PHYSICAL AND OPERATING CONDITIONS EFFECTS ON SILICA GEL/WATER ADSORPTION CHILLER PERFORMANCE

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Presentation outline

• **Background**
• **Chiller modeling**
  – Simulated chiller
  – Modeling technique
  – Governing equations
  – Performance indicators
  – Validation study
• **Fin spacing**
  – Bed physical performance
  – Bed thermal performance
  – Chiller performance
• **Operation temperature**
  – Cooling capacity and GT lift
  – Efficiency and GT lift
  – COP and GT lift
• **Cycle time**
  – Operation modes
  – Cooling capacity
  – Optimum timing combination
• **Conclusion**
Background

• **Advantages of adsorption refrigeration systems**
  - Environmentally friendly system.
  - Large energy saving potential when it is applied in:
    • Combined Cooling, Heating and Power (CCHP) system
    • Sustainable Building Climatisation (SBC) using solar energy as heat source.
  - Durability, long life time and low maintenance cost.

• **Advantages of silica gel/water adsorption system**
  - Silica gel/water adsorption cycle can be powered using low grade heat sources (55-100°C).
  - Silica gel/water pair has relatively high equilibrium Ads/Des rate.
  - Water has high latent heat of evaporation.
  - Water is thermally stable within wide range of operating temperatures.
  - Water is compatible with wide range of materials
TWO-BED SILICA GEL/WATER ADSORPTION CHILLER SIMULATION MODEL
Chiller modeling: Simulated chiller

The simulated two-bed silica gel/water adsorption chiller is produced by Weatherite Holding Ltd, UK.

Schematic diagram for the adsorption chiller produced by Weatherite

One module construction

One module covered by fine mesh

Bed design of the adsorption chiller
• Adsorption refrigeration system modeling is a primary tool for design and optimisation purposes.

• **The published simulation techniques so far are:**
  – Lumped-parameter simulation technique.
  – Lumped analytical simulation techniques.
  – Dynamic simulation technique.
  – Distributed parameter simulation technique.
  – Simulation using object oriented simulation tool ‘MODELICA’.

• All these simulation techniques present the overall heat transfer coefficient for all heat exchangers and adsorbent bed as a constant value.

• That limits the prediction capability of any physical change effect on the adsorption chiller performance, especially the adsorbent bed.
Chiller modeling: Modeling technique (2)

- This paper presents a new adsorption chiller simulation technique ‘Empirical lumped analytical simulation model’.
- Empirical lumped analytical sub-models were constructed for evaporator, condenser, adsorber and desorber based on their physical characteristics. They were integrated to form the chiller simulation model.

The governing equations were solved by MATLAB platform and materials thermophysical properties are calculated using REFPROP
Chiller modeling: Modeling governing equations

- **Energy balance**
  - **Adsorbent bed**
    \[
    \left( \left( \sum_{n=1}^{N_{\text{bed}}} dU_{n}A_{\text{bed}} - n \times \text{LMTD}_{\text{bed}} \right) + \left( \phi \cdot \delta \right) \gamma \left( h_{g} (T_{\text{Hex}}) - h_{g} (P_{\text{Hex}}, T_{\text{bed}}) \right) \right) dT_{\text{bed}} / dt = \left( 1 - \zeta \right) \left( N_{\text{bed}} \right) \sum_{n=1}^{n=N_{\text{bed}}} dU_{\text{bed} - n} \times \text{LMTD}_{\text{bed}} + \phi M_{\text{sg}} \Delta H_{\text{sg}} / dt \]
  - **Evaporator**
    \[
    \left[ C_{P_{\text{ref}}, f} (T_{\text{evap}}) M_{\text{ref},\text{evap}} + C_{\text{evap}-\text{met}} M_{\text{evap}-\text{met}} \right] dT_{\text{evap}} / dt = U_{\text{evap}} \times \text{LMTD}_{\text{evap}} + \phi \left[ h_{\text{ref, evap, in}} - h_{\text{ref, evap, out}} \right] M_{\text{sg}} dw_{\text{sg}} / dt + dE_{\text{pump}} / dt \]
  - **Condenser**
    \[
    \left[ C_{P_{\text{ref}}, l} (T_{\text{cond}}) M_{\text{ref},\text{cond}} + C_{\text{cond}-\text{met}} M_{\text{cond}-\text{met}} \right] dT_{\text{cond}} / dt = U_{\text{cond}} \times \text{LMTD}_{\text{cond}} + \phi \left[ h_{\text{ref, cond, l}} - h_{\text{ref, cond, g}} \right] M_{\text{sg}} dw_{\text{sg}} / dt \]

- **Refrigerant mass balance**
  \[
  dM_{\text{ref, f, evap}} / dt = -\phi \cdot M_{\text{sg}} \left( dw_{\text{des}} / dt + dw_{\text{ads}} / dt \right) \]

- **Water vapor adsorption rate**
  \[
  \frac{dw}{dt} = \left( 15 D_{s} / R_{p}^{2} \right) \exp \left( - \frac{E_{a}}{RT} \right) \left( w^{*} - w \right) \]
Chiller modeling: Performance indicators

- **Adsorbent bed**
  - Heat capacity ratio
    \[
    HCR = \frac{M_{sg} C_{sg}}{M_{met} C_{met}}
    \]
  - Number of transfer unit
    \[
    NTU = \frac{U A_{bed}}{\dot{m}_w C_w}
    \]

- **Chiller cooling capacity**
  \[
  Q_{evap} = \frac{\int_{0}^{t_{cycle}} \dot{m}_{chw} C_w (T_{chw,in} - T_{chw,out}) dt}{t_{cycle}}
  \]

- **Chiller heating capacity**
  \[
  Q_{heat} = \frac{\int_{0}^{t_{cycle}} \dot{m}_{hw} C_w (T_{hw,in} - T_{hw,out}) dt}{t_{cycle}}
  \]

- **Chiller COP**
  \[
  COP = \frac{Q_{evap}}{Q_{heat}}
  \]

- **Chiller efficiency**
  \[
  \eta_{chiller} = \frac{COP}{COP_{Carnot}}
  \]
Based on the Comparison between predicted and actual heating, cooling and chilled water outlet temperature, there are a good agreement.
Chiller modeling: validation study (2)

Using 372 data points, deviation analysis has been achieved. The equation for average percent deviation (A-PD) and absolute percent deviation (ABS-PD) are given by:

\[ A - PD = \frac{\sum (\%\, Deviation)}{N_{\text{data point}}} \]
\[ ABS - PD = \frac{\sum abs(\%\, Deviation)}{N_{\text{data point}}} \]

<table>
<thead>
<tr>
<th>Term</th>
<th>A-PD</th>
<th>ABS-PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water outlet temperature</td>
<td>-1.6%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Cooling water outlet temperature</td>
<td>-1.1%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Chilled water outlet temperature</td>
<td>-16.5%</td>
<td>16.5%</td>
</tr>
<tr>
<td>Cooling capacity</td>
<td>12.9%</td>
<td>12.9%</td>
</tr>
<tr>
<td>Heating capacity</td>
<td>10.9%</td>
<td>10.9%</td>
</tr>
<tr>
<td>Chiller COP</td>
<td>2.8%</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

Based on average inlet and predicted data of one steady cycle using 4 different runs, ABS-PD have been analysed as:

<table>
<thead>
<tr>
<th>Term</th>
<th>RUN-1</th>
<th>RUN-2</th>
<th>RUN-3</th>
<th>RUN-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{hw,o}} )</td>
<td>1.6</td>
<td>1.5</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td>( T_{\text{cw,o}} )</td>
<td>0.9</td>
<td>0.8</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>( T_{\text{chw,o}} )</td>
<td>12.3</td>
<td>13.1</td>
<td>13.3</td>
<td>15.7</td>
</tr>
<tr>
<td>( Q_{\text{heat}} )</td>
<td>10.3</td>
<td>9.9</td>
<td>9.9</td>
<td>10.6</td>
</tr>
<tr>
<td>( Q_{\text{cool}} )</td>
<td>13.1</td>
<td>13.6</td>
<td>13.5</td>
<td>17.8</td>
</tr>
<tr>
<td>COP</td>
<td>3.7</td>
<td>3.9</td>
<td>3.8</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Model absolute average percent deviation should be below 30% to be acceptable.
FIN SPACING AND CHILLER PERFORMANCE
**Fin spacing: Bed physical performance**

- HCR is the ratio between heat capacity of silica gel and adsorbent bed heat exchanger metal.
- Higher HCR means higher heat absorbed by silica gel relative to metal which is necessary to improve adsorption chiller heat transfer performance.
• NTU is a dimensionless parameter whose magnitude influences heat exchanger thermal performance.

• As fin width does not affect the adsorbent bed thermal performance the effect of fin spacing only on chiller performance have been achieved.
In normal bed design as fin spacing reduces from max to min ratio:

- Chiller cooling capacity increased by 27.7%.
- Heating capacity increased by 32.4% to heat up the excess amount of metal.
- Chiller COP slightly reduces by 3.7% because of the rate of heating capacity increase higher than the rate of cooling capacity increase.
OPERATING TEMPERATURES AND CHILLER PERFORMANCE
Operation temperature: Cooling capacity and GT lift

- To evaluate the influence of operating temperatures on chiller performance a term named Generation Temperature Lift (GTL) is used which is the difference between heating and cooling water inlet temperatures.
- Chilled water inlet temperature is mainly based on zone load, where it is kept constant.

- As generation temperature lift increases chiller cooling capacity increases gradually for all cooling water inlet temperature.
- At fixed generation temperature, as cooling water inlet temperature reduces chiller cooling capacity increases.
Operation temperature: Efficiency and GT lift

- At low cooling water inlet temperature, the chiller efficiency decreases with increasing the generation temperature lift over the tested range.
- At higher cooling water temperature ($T_{cw}>30^\circ C$), the chiller COP initially increases to a certain point and then reduces with increasing the generation temperature lift.

Dropping chiller efficiency

- The first reason of dropping chiller efficiency is the insufficient refrigerant circulation to generate cooling power. That can be recognised while chiller operates under low generation temperature lift accompanied with high cooling water temperature.
- The second one is the significant heat losses in case of high generation temperature lift.
Operation temperature: COP and GT lift

- At low cooling water temperature, the chiller COP decreases with increasing the generation temperature lift over the tested range.
- At higher cooling water temperature ($T_{cw}>30^\circ C$), the chiller COP initially increases to a certain point and then remains relatively constant with increasing the generation temperature lift.

Load control strategy ($T_{cw}>30^\circ C$):
- **Example**, at cooling water temperature of 35°C, the chiller cooling capacity increased almost linearly (from 180 to 342kW) with increasing the generation temperature lift (from 40 to 65K). That reduces chiller COP by extremely tiny value (from 0.63 to 0.60) and its efficiency as well (from 0.68 to 0.52).
CYCLE TIME AND CHILLER PERFORMANCE
Cycle time: Operation modes (1)

Mode [ A ] – Ads/Des
- Ads/Des Mode
- 425 second

Mode [ B ] - Mass recovery
- Mass Rec Mode
- 35 second

Mode [ C ] - heat recovery
- Heat Rec Mode
- 20 second

Total cycle time 480 second
Cycle time: Operation modes (2)

Mode [D] – Ads/Des

Mode [E] - Mass recovery

Mode [F] - Heat recovery

- Ads/Des Mode 425 second
- Mass Rec Mode 35 second
- Heat Rec Mode 20 second
- Total cycle time 480 second
While investigating the influence of cycle time on chiller performance the adsorbent bed fin configuration and operating temperatures are kept at its design values.

Zone of maximum cooling capacity
6.1% Increase in cooling capacity compared by design conditions

Chiller cooling capacity versus Ads/Des time and mass recovery time and at recovery time of 20 seconds

Chiller cooling capacity versus Ads/Des time and mass recovery time and at recovery time of 60 seconds

Chiller cooling capacity versus Ads/Des time and mass recovery time and at recovery time of 100 seconds
A global optimisation technique is required, where most of the currently published work on the effect of operation conditions are based on parametric runs of chosen optimum parameters.

**Genetic algorithm technique is used where:**
- One of the robust population based global optimisation techniques
- GA has the advantage over standard optimisation algorithms of solving problems of discontinuous, non differentiable, stochastic and/or highly nonlinear objective function

**Optimisation parameters:**
- The cooling capacity is the objective function.
- Number of population for each individual per generation = 20
- Number of elite individuals = 2
- Crossover fraction = 0.8
- The rest of individuals were managed by means of mutation.

**The global optimum time periods obtained are ‘off design values’:**
- 345 seconds for Ads/Des time-------- (425s).
- 12 seconds for mass recovery time---- (35s).
- 14 seconds heat recovery time--------- (20s).

**Chiller performance changed compared by design cycle timing where:**
- Chiller cooling capacity increased by 8.27%.
- Chiller COP reduced from 0.66 to 0.60.
The following points can be concluded:

• The presented simulation model predicted the performance of actual 450kW adsorption water chiller with good accuracy.

• The model is a global model that has the ability to investigate the effect of various physical and operation parameters on the performance of the adsorption chiller.

• Reducing fin spacing can increase the cooling capacity but can reduce the chiller COP due to increasing the metal content of the chiller.

• Using cooling water inlet temperature over 30, generation temperature lift can be used as a load control tool.

• Using optimal cycle time, chiller cooling capacity can be increased by 8% and the COP reduces from 0.66 to 0.6.