Performance Analysis of Waste Heat Driven Pressurized Adsorption Chiller*  

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Abstract  
This article presents the transient modeling and performance of waste heat driven pressurized adsorption chillers for refrigeration at subzero applications. This innovative adsorption chiller employs pitch-based activated carbon of type Maxsorb III (adsorbent) with refrigerant R134a as the adsorbent-adsorbate pair. It consists of an evaporator, a condenser and two adsorber/desorber beds, and it utilizes a low-grade heat source to power the batch-operated cycle. The ranges of heat source temperatures are between 55 to 90 °C whilst the cooling water temperature needed to reject heat is at 30 °C. A parametric analysis is presented in the study where the effects of inlet temperature, adsorption/desorption cycle time and switching time on the system performance are reported in terms of cooling capacity and coefficient of performance.  

Key words: Pressurized Adsorption Chiller, Activated Carbon, Waste Heat  

1. Introduction  
Thermally-driven sorption refrigeration systems have received increasing interest in recent years as they can be driven by low-grade heat sources, have no major moving parts, long lasting, less maintenance and environmentally benign(1,2). It is considered to be the alternatives of conventional vapor compression cycles. As the system is a waste heat driven system, Ng(3) has classified that the coefficient of performance (COP) of such thermally activated adsorption systems is normally less than 1. Extensive studies have been conducted to estimate the performance of adsorption cooling systems using different combinations of adsorbent/adsorbate pairs(4)-(8). The adsorption systems can either operate at sub-atmospheric pressures using water-silica gel and methanol-activated carbon pairs; or at high pressures when the adsorbent-adsorbate pairs are of the ammonia-activated carbon or the R134a-activated carbon. The major advantage of such working fluids is zero ozone depletion and thus environment friendly. The latter refrigerant based adsorption cycle enables sub-zero evaporating temperatures to be achieved at the evaporators.  

In current study, both the equilibrium and transient analyses (simulation) of the
pressurized adsorption chiller using activated carbon Maxsorb III/R134a working pair are investigated at different evaporative temperatures, operating and switching time, and their results are presented in terms of cooling capacity and coefficient of performance. The waste-heat driven pressurized adsorption chiller consists mainly of an evaporator, condenser, and two adsorber beds. Pressure equalization between the two adsorber beds during the switching process enhances the performance of the system.

2. Theory—Adsorption Parameters

2.1 Adsorption isotherm

The Dubinin-Astakhov (D-A) isotherm model for adsorption of vapors and gases onto non-homogeneous carbonaceous solids with wider pore size distribution has been used to correlate the experimental equilibrium uptake values. This D-A model allowed for the surface heterogeneity and also extended to high-pressure region.

\[
\frac{q}{q_0} = \exp \left[ -\left( \frac{A}{E_a} \right)^n \right]
\]

Here \( q \) indicates the amount of uptake measured in kg kg\(^{-1}\) (unit mass of vapor uptake per unit mass of adsorbent), \( q_0 \) is the limiting uptake of adsorption space for the adsorbent in kg kg\(^{-1}\), \( E_a \) is the characteristic/activation energy of the adsorption system in J kg\(^{-1}\), \( n \) is the structural heterogeneity parameter and \( A \) is the adsorption potential given in Eq. (2).

\[
A = RT \ln \left( \frac{P}{P_s} \right)
\]

\( R \) is the gas constant in J kg\(^{-1} \) K\(^{-1}\), \( P_s \) is the saturation pressure. \( P \) and \( T \) are the equilibrium pressure (kPa) and temperature (K), respectively.

Table 1 presents the regressed adsorption isotherm parameters for R134a with Maxsorb III from experiment.

<table>
<thead>
<tr>
<th></th>
<th>Maxsorb III-R134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_0 ) [kg kg(^{-1})]</td>
<td>2.21</td>
</tr>
<tr>
<td>( E_a ) [kJ kg(^{-1})]</td>
<td>71.75</td>
</tr>
<tr>
<td>( n ) [-]</td>
<td>1.26</td>
</tr>
</tbody>
</table>

2.2 Adsorption kinetics

The linear driving force model (LDF), as shown in Eq. (3) is widely used to describe the adsorption of adsorbate onto adsorbent surface. It is a simplified expression of intra-pellet diffusion equation at which the uptake rate of adsorbate is linearly proportional to the difference between the equilibrium uptake, \( q^* \) and the instantaneous uptake, \( q(t) \). The equilibrium uptake can be obtained from the isotherm equation.

\[
\frac{dq}{dt} = k_a \alpha_s \left[ q^* - q(t) \right]
\]

where \( k_a \alpha_s \), the effective particle-phase transfer coefficient in s\(^{-1}\) is function of adsorbate concentration.

The effective mass transfer coefficient can be expressed as the function of the surface diffusion as given by Eqs. (4)~(6)

\[
k_a \alpha_s = \frac{F D_s}{R_p^2}
\]

(4)
where $F_0$ is a dimensionless constant, $D_s$ is the surface diffusion in m$^2$ s$^{-1}$, and $R_p$ is the particle radius, m. The relation between the surface diffusion and adsorption temperature can be given by the Arrhenius form as

$$D_s = D_{so} \exp\left(-\frac{E_a}{RT}\right)$$

(5)

where $E_a$ is the activation energy of the adsorbate derived from adsorption isotherm experiment. Similarly, the pre-exponential factor $D_{so}$ in m$^2$ s$^{-1}$ can be obtained from kinetics experiments. Substitute Eq. (5) into Eq. (4), the effective mass transfer coefficient become

$$k_{sa} = D_s' \exp\left(-\frac{E_a}{RT}\right)$$

(6)

where $D_s'$ equal to $F_0D_{so}/R_p^2$.

The LDF model can finally presented as

$$\frac{dq}{dT} = D_s' \exp\left(-\frac{E_a}{RT}\right)\left[q - q_v\right]$$

(7)

In current study, the $D_s'$ is assumed to be 0.152 s$^{-1}$.

### 2.3 Isosteric Heat of Adsorption

Isosteric heat of adsorption is conventionally expressed as a function of concentration as its dependence on temperature is relatively weak$^{11,12}$. Clausius-Clapeyron equation is commonly used to estimate heat of adsorption at constant concentration as

$$Q_s = -R\frac{\partial \ln P}{\partial (1/T)}$$

(8)

$Q_s$ denotes the isosteric heat of adsorption in J kg$^{-1}$, $R$ is the gas constant in J kg$^{-1}$ K$^{-1}$, $P$ is the equilibrium pressure in kPa and $T$ is the adsorbent temperature in K. Critoph$^{[13]}$ had proposed a relation to estimate the isosteric heat of adsorption for practical applications in solar adsorption cooling system by integrate from Eq. (8). However the relation only valid for shallow temperature ranges. There are researchers used average value of heat of adsorption within certain concentration range for system design and analysis$^{5,14-15}$.

In current study, heat of adsorption, $Q_s$ as a function of vapor uptake, is calculated from the measured isotherm using correlation proposed by Chakraborty et al.$^{16}$, as shown

$$Q_s = RT^2\left[\left(\frac{\partial \ln P}{\partial T}\right)_{n_v}\right] + T_v \frac{dP}{dT}(P,T)$$

(9)

The first term of the right hand side indicates the conventional form of the isosteric heat of adsorption derived from Clausius-Clapeyron equation and the second term defines the behavior of adsorbed mass with respect to both temperature and pressure change during adsorbate uptake, which occurs due to the non-ideality of the gaseous phase. Using the D-A equation, one can define $Q_s$ as follow,

$$Q_s = h_v + E_a \ln\left(\frac{q}{q_v}\right) + T_v \frac{dP}{dT}(P,T)$$

(10)

where $v_v$ is the specific volume (m$^3$ kg$^{-1}$) of the vapor phase, and $dP/dT$ represents the gradient of the pressure with the temperature of the adsorbate.
3. Mathematical Modeling of Adsorption Cooling Cycle

The waste-heat driven pressurized adsorption chiller consists mainly of an evaporator, condenser, and two reactor beds. Both the equilibrium and transient modeling are simulated to study the performance of the adsorption cycle. At the beginning of each cycle, the reactor beds are isolated from the evaporator and condenser, i.e., the isosteric phase. During the operation process, each of the reactor beds is interacted with either the evaporator or condenser, for the adsorption and desorption process respectively. Mass transfer occurred across the bed and condenser and evaporator. After the operation process, the reactor beds are again isolated during the switching process. The roles of reactor beds are inter-changed (adsorption bed converts into desorption mode and desorption bed changes into adsorption mode), no latent heat is transferred from the evaporator to the cold bed and from hot bed to the condenser. After sufficient time of pre-heating or pre-cooling for reactor beds, the beds are then ready for the next operation cycle. To simplify the mathematical modeling of the adsorption refrigeration system, the following assumptions are made: (i) the temperature is uniform in the adsorbent (Maxsorb III) layer, (ii) the adsorbate vapor is adsorbed uniformly in the reactor bed, and (iii) both the solid and vapor phases exist at thermodynamic equilibrium.

3.1 Equilibrium Modeling

Parametric analysis is carried out to study the performances of a single-stage idealized adsorption cooling system (Maxsorb III-R134a). The detailed modeling and analysis for the thermodynamic processes had discussed previously by Loh et al.\(^{17}\). The idealized cooling cycle, which is time independent, was simulated in accordance to ARI Standard 560 (at evaporator temperature, \(T_e\) equal to 6.7 °C and condenser temperature, \(T_c\) equal to 29.4 °C). The equilibrium model was adopted to evaluate the cycle performance in terms of specific cooling effect (SCE) and Coefficient of Performance (COP). This model is a thermodynamically equilibrium model. This means that all thermal contributions were calculated based on heat and mass balance provided by Dühring diagram\(^{17}\). Effect of operating temperatures such as regeneration and evaporator temperatures on the cycle performance are also introduced. In our analysis, the COP of the adsorption cooling cycle is defined as the ratio of the SCE and heat input to the system, \(Q_h\) as shown in Eq. (11)

\[
COP = \frac{SCE}{Q_h}
\]  

(11)

The heat added to the system Eq. (12), is simply the summation of both the heat added to the adsorptive, Eq. (13) and heat added to adsorbate or refrigerant, Eq. (14)

\[
Q_h = Q_{eab} + Q_{ref}
\]

(12)

\[
Q_{eab} = \int_{T_e}^{T_{eab}} c_{p,ab}dT
\]

(13)

\[
Q_{ref} = q_{max} \int_{T_e}^{T_{ref}} c_{p,ref}dT + \int_{T_e}^{T_{ref}} q_{c,ref}dT + \int_{q_{min}}^{q_{max}} Q_q dq
\]

(14)

\[
SCE = (q_{max} - q_{min}) \left[ h_f - \int_{T_e}^{T_{ref}} c_{p,ref}dT \right]
\]

(15)

The first term of Eq. (14) is the isosteric heating of the adsorbate, while the second and third terms represent the sensible heat added to the adsorbate and heat of adsorption, respectively. Heat of adsorption is deduced through experimental isotherm data for R134a,
on activated carbon powder (Maxsorb III) using Eq. (10). The specific cooling effect is defined as the difference between the evaporator load and heat dissipated to cool the adsorbate from condenser temperature to evaporator temperature, i.e. Eq. (15).

3.2 Transient Modeling

3.2.1 Operation Process

The energy and mass balance equations of the major components such as evaporator, condenser, and two adsorber/desorber beds are solved numerically. The computed values of the variable are updated. The calculation procedures commenced with the initialization of variables, the system geometries and the adsorption characteristics. It is emphasized that the coupled ordinary differential equations for energy and mass balance are solved by an iterative method, employing the fifth order Gear’s Differentiation Formulae (GDF) method found in the DIVPAG subroutine of the IMSL FORTRAN Developer Studio software.

The key parameters analyzed in the simulation are (a) the temperature profiles of the adsorber, desorber, condenser and evaporator, (b) the coefficient of performance and (c) the load surface temperature of the pressurized adsorption chiller for a fixed cooling capacity. The load temperature is estimated using the Rohsenow’s boiling correlation of refrigerant R134a\(^{(18)}\). The current simulations are based on per unit mass of the adsorbent. The values used in the present transient simulation are shown in Table 2.

| Table 2. Specification of component and material properties used in simulation code |
|----------------------------------|------------------|--------|--------------|------------------|
| Surface area, \( A \) [m^2] | Overall heat transfer coefficient, \( U \) [W m^{-2} K^{-1}] | Mass, \( m \) [kg] | Specific heat capacity, \( c_p \) [J kg^{-1} K^{-1}] |
| Condenser | 0.08 | 800 | 2.5 | 386.0 |
| Evaporator | 0.002581 | 1000 | 2 | 386.0 |
| Adsorber Bed | 0.0169 | 2400 | 3.7 | 386.0 |
| Desorber Bed | 0.0169 | 2400 | 3.7 | 386.0 |
| Adsorbent \( \text{(Maxsorb III)} \) | - | - | 1 | 930.0\(^{(19)}\) |

<table>
<thead>
<tr>
<th>Temperature, ( T ) [°C]</th>
<th>Flow rate, ( \dot{m} ) [kg s^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water inlet</td>
<td>85</td>
</tr>
<tr>
<td>Cold water inlet</td>
<td>30</td>
</tr>
</tbody>
</table>

3.2.1.1 Energy balance for adsorber bed

During the operation process, the adsorption bed interacts with the evaporator. The energy balance equation is written as follows

\[
\left( m_{c_p} \right)_{eff} + \left[ m_{c_p} \left( P, T_{wb} \right) \right]_{ads} \frac{dT_{ads}}{dt} = m_w \left( \frac{dq_{ads}}{dt} \right) + m_w c_p \left( T_{ads} - T_{cw} \right)
\]

(16)

The terms on left hand side represent the sensible heat required to cool the effective mass (copper finned-tube heat exchanger and activated carbon, Maxsorb III), and adsorbed phase refrigerant, respectively. The adsorbed mass is calculated as the mass of adsorbate under equilibrium condition at respective pressures and temperatures. Whereas the first term on the right hand side denotes the heat generation by adsorption and last term is the heat rejection from the adsorption bed by external cooling source. It is assume that no heat losses to the surrounding.
The outlet temperature of the cooling source is calculated by log mean temperature difference method (LMTD) and it is given by

\[ T_{o,ref} = T_{s,ref} + (T_{i,ref} - T_{s,ref}) \exp \left( \frac{U_{bed,ref} \Delta_{bed,ref}}{mc_p,T_{o,ref}} \right) \] (17)

3.2.1.2 Energy balance for desorber bed

For desorption process, the desorber bed is interacts with the condenser. The energy balance is as

\[ \left( mc_p \right)_d + \left( m_{ref,c,ref,c} \left( T_{i,c} \right) \right)_{des} \frac{dT_{des}}{dt} = m_{m,c} \left( \frac{dq_{des}}{dt} \right) - Q_m - \Delta_{p,c} \left( T_{i,des} - T_{o,des} \right) \] (18)

The left hand side terms are similar to the adsorption bed. Whereas the first term on the right hand side denotes the isosteric heat of desorption and last term is the heat added to the desorption bed by external heating source. Similarly, the hot water outlet temperature is calculated as

\[ T_{o,des} = T_{des} + (T_{i,des} - T_{des}) \exp \left( \frac{U_{bed,des} \Delta_{bed,des}}{mc_p,T_{o,des}} \right) \] (19)

3.2.1.3 Energy balance for condenser

The condenser is of air-cooled finned type. It liquefies the refrigerant from the desorption bed and delivers the condensate to the evaporator through a capillary. In current studies, the condenser and desorption bed are always maintained at the refrigerant saturated vapor pressure. The energy balance for the condenser is

\[ \left( mc_p \right)_{cd} + \left( m_{ref,c,ref,c} \left( T_{i,c} \right) \right)_{cd} \frac{dT_{cd}}{dt} = -U_{c} A_{c} \left( T_{s,cd} - T_{w,cd} \right) + \gamma h_{c} \left( T_{c} \right) m_{m,c} \left( \frac{dq_{des}}{dt} \right) - \left( \theta h_{c} \left( P_{cd,des} \right) + (1-\theta) h_{c} \left( T_{c} \right) - \theta(1-\gamma) h_{c} \left( T_{c} \right) \right) m_{m,c} \left( \frac{dq_{des}}{dt} \right) \] (20)

where \( \theta \) equals to 1 and 0 during desorption and adsorption processes, respectively. The left hand side term represents the sensible heat of the condenser material and the condensate left inside the condenser. While the three terms on the right hand side denote the heat removal to the surrounding air, heat generation by condensation, and the sensible heat of adsorbate desorbed during regeneration, respectively.

In current study, the condenser is designed to contain a certain maximum amount of condensate, \( m_{max,ref,c} \). The condensate will flow back through a capillary tube into the evaporator for any amount greater than this.

The following criteria identify the value of \( \gamma \) in En. (20),

\[ m_{ref,c,ref,c} < m_{max,ref,c} , \gamma = 1 \]

\[ m_{ref,c,ref,c} = m_{max,ref,c} \text{ and } \frac{dq_{des}}{dt} \leq 0 , \gamma = 0 \]

\[ m_{ref,c,ref,c} = m_{max,ref,c} \text{ and } \frac{dq_{des}}{dt} > 0 , \gamma = 1 \]
3.2.1.4 Energy balance for evaporator

The energy balance for evaporator is identical to that of the condenser as

\[
\frac{d(T_m - T_i)}{dt} + h_i(T_e) \frac{dm_{ref,e}}{dt} = q''(1-\gamma)h_i(T_e)m_w \left( \frac{dq_{sw}}{dt} \right) - \left[ \frac{(1-\delta)h_v(P_v,T_{sw}) + \delta h_i(T_e)}{m_w} \right] \frac{dq_{sw}}{dt}
\]

where \( q'' \) is the constant heat flux of the cooling components. The value \( \delta \) is the switching function which depends on the processes in the bed, i.e. 1 for adsorption and 0 for desorption processes. The first left hand side term represents the sensible heat of the evaporator material and the condensate. The second term shows the enthalpy of evaporated liquid during pool boiling. The first term on right hand side denotes the heat generated by the load, follows by the sensible heat of incoming condensate from condenser, and last term is the heat of evaporation.

The load surface temperature is estimated using the Rohsenow’s boiling correlation as,

\[
T_{load} = T_e + \left( \frac{C_p h_i P_{rf}^{1.7}}{e_{p,f}} \right) \left[ \frac{\sigma}{g(\rho_l - \rho_v)} \right]^{0.33}
\]

\( C_p \) is the liquid-surface combination coefficient, \( g \) is the gravitational acceleration, \( \sigma \) is the surface tension of the fluid, \( P_{rf} \) denotes the fluid phase Prandtl number, and \( \rho_l \) and \( \rho_v \) are the density of the liquid and vapor phase. The energy flows diagram for the operation process can be found in Figure 1.

3.2.1.5 Mass balance for adsorbate

The mass balance of adsorbate is expressed by neglecting the gas phase as,

\[
\frac{dm_{ref,e}}{dt} = m_w \left[ (1-\delta)(1-\gamma) \frac{dq_{sw}}{dt} - \frac{dq_{sw}}{dt} \right]
\]

where \( \delta \) and \( \gamma \) are the switching functions to designate the role of the desorber where the vapor are condensed at the condenser.

3.2.2 Switching Process

3.2.2.1 Energy balance for adsorber bed

During the switching process, the adsorption bed changes to desorption mode, vice versa. There is no interaction between reactor beds with evaporator and condenser. The governing energy balance equation for the bed switches from desorption to adsorption mode is

\[
\left\{ \left( m_c \right)_e \frac{dT_{ad}}{dt} + \left[ m_c e(P,T_{ad}) \right]_{ad} \right\} = m_w c_{p,w} (T_{ad} - T_{ad})
\]

3.2.2.2 Energy balance for desorber bed

Similarly, for bed switches from adsorption to desorption mode, the equation is

\[
\left\{ \left( m_c \right)_d + \left[ m_c d(P,T_{ad}) \right]_{ad} \right\} \frac{dT_{sw}}{dt} = m_w c_{p,w} (T_{ad} - T_{ad})
\]

3.2.2.3 Energy balance for condenser

The behavior of condenser is described by equation (26) below,
3.2.2.4 Energy balance for evaporator

The behavior of evaporator is as follows,

\[
\left( m_{p} \right) \left[ m_{\text{ref}, c_{p}, f} \left( T_{e} \right) \right] \frac{dT_{e}}{dt} = h_{i} \left( T_{e} \right) m_{w} \left( \frac{dq_{\text{ads}}}{dt} \right) - U_{e} A_{e} \left( T_{e} - T_{\text{evap}} \right)
\]  

(26)

These energy balance equations are based on the fact that pressure and temperature change in tandem, and \( t \) is defines as time.

The cycle-average coefficient of performance (COP) of the waste-heat driven adsorption cycle is calculated as the ratio of the cycle-average heat extraction at evaporator to cycle-average heat or power input.

\[
\text{COP} = \frac{Q_{e}}{Q_{c}} = \frac{m_{\text{ref}, c_{p}, e} \left( T_{\text{evap}} - T_{\text{ref}_{e}} \right)}{Q_{c}}
\]  

(28)

Figure 1. Block diagram to highlight the sensible (solid line arrows) and latent (dashed line arrows) heats flow of a waste heat driven pressurized adsorption of chiller.
4. Results and Discussion

Figure 2 represents the performance analysis of the equilibrium model in terms of coefficient of performance (COP) and specific cooling effect (SCE) with respect to regeneration temperature, \( T_{\text{regen}} \) for Maxsorb III-R134a working pair. From Fig. 2, it is clearly illustrated that the COP increases sharply at relatively low regeneration temperature but exhibits asymptotic behavior at higher regeneration temperature. This happens due to the fact that the requirement of heat input is significantly higher when temperature difference between heat source and heat sink becomes greater. The COP for Maxsorb III/R134a at 70 °C regeneration temperature is about 0.24, however, the COP approaching 0.28 when the regeneration temperature increases to 80 °C. Contrary to COP, SCE increases linearly with the regeneration temperature. The simulated value for SCE at 80 °C regeneration temperature is 78 kJ kg\(^{-1}\).

Similarly from Fig. 2, the SCE approaching zero when the regeneration temperature reached to 55 °C, meaning no cooling effects for regeneration temperature below 55 °C. Hence one can deduce that the lowest regeneration temperature for the present single-stage adsorption chiller is at 55 °C. However, the regeneration temperature can be further lower by two-stage or multi-stage refrigeration systems\(^{15}\).

![Figure 2](image)

Figure 2. Effects of regeneration temperature on equilibrium cooling cycles SCE and COP simulated in accordance to ARI Standard 560, i.e. evaporator and condenser temperatures at 6.7 and 29.4 °C, respectively.

Figure 3 shows the prediction of the temporal histories for the reactors (adsorption and desorption beds), the condenser, the load surface and the evaporator by using the transient mathematical model. At the very short cycle times, say a few tens of seconds, the COP is expected to be low due to incomplete vapor uptake onto the Maxsorb III and the large amount of sensible heat of the heat exchanger modules as compared to latent heat transfer. In contrast, a very large cycle time (a few hours) for the cycle would saturate the adsorbed vapor onto the Maxsorb III and cooling rate would decrease. Thus, there exist in between these extreme cycle intervals that an optimal COP would be located for the pressurized adsorption chillers.

The temperature profiles depicted in Fig. 3 is simulated at 2.75 W cm\(^{-2}\) heat inputs, with operation and switching time of 500 and 80 sec, respectively. From Fig. 3, the evaporator reached to the minimum temperature around 10 °C. The cyclic average energy and mass balances for the simulation are found to be around 3% and 0.005% respectively.
Figure 3. Temperature profiles of major components of the waste-heat driven pressurized adsorption chiller with input heat flux of 2.75 W cm$^{-2}$.

Figure 4 represents a narrow region of the waste-heat driven adsorption chillers operation (cycle time intervals) where the COP shows a monotonic increasing before the optima is reached. On the other hand, the load and evaporator temperatures have demonstrated their minima. These simulations have a fixed input heat flux, 2.75 W cm$^{-2}$ supplied by the heater embedded inside the evaporator. From the results, the lowest load surface temperature is found to be 14 °C and the cycle time is at 600 sec, whilst the COP is computed to be about 0.24.

Figure 4. Effects of operation time on chiller average cooling load temperature, evaporator temperature and COP. The dotted line shows the minimum cooling load temperature at 600 sec cycle time with input heat flux of 2.75 W cm$^{-2}$.

Figure 5 presents the chillers operation (cycle time intervals) with the evaporator temperatures for Maxsorb III/R134a at different fixed input heat flux, i.e. 2.75, 1.75 and 1.075 W cm$^{-2}$. The evaporator experienced higher temperature with higher heat flux input. One can see that the evaporator temperatures demonstrated their minima at respective heat flux input. The minimum evaporator temperature shifted towards longer operation time as the cooling load decreases (shown in dotted line). The minimum evaporator temperature
occurred in between 500 to 800 sec operation cycle time, for respective cooling load. Similarly, the Maxsorb III/R134a working pair demonstrated the sub-zero cooling effects (-2 °C) with the heat flux input at 1.075 W cm⁻². The evaporator temperatures are ranging from -2 to 12 °C.

![Figure 5](image)

**Figure 5.** Effects of operation time on chiller average evaporator temperature at respective heat input.

![Figure 6](image)

**Figure 6.** Comparisons between coefficients of performance (COP) for equilibrium and transient modeling.

Figure 6 shows that the COP of the equilibrium model and transient modeling (for operation time from 700 sec to 1000 sec) at 85 °C. The transient modeling COP approaching the equilibrium model for operation time of 1000 sec, i.e. equal to 0.304 and 0.31, respectively. This signifies that the COP of the transient modeling will approach the equilibrium model when the operation cycle time increases. In other words, the idealized equilibrium model is as good as to predict the optimum COP of the adsorption cooling cycle at respective operating temperatures without going through the tedious transient modeling of the chiller equations. However, in order to understand the actual performance for the adsorption system, the transient modeling is preferable.
5. Conclusions

From adsorption isotherm data, quantitative analysis on the COP and cooling effects of Maxsorb III/R134a pairs were evaluated. It can be seen that the evaporator temperature exhibits a minima at different cycle time and cooling capacity; with decreasing cooling capacity, the minima needed longer operating cycle interval time. The idealized equilibrium model is found to be suitable for predicting the maximum COP of chillers at assorted operating conditions. For estimating the minimum surface temperatures, the transient modeling is required since these minima may not occur at optima COP. The simulation shows that the low sub-zero temperature designs may require an increase in the amount of adsorbent. This study has provided the authors a greater confidence in design such heat-activated adsorption cycles at both steady state and transient operations.

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Nomenclature

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<th>symbol</th>
<th>description</th>
<th>unit</th>
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<tr>
<td>$A$</td>
<td>adsorption potential or surface area</td>
<td>J kg$^{-1}$, m$^2$</td>
</tr>
<tr>
<td>$COP$</td>
<td>coefficient of performance</td>
<td>-</td>
</tr>
<tr>
<td>$C_{sf}$</td>
<td>liquid-surface combination coefficient</td>
<td>-</td>
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<td>$c_p$</td>
<td>specific heat capacity at constant pressure</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
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<td>$D_s$</td>
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<td>$E_a$</td>
<td>characteristic or activation energy of adsorption system</td>
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<td>$g$</td>
<td>gravitational acceleration</td>
<td>m s$^{-2}$</td>
</tr>
<tr>
<td>$h$</td>
<td>specific enthalpy</td>
<td>J kg$^{-1}$</td>
</tr>
<tr>
<td>$k_oa_{ev}$</td>
<td>effective mass transfer coefficient</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$m$</td>
<td>mass</td>
<td>kg</td>
</tr>
<tr>
<td>$m$</td>
<td>mass flow rate</td>
<td>kg s$^{-1}$</td>
</tr>
<tr>
<td>$n$</td>
<td>structural heterogeneity parameter</td>
<td>-</td>
</tr>
<tr>
<td>$P$</td>
<td>pressure</td>
<td>kPa</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
<td>-</td>
</tr>
<tr>
<td>$q$, $q^*$</td>
<td>equilibrium adsorption capacity per unit mass of adsorbent at respective pressure and temperature</td>
<td>kg kg$^{-1}$</td>
</tr>
<tr>
<td>$q_o$</td>
<td>limiting uptake of adsorption space</td>
<td>kg kg$^{-1}$</td>
</tr>
<tr>
<td>$q(t)$</td>
<td>instantaneous uptake capacity</td>
<td>kg kg$^{-1}$</td>
</tr>
<tr>
<td>$q^<em>$$^</em>$</td>
<td>heat flux input to evaporator</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$Q$</td>
<td>sensible heat</td>
<td>J kg$^{-1}$</td>
</tr>
<tr>
<td>$Q_{is}$</td>
<td>isosteric heat of adsorption</td>
<td>J kg$^{-1}$</td>
</tr>
<tr>
<td>$R$</td>
<td>universal gas constant</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$R_p$</td>
<td>adsorbent particle radius</td>
<td>m</td>
</tr>
<tr>
<td>$SCE$</td>
<td>specific cooling effect</td>
<td>J kg$^{-1}$</td>
</tr>
</tbody>
</table>
Greek symbols | description | unit
---|---|---
\(\theta\) | switching function designating the role of reactor | -
\(\delta\) | switching function designating the role of reactor | -
\(\gamma\) | selection function for return condensate | -
\(\sigma\) | surface tension of the fluid | kg s\(^{-2}\)
\(\rho_f\) | density of the liquid phase | kg m\(^{-3}\)
\(\rho_g\) | density of the vapor phase | kg m\(^{-3}\)

Subscripts | Description
---|---
abe | adsorbed phase
ac | activate carbon
adb | adsorbent
ads | adsorption
air | ambient air
bed | reactor or bed
c | condenser
cw | cold water
des | desorption
e | evaporator
eff | effective, combination of copper finned-tube heat exchanger and activated carbon, Maxsorb III
e,a | end of adsorption process
e,d | end of desorption process
f | liquid
fg | difference between saturated vapor and saturated liquid
g | vapor
h | adsorption system
hw | hot water
i | inlet
max | maximum
min | minimum
o | outlet
p | adsorbent particle
ref | refrigerant or adsorbate
regen | regeneration or desorption
s | surface or saturated
st | isosteric
s,d | start of desorption process

References


(3) Ng, K. C., Thermodynamic Tools for Chiller Diagnostics and Optimization, *Heat*


