads,H}}{dt} \right) + W_L \left(\frac{dq_{des-c,L}}{dt} + \frac{dq_{e-ads,L}}{dt} \right) \right) \tag{19}$$

where subscript des-c and e-ads stand for the refrigerant vapor that flows from the desorber to the condenser and from the evaporator to the adsorber, respectively.

3.6. Adsorbent mass ratio

The adsorbent mass ratio W_r is defined as the ratio between the LTA and the HTA adsorbent mass. It can be expressed as:

$$W_r = \frac{W_L}{W_H} \tag{20}$$

3.7. Performance indicators

The coefficient of performance (COP) shows the system's efficiency. During the heating mode of the HTA, the total heat input $Q_{H,tot}$ in one cycle can be estimated as:

$$Q_{H,tot} = F_{H,oil} Cp_{oil} \int_{0}^{t_{cycle}} \left(T_{H,in} - T_{H,out} \right) dt \tag{21}$$

The total heat released Q_e by the evaporator (cooling effect) is as follows:

$$Q_{e,tot} = F_e Cp_w \int_{0}^{t_{cycle}} \left(T_{e,in} - T_{e,out} \right) dt \tag{22}$$

Therefore, the COP can be written as the ratio between the heat released by the evaporator and the heat source input of the HTA:

$$COP = \frac{Q_{e,tot}}{Q_{h,tot}} \tag{23}$$

The specific cooling power (SCP) measures the chiller's capacity to produce a cooling effect in relation to the total mass of the adsorbent that is used. The SCP value can be expressed as:

$$SCP = \frac{Q_{e,tot}}{t_{cycle} W_{tot}}$$ (24)

Table 3. Standard operating conditions.

Parameter		Value	Unit
Hot water in	Temperature	110	^{o}C
	Flow rate	1.5	kg/s
Cooling water in	Temperature	30	^{o}C
	Flow rate	0.9	kg/s
	(ads+cond)	1.5 + 1.55	
Chilled water in	Temperature	14	^{o}C
	Flow rate	1	kg/s
Cycle time		1,500	s
Mass recovery time		100	s
Pre-heating/cooling time		60	s

Table 4. Value adopted in simulation [21].

Symbol	Value	Unit
$W_{L,H}$	47	kg
$C_{L,H}$	924	J/kg K
Qst	2.8×10^6	J/kg
Ea	2.33×10^3	J/kg
Ds0	2.54×10^{-4}	m^2/K
L	2.5×10^6	J/kg
$U_{hex}A_{hex}$	4.34	kW/K
$U_{c,hex}A_{c,hex}$	12	kW/K
$U_{c,hex}A_{c,hex}$	4.33	kW/K
$W_{hex}C_{hex}/W_{L,H}C_{L,H}$	1.8	-

4. Results and Discussion

4.1. Calculation procedure

The models are solved simultaneously using the finite difference method with a time step of one second. The following simplifying assumptions are made:

   a. Adsorption equilibrium is attained at all times;

b. The temperature and the amount adsorbed inside of each heat exchanger are uniform;

c. The refrigerant mass flows are equivalent among the evaporator and the adsorber, and the condenser and the desorber;

d. During the mass recovery process, the desorber pressure and the adsorber pressure are assumed to be equal for the two beds (adsober/desorber). The rate of refrigerant adsorption and desorption should be equal and can be approached by adjusting the pressure level in the iteration technique.
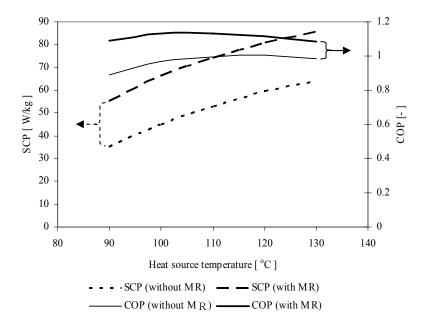
The operating conditions and the baseline parameters for the base case are shown in Tables 3. In the beginning of the calculation, the initial values are assumed and adjusted by an iterating process. The convergent criterion that is used in this iteration is taken as 10^{-3}.

4.2. Performance comparison between the cascading cycle without mass recovery and the proposed cycle with mass recovery

Figure 6 shows a comparison of the SCP and the COP values between the conventional and the proposed cascading cycle; these values are based on the input parameters presented in Table 3. It can be seen that the proposed cascading cycle produces better SCP and COP value than the conventional cascading cycle without mass recovery. If the heat source temperature is fixed at 110 ºC, the mass recovery that is applied to the cascading adsorption cycle will cause 40.2% of the SCP value to increase in the conventional cascading cycle without mass recovery. However, the increase of the COP value is not significant, being only 13.4%. The mass recovery cycle that is applied to the LTA causes an increase in the span of the maximum and minimum concentration of LTA. Thus, the refrigerant that can be adsorbed/desorbed will increase, as will the cooling power. The advantage of applying the mass recovery cycle is that the cooling power can be increased significantly without increasing the temperature of the driving force.

It can also be noted here that the proposed cycle with mass recovery passes through a two-step heat recovery process using both of the LTA adsobers in one cycle of a HTA adsorber. The first heat recovery process with LTA1 is completed when the temperature of HTA2 is at a high temperature (the end of the desorption process/start pre-cooling) (Figure 5), while LTA1 is at the beginning of the desorption process and needs more heat for the desorption process (mode A). Next, to produce more cooling power, HTA2 requires more cooling input. The adsorption heat can be released further by connecting it to the LTA2 for the second heat recovery process. The HTA adsorber then passes through the double cooling process (Figure 2, path: 4–5 and 5–1) and produces a high SCP, while the LTA adsober passes through a double heating process (Figure 2, path: 2'–3' and 3'–4'–5'). With this scheme, the cooling power, as well as the COP of the proposed cycle with mass recovery, is superior to that of the cascading cycle without mass recovery.

Figure 6. Performance comparison between the cascading cycle with and without mass recovery (MR).

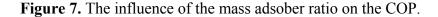*4.3. Influence of the adsorbent mass ratio on the performance*

The distribution of the adsorbent mass between the HTC and LTC is one of the factors influencing cycle performance. The HTC and LTC work in different ranges of desorption temperatures and different LTC driving forces, which depend on the adsorption heat of the HTC. Since the amount of adsorption heat that is produced by the HTA is directly influenced by the mass adsorber of the HTA, the optimum combination of the adsorber mass of the HTA and the LTA should be investigated, to provide an optimum performance. In the real design, the size of the heat exchanger depends on the adsorbent mass that is installed in the bed. Thus, in the calculation, the weight (W_{hex}) and surface area (A_{hex}) of the heat exchangers are assumed to be linear with the adsorbent mass $(W_{H,L})$ of each bed.

Figures 7 and 8 show the influence of the adsorber mass ratio on the performance for five different heat source temperatures with fixed input parameters, as shown in Table 3. An increase in the heat source temperature causes the performance to significantly increase (Figure 7). This increase is caused by the increase of uptake differences, which can increase the amount of refrigerant that is released/adsorbed.

Figure 7 shows that increasing the adsorber mass does not really affect the COP value. The COP value is relatively stagnant between 0.9 to 1.1 for each of the heat source temperatures observed. However, the influence is significant in the SCP value (Figure 8). The increase in the adsorber mass from 0.5 to 2 for each of the observed temperatures will increase the SCP value until the optimum point is reached; then, the SCP value will decrease drastically due to the increase in the mass adsorber ratio.

As can be seen from Equation 20, if the total adsorber is constant, higher adsorber mass ratio values will lead to a higher LTA in comparison to the HTA. The higher LTAs (higher adsorber mass ratio) require more LTA desorption heat. However, the sensible and adsorption heat that is produced by the

HTA is smaller then, and not proportional to, the amount of required LTA desorption heat. In other words, the insufficient amount of adsorber will cause the HTA to produce only a small amount of cooling power, which will lead to a drastic decrease in the SCP value at higher adsorber mass ratios. Meanwhile, if the desorption process is incomplete, the LTA will not produce optimum cooling power. The optimum adsorber mass ratio should be selected to achieve an optimum SCP value.

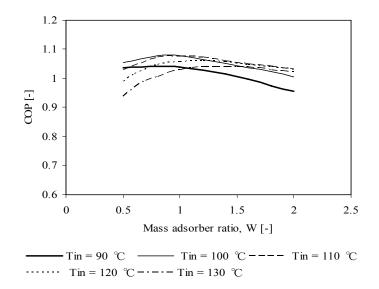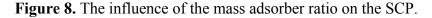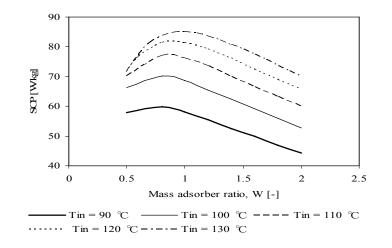**Figure 7.** The influence of the mass adsober ratio on the COP.

Figure 8 also shows that for each observed desorption temperature, there is an adsober mass distribution that produces an optimum SCP value. For example, when the heat source temperature is at 90 ℃, an optimum SCP value (60.4 W/kg) will be produced if the adsorber mass ratio is 0.7. Meanwhile, when the heat source temperature is at 120 ℃, an optimum SCP value (81.8 W/kg) will be produced if the adsorber mass ratio is 0.9. The increase in the heat source temperature will cause the increase in the sensible/adsorption heat produced by the HTA. The high temperature HTA is able to deliver more energy for greater LTA. However, the greater mass of HTA requires more energy input, which caused low the COP value. It can be seen from Figure 7, that if adsober mass ratio is at 0.5, the higher heat source temperature, the lower COP value will be.

Figure 8. The influence of the mass adsorber ratio on the SCP.

4.4. Performance comparison with a conventional single stage cycle

Figures 9 and 10 compare the COP and SCP, respectively of the proposed cascading cycle, with and without mass recovery, and a single-stage cycle. If the performance of one cycle is comparable to the other cycles, it is important to consider the outlet temperature of the chilled water; performance is strongly dependent on the evaporating temperature outlet. Therefore, the average chilled water outlet temperature in the calculation is fixed at 10 ºC for the sake of comparison.

Figure 9. COP comparisons among the cascading cycle with mass recovery, without mass recovery and single-stage cycle.
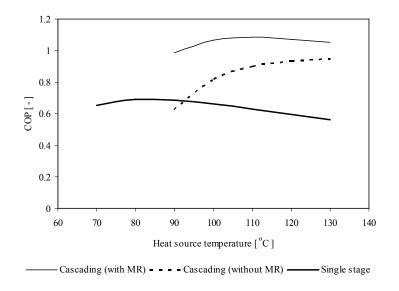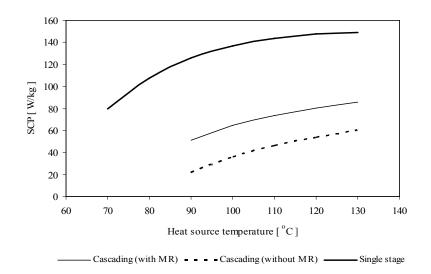
Figure 10. SCP comparisons among the cascading cycle with mass recovery, without mass recovery and single-stage cycle.

According to Figure 9, the proposed cycle with mass recovery produces the highest COP value of all cycles. Additionally, the COP conventional cascading cycle will decrease drastically if the heat

source temperature is less than 100 ºC. However, the proposed cascading cycle is able to produce a high COP, even at low temperatures of 90–110 ºC. This high COP production is possible because the double cooling/heating scheme in the proposed cycle will cause a maximum LTA desorption temperature that is higher than the conventional cycle and a minimum HTA adsorption temperature that is lower than the conventional cycle.

The proposed cycle is incapable of producing a higher SCP than the conventional single stage, as shown in Figure 10. In the adsorption refrigeration cycle, during the adsorption-evaporation process, the high cooling power is determined by cooling the temperature when releasing the adsorption heat. The lower temperature of the cooler adsorber generates a better adsorption process, which is reflected by a greater amount of refrigerant than can be adsorbed by the adsorber. Since the cooling temperature of the single stage is fixed at 30 ºC, the adsorption process will be more efficient when adsorbing refrigerant that is produced at a high cooling power. In contrast with the single stage cycle, in the cascading cycle, the cooling temperature of the top cycle is determined by a heat recovery process with the bottom cycle, which results in a higher cooling temperature. This will lead to a low cooling power due to the high adsorption cooling temperature.

5. Conclusions

The performances of the conventional cascading and the advanced cascading, which employ a mass recovery cycle, have been analyzed in terms of the COP and the SCP. It can be concluded that, in the comparison between the conventional and the proposed cycle at the observed heat source temperature, the COP and SCP values of the proposed cycle are superior to those of the conventional cycle. Employing the mass recovery cycle improves the SCP value and also produces a higher COP value, which is produced by the conventional cascading cycle. Additionally, there is an interval point of the adsorber ratio that can be chosen to produce optimum COP and SCP values. The cascading adsorption cycles produce higher COP values (>l) but lower SCP values, in comparison with the conventional single-stage cycle. Since the heat input is only provided to the HTA, the cascading cycle produces a high COP in comparison to that of the conventional single-stage cycle. However, the high cooling temperature of the HTA causes a low cooling power to be produced by the cascading cycle.

Nomenclature

A	area (m^2)
C	specific heat (J/kg K)
Ds_o	surface specific heat (m^2/s)
Ea	activation energy (J/kg)
F	mass flow (kg/s)
L	latent heat of vaporization (J/kg)
Ps	saturated vapor pressure (Pa)
q	fraction of refrigerant that can be adsorbed by the adsorbent (kg/kg)
q^*	fraction of refrigerant that can be adsorbed by the adsorbent under saturation condition (kg/kg)
Q_{in}	driving heat (W)
Q_{eva}	average cooling output (W)

Qst   isosteric heat of adsorption (J/kg)

R   gas constant (J/kg K)

Rp   average radius of a particle (m)

T   Temperature (K)

t   time (s)

tcycle   cycle time (s)

W   weight (kg)

Wr   adsorber mass ratio (-)

Subscripts

ads   adsorption

c   condenser

cw   cooling water

des   desorption

e   evaporator

ew   water in evaporator

H   high temperature absorber (HTA)

hr   heat recovery

hex   adsorber/desorber heat exchanger

hot   hot water

in   inlet

L   low temperature absorber (LTA)

oil   heat exchange fluid

out   outlet

s   silica gel

tot   total

v   vapor

w   water

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