PERFORMANCE ANALYSIS AND CYCLE TIME OPTIMIZATION OF A SINGLE EVAPORATOR THREE-BED SOLID-SORPTION REFRIGERATION SYSTEM DRIVEN BY LOW-TEMPERATURE HEAT SOURCE

Bartosz ZAJACZKOWSKI
Wroclaw University of Technology, Faculty of Mechanical and Power Engineering
Wyb. Wyspianskiego 27, Wroclaw, 50-370, Poland
bartosz.zajaczkowski@pwr.edu.pl

ABSTRACT

This paper discusses performance analysis and cycle time optimization of a three-bed silica-gel/water adsorption chiller. Presented study builds upon the fact that desorption phase requires noticeably less time than adsorption phase, i.e. desorption is 2.2-3.5 times faster than adsorption. The operating cycle was simulated using a numerical model. Lengths of adsorption/desorption phases and the offset time between individual adsorbers were varied for optimal performance.

The results show that third bed increased cooling capacity of adsorption chiller. The optimal total cycle time that yields the highest cooling capacity is slightly shorter than in a two-bed setup. The difference is larger if the chiller is driven by lower temperature, 65°C instead of 85°C. The optimal ratio between the time of desorption and the time of adsorption in a three-bed system is \( f \approx 0.6 \), while it is \( f \approx 0.8 \) in a two-bed system.

The actual percentage of improvement depends on operating conditions and system design.

In order to reduce temperature fluctuations in chilled water, Miyazaki et al. (2009) proposed a modification to the time allocation. Similar time allocation was also suggested in the paper of El-Sharkawy et al. (2013). In proposed allocation (for a two-bed system) the adsorption time takes exactly half of the cycle. The other half is divided between desorption phase and two isosteric phases. In result the evaporator is always...
connected to one of the beds. Therefore, cooling output is more stable and temperature fluctuations in chilled water are noticeably reduced.

Saha et al. (2003) conducted a numerical analysis of a three-bed non-regenerative silica gel-water adsorption chiller using lumped parameter model. The authors analysed variations of the cooling capacity and the COP by changing inlet temperatures of heat transfer fluids and lengths of adsorption/desorption phases. They also studied the influence of driving source temperature on the efficiency of waste heat recovery.

Miyazaki and Akisawa (2009) have rewritten the two-bed lumped parameter model using dimensionless parameters and optimized the cycle time with the particle swarm optimization method (PSO). The research explored the influence of operating conditions and parameters of heat exchanger on the optimum performances. The authors established that the optimal adsorption/desorption time is approx. 450 s. More recently, Fezal et al. (2013) also used the PSO method for cycle time optimization in a three bed chiller with mass recovery. However, the authors analysed only one specific type of a three-bed chiller that consists two large and one small adsorbent bed.

In this paper an upgrade from a two-bed chiller to a three-bed setup is modelled and studied. The size and heat transfer parameters of the additional bed are identical as in the initial pair. Cycle time optimization for a three-bed setup is presented. Two independent parameters are controlled in the process: the ratio between the time of desorption and the time of adsorption $f$ and the offset time between working cycles of each involved adsorbent bed. The entire range of time allocations in a three-bed setup is analysed in search for the optimal performance.

The aim of this work is the improvement of the cooling capacity and the COP, due to adjustment of adsorption and desorption times and determination of the optimal values that ensure reaching the maximum.

2. MODEL DESCRIPTION

Schematic diagram of a three-bed adsorption chiller is presented in Figure 1. The system comprises five heat exchangers and six valves that control the flow of refrigerant. Each bed can be either connected to evaporator (adsorption mode), condenser (regeneration mode) or it can be cut off from both (isosteric heating or cooling) i.e. in this system advanced heat and mass recovery modes are not implemented.

![Figure 1. A three-bed adsorption chiller. Bed A is in desorption mode, bed B and C are in adsorption mode.](image)

Calculations are based on a differential lumped parameter model. Balance equations are solved numerically using code written in Python. Simulation results for a two-bed setup were compared to experimental values reported in publications (Boelman et al., 1995a, 1995b) (see Figure 2). Then, the model has been extended to take under consideration the additional adsorbent bed, and to allow simulation in the entire range of $f$ and $x$ ratios.
2.1. Energy and mass balance equations

Adsorber balance is described by lumped parameter model. Thermodynamic parameters of bed, such as pressure, temperature and concentration, are the same within its volume.

\[
\left( M_{ads}c_{p,ads} + M_{ref}c_{p,ref} + M_{met}c_{p,met} \right) \frac{dT_{bed}}{dt} = \theta M_{ads} \frac{dq}{dt} \Delta H_{ads} - \dot{m}_{hbf}c_{p,hbf}(T_{hbf,out} - T_{hbf,in})
\]

(1)

Heat transfer fluid has parameters (inlet temperature, mass flow and specific heat) of cooling water if bed is connected to cooling tower, and of the driving source if it is connected to driving heat source. The left hand side of eq. (1) represents the change of internal energy of bed. \( M \) is the mass, while index \( ads \) means adsorbent, \( ref \) means adsorbate/refrigerant and \( met \) stands for metallic parts – aluminium fins and copper tubes. The right hand side includes heat of adsorption/desorption and heat supplied/removed by heat transfer fluid. \( \theta = 0 \) during isosteric modes or \( \theta = 1 \) during adsorption and desorption modes. \( \Delta H_{ads} \) is the isosteric heat of adsorption.

Evaporator/condenser balance is as follows:

\[
\left( c_{p,water}M_{ref,eva} + c_{p,Ca}M_{eva,cond} \right) \frac{dT_{eva,cond}}{dt} = -L_eM_{ads} \frac{dq}{dt} + \dot{m}_{chill,cool}(T_{chill,cool,in} - T_{chill,cool,out})
\]

(2)

In case of the evaporator, the subscripts \( eva \) and \( chill \) denote evaporator and chilled water. In case of the condenser, the subscripts \( cond \) and \( cool \) denote condenser and cooling water respectively. \( L_e \) is the heat of evaporation of water. The left hand side of eq. (2) represents the change of internal energy of evaporator/condenser. The right hand side includes heat of evaporation/condensation and heat supplied/removed by chilled/cooling water respectively. In order to make calculation results comparable with the work of El-Sharkawy et al. (2013) energy transferred with gas phase and with liquid condensate has been omitted.

Outlet temperatures of heat transfer fluid, cooling water and chilled water are calculated using the log mean temperature method.

\[
T_{out} = T_{hex} + (T_{in} - T_{hex}) \exp \left( -\frac{(UA)_{hex}}{\dot{m}c_p} \right)
\]

(3)

Index \( hex \) stands for the heat exchanger (evaporator, condenser or bed respectively), \( m \) and \( c_p \) are the mass flow and specific heat of a heat transfer fluid that supplies/removes heat from the heat exchanger, while indexes \( in \) and \( out \) refers to its inlet and outlet temperature. \( U \) and \( A \) represents the overall heat transfer coefficient and the heat transfer area in the heat exchanger.

The mass balance of liquid refrigerant in evaporator assumes that condensate is not stored in condenser and returns to evaporator. The equation include uptake variations in all the beds:
\[
\frac{dm_{\text{ref}}}{dt} = M_{\text{ads}} \left( \frac{dq_{\text{bedA}}}{dt} + \frac{dq_{\text{bedB}}}{dt} + \frac{dq_{\text{bedC}}}{dt} \right)
\]

(4)

where \( m_{\text{ref}} \) is the mass of refrigerant stored in evaporator in liquid phase and \( M_{\text{ads}} \) is the fixed mass of silica gel in each of adsorbent beds.

2.2. Adsorption kinetics

The LDF equation is an accurate and widely accepted approximation of a solid diffusion model. It is a first-order linear differential equation that is easy to solve and doesn’t require significant computing power. Its speed and precision are the main reasons of wide application of LDF model in numerical simulations of heat and mass transfer in adsorbent beds (Sakoda and Suzuki, 1984). The LDF equation is as follows:

\[
\frac{dq}{dt} = \frac{F_0 D_{\text{app}}}{R_p^2} (q^* - q)
\]

(5)

The LDF equation is accompanied by adsorption equilibrium equation. Literature reports several equilibrium equations used by various researches. Here, equilibrium adsorption capacity is calculated with modified Freundlich equation that has been first proposed by Saha et al. (1995).

\[
q^* = A(T_{\text{bed}}) \frac{P_{\text{sat}}(T_r)}{P_{\text{sat}}(T_{\text{bed}})^B(T_{\text{bed}})}
\]

(1)

Constants in Freundlich equation are substituted by two polynomial functions of adsorbent temperature.

\[
A(T_{\text{bed}}) = -6.5314 + 0.072452 \times T - 0.23951 \times 10^{-3} \times T^2 + 0.25493 \times 10^{-6} \times T^3
\]

(1)

\[
B(T_{\text{bed}}) = -15.587 + 0.15915 \times T - 0.50612 \times 10^{-3} \times T^2 + 0.5329 \times 10^{-6} \times T^3
\]

(1)

Table 1. Parameters and values used in calculations (Boelman et al., 1995a; El-Sharkawy et al., 2013), where \( A \) is the heat transfer area, \( U \) is the overall heat transfer coefficient, \( D_{\text{app}} \) is the apparent diffusivity, \( E_a \) is the activation energy, \( L_e \) is the heat of evaporation/condensation, \( DH_{\text{ads}} \) is the heat of adsorption, \( R_p \) is the particle radius, \( T_{\text{in}} \) is the inlet temperature of heat transfer fluid, \( c_p \) is the specific heat, \( M \) is the mass, and \( m \) is the mass flow of heat transfer fluid.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{\text{cond}} )</td>
<td>3.73</td>
<td>( m^2 )</td>
<td>( c_p )-water</td>
<td>4186</td>
<td>J/kgK</td>
</tr>
<tr>
<td>( A_{\text{evap}} )</td>
<td>1.91</td>
<td>( m^2 )</td>
<td>( c_p )-Al</td>
<td>905</td>
<td>J/kgK</td>
</tr>
<tr>
<td>( A_{\text{ads}} )</td>
<td>2.46</td>
<td>( m^2 )</td>
<td>( c_p )-Cu</td>
<td>386</td>
<td>J/kgK</td>
</tr>
<tr>
<td>( U_{\text{cond}} )</td>
<td>4115.23</td>
<td>( W/m^2K )</td>
<td>( c_p )-ads</td>
<td>924</td>
<td>J/kgK</td>
</tr>
<tr>
<td>( U_{\text{evap}} )</td>
<td>2557.54</td>
<td>( W/m^2K )</td>
<td>( M_{\text{ads}} )</td>
<td>47</td>
<td>kg</td>
</tr>
<tr>
<td>( U_{\text{ads}} )</td>
<td>1602.56</td>
<td>( W/m^2K )</td>
<td>( M_{\text{cond}} )</td>
<td>24.28</td>
<td>kg</td>
</tr>
<tr>
<td>( U_{\text{des}} )</td>
<td>1724.14</td>
<td>( W/m^2K )</td>
<td>( M_{\text{evap}} )</td>
<td>12.45</td>
<td>kg</td>
</tr>
<tr>
<td>( D_{\text{app}} )</td>
<td>2.54e-4</td>
<td>( m^2/s )</td>
<td>( M_{\text{ref-evap}} )</td>
<td>50</td>
<td>kg</td>
</tr>
<tr>
<td>( E_a )</td>
<td>4.264</td>
<td>J/mol</td>
<td>( M_{\text{met,Al}} )</td>
<td>64.04</td>
<td>kg</td>
</tr>
<tr>
<td>( L_e )</td>
<td>2.56</td>
<td>J/kg</td>
<td>( M_{\text{met,Cu}} )</td>
<td>51.20</td>
<td>kg</td>
</tr>
<tr>
<td>( \Delta H_{\text{ads}} )</td>
<td>2.866</td>
<td>J/kg</td>
<td>( m_{\text{htf}} )</td>
<td>1.3</td>
<td>kg/s</td>
</tr>
<tr>
<td>( R_p )</td>
<td>1.76e-4</td>
<td>( m )</td>
<td>( m_{\text{cool}} )</td>
<td>(1.3+1.6)</td>
<td>kg/s (ads+cond)</td>
</tr>
<tr>
<td>( T_{\text{htf-in}} )</td>
<td>85</td>
<td>( ^\circ C )</td>
<td>( m_{\text{chill}} )</td>
<td>0.7</td>
<td>kg/s</td>
</tr>
<tr>
<td>( T_{\text{cool-in}} )</td>
<td>31</td>
<td>( ^\circ C )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{\text{chill-in}} )</td>
<td>14</td>
<td>( ^\circ C )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3. Cycle time allocation
Two different factors \( f \) and \( x \) are considered in this analysis. Parameter \( f \) is the ratio between lengths of desorption phase \( t_{\text{desorption}} \) and adsorption phase, which is similar to that used by El-Sharkawy et al. (2013). Introducing ratio \( f \) produces the following set of equations that allows determination of adsorption and desorption phase lengths.

\[
t_{\text{adsorption}} = \frac{t_{\text{cycle}} - 2 \times t_{\text{switch}}}{1 + f}
\]

\[
t_{\text{desorption}} = f \times t_{\text{adsorption}}
\]

2.4. Performance
Performance of an adsorption chiller is evaluated in terms of cooling capacity and COP that are calculated as follows:

\[
Q_{\text{chill}} = \int_0^{t_{\text{cycle}}} (m c_p)_{\text{chill}} (T_{\text{chill-in}} - T_{\text{chill-out}}) \, dt
\]

\[
\text{COP} = \frac{\int_0^{t_{\text{cycle}}} (m c_p)_{\text{chill}} (T_{\text{chill-in}} - T_{\text{chill-out}}) \, dt}{\int_0^{t_{\text{cycle}}} (m c_p)_{\text{hfl}} (T_{\text{hfl-in}} - T_{\text{hfl-out}}) \, dt}
\]

3. RESULTS AND DISCUSSION

3.1. Performance comparison of two beds vs. three beds
Two-bed and three-bed adsorption systems compared here are essentially identical, because all the masses, mass flows, temperatures and heat transfer coefficients are assumed to be the same. The only difference is the presence of additional bed that contributes to cooling effect (when connected to evaporator) and requires additional heating (when regenerated). In both compared cases \( f = 1 \) (adsorption and desorption times are equal) and the switching time is set at 30 s. The result of comparison is presented in Figure 2. For comparison the offset time between beds depends on the number of beds \( n \):

\[
t_{\text{offset}} = \frac{t_{\text{cycle}}}{n}
\]

Three-bed system offers approx. 20-30% higher cooling capacity (see Figure 3a). Both setups show similar performance in terms of COP, though the COP of a three-bed unit is lower (see Figure 3b), which can be explained by increased thermal mass of the device.

![Figure 3. Comparison between (otherwise identical) two-bed (continuous line) and three-bed (dashed line) adsorption chiller driven by temperature 85°C and 65°C: (a) cooling capacity, (b) COP.](image)

3.2. Adsorption/desorption time and offset time allocation
In a two-bed setup the cooling capacity and the COP increase at $f = 0.8–1.0$ for adsorption times between 350–600 s (total cycle time approx. 650–1250 s) and switching time about 30–35 s (El-Sharkawy et al., 2013), proving that it is possible to take advantage of the fact that kinetics of desorption is faster than kinetics of adsorption. Reducing $f$ yields similar effect in a three-bed setup. However, both the cooling capacity and the COP peak at different value of $f$. Also, in a three-bed setup the allocation of phase times is more complicated and might influence performance.

The offset ratio $x$ has been introduced, in order to evaluate the influence of the entire range of possible time allocations of phases. It reflects the ratio of the offset time $t_{offset}$ to the total cycle time $t_{cycle}$. The beginning of desorption phase in beds B and C is determined in such a way that desorption phase in bed B starts $t_{offset}$ seconds later and desorption phase in bed C starts $t_{offset}$ seconds earlier than in bed A. The arrows in Figure 4 visualize the concept in detail.

![Figure 4. Cycle time allocation in a three-bed system for different offsets $x$ and $f = 1$.](image)

Saha et al. (2003) evaluated system behaviour for three different total cycle lengths, assuming that each bed operate out of phase of adsorption time for second and third bed correspondingly. Using offset ratio notation proposed here, the value of $x$ used by the authors is $x \sim 0.3$. The optimization presented here has been conducted for the total cycle time $t_{cycle} = 660$ s and switching time $t_{switch} = 30$ s. Since there is a symmetry at $x = 0.5$ (see Figure 4), only half of the range of $x$ is shown in Figure 5 and 6 Contour plots were generated based on calculated 625 evaluation points.

![Figure 5. Cooling capacity of a three-bed sorption system driven by 85°C source, evaluated for the entire range of adsorption to desorption time ratio $f$ and offset time ratio $x$.](image)
Figure 6. COP of a three-bed sorption system driven by 85°C source, evaluated for the entire range of adsorption time to desorption time ratio \( f \) and offset time ratio \( x \).

The above diagrams show that it is indeed possible to maximize the cooling capacity and the COP in a three-bed system by taking advantage of shorter desorption phase and proper selection of the offset time. The highest cooling capacity and the highest COP are achieved for \( x = 0.33 \) and \( f = 0.60 - 0.65 \). However, additional local maximum of COP can be noticed for \( x = 0.3 \) and \( f = 0.55 \). Full range of calculations were done for both driving temperature levels 85°C and 65°C, showing that in both cases the highest values are reached for the same values of \( f \) and \( x \).

Figure 7. Steady state temperature profiles in a three-bed sorption system driven by 85°C source, for the optimal offset time ratio \( x = 0.3333 \).

3.3. Optimal length of desorption phase

Figure 8 shows comparison of cooling capacities (a) and COP (b) of a three-bed system (driven by 85°C source) in the entire range of adsorption cycle times, before and after the optimal \( f \) ratio has been implemented. Reduction of \( f \) yields higher cooling capacity. However, reaching the maximum requires slightly longer adsorption phase: the optimal \( t_{\text{adsorption}} = 340 \) s. Reduced desorption time gives better performance, but only if the length of an adsorption phase \( t_{\text{adsorption}} > 200 \) s. Otherwise, the capacity of bed is not utilized in full, because the adsorption kinetics becomes the limiting factor.

4. CONCLUSIONS

The results show that adding third (otherwise identical) bed increased cooling capacity of adsorption chiller by 20-30\% (see Figure 3a), but at the same time it reduced its COP by 8-10\% (see Figure 3b). Decrease of the COP is more significant at shorter cycle times. The optimal total cycle time for the highest cooling capacity is shorter than in a two-bed setup by approx. 50 s (at 85°C), and approx. 100 s (at 65°C).
In a two-bed system the time of desorption can be shortened yielding higher cooling capacity, because desorption occurs faster than adsorption. The same feature can be implemented in a three-bed setup. However, for the optimal performance the \( f \) ratio must be even lower than in a two-bed device. Obtained optimal value of the ratio between time of desorption and time of adsorption in a three-bed system \( f = 0.60 - 0.65 \) (while \( f \approx 0.8 \) in a two-bed system). The optimal offset time set between adsorbent beds \( x \) is approx. \( 1/3 \) of the total cycle time, regardless of the driving temperature and the value of \( f \) ratio (see Figures 4 and 5). Reduction of \( f \) leads to higher cooling capacities. The new maximum cooling capacity require slightly longer adsorption phase (here, optimal \( t_{\text{adsorption}} = 340 \) s for \( f = 0.6 \) and \( t_{\text{adsorption}} = 300 \) s for \( f = 1.0 \)). For the optimal ratio \( f \), the increase of performance is only observed if adsorption phase is longer than \( t_{\text{adsorption}} > 200 \) s (see Figure 8). If the phase is shorter, adsorption kinetics becomes limiting factor and reduction of \( f \) produces negative effect. The cycle time optimization presented in this paper allowed increasing cooling capacity of a three-bed setup by \( \sim 6\% \).

5. REFERENCES


