Solar driven Air Conditioning & Refrigeration Systems corresponding to various heating source temperatures

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Solar thermal application in buildings

Solar thermal utilization in buildings

- Hot water
- Heating
- Cooling
- Hybrid system

Technologies in use

Demonstration and close to large scale application

The target technology
Major technologies in SJTU

- Adsorption ice maker (2008)
- Single effect LiBr-water absorption (2009)
- Rotary desiccant cooling (2007)
- Two stage desiccant cooling (2009)
- Single/Double effect LiBr-water (2012)
New R&D Progresses in 2013-2014

1. Modular silica gel-water adsorption chiller (55°C - 90°C)
2. Single / double effect LiBr-water absorption chiller (80°C - 95°C for solar cooling with fossil fuel as backup)
3. The 1.n effect LiBr-water absorption chiller (90°C - 135°C)
4. CaCl₂/AC-ammonia adsorption refrigerator (100°C - 140°C)
5. Ammonia water absorption ice maker with perfect internal heat recovery (140°C - 170°C)
1. Modular silica gel-water adsorption chiller

1. Modular silica gel-water adsorption chiller (55° C - 90° C)
1.1. Appearance

Cooling power: 50kW
Size: 2.7m × 2.1m × 2m
Design COP: 0.4~0.6

Designed by

Manufactured by

No.1

No.2
1.2. System Schematic

Flow Chart of Adsorption Chiller Structure

- 2 adsorbers
- 2 condensers
- 2 evaporators
- 8 valves
- 1 chiller water pump
- 1 chiller water tank
1.3. Modular design of adsorber

Fin-tube type
19 independent sub adsorbers
Adsorbent: 342kg
Heat transfer area: 22 m²
1.4. Condenser & Evaporator

- **Condenser**
  - Shell-tube type

- **Evaporator**
  - Shell-tube type
  - Capillary-assisted evaporation

Capillary-assisted evaporation
System performances Tests

<table>
<thead>
<tr>
<th>No.</th>
<th>$T_{g,I}$ (°C)</th>
<th>$T_{l,I}$ (°C)</th>
<th>$T_{e,o}$ (°C)</th>
<th>$Q_e$, kW</th>
<th>COP</th>
<th>SCP (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85.87</td>
<td>29.84</td>
<td>11.19</td>
<td>41.1</td>
<td>0.515</td>
<td>120</td>
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<tr>
<td>2</td>
<td>85.41</td>
<td>30.28</td>
<td>9.13</td>
<td>29.6</td>
<td>0.344</td>
<td>86</td>
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<tr>
<td>3</td>
<td>82.17</td>
<td>32.14</td>
<td>14.74</td>
<td>50.1</td>
<td>0.627</td>
<td>140</td>
</tr>
<tr>
<td>4</td>
<td>61.82</td>
<td>29.42</td>
<td>13.16</td>
<td>17.1</td>
<td>0.358</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>85.77</td>
<td>29.97</td>
<td>11.50</td>
<td>40.9</td>
<td>0.431</td>
<td>120</td>
</tr>
</tbody>
</table>
1.5. Application

- Solar heating and cooling system in Shandong Auhua New Energy Co., Ltd.
System design (Sino – Denmark joint Project)
Systems involved

- Solar heating and cooling system in Shandong Auhua New Energy Co., Ltd.

- Solar heating system
  - 1300 m²

- Ground source system

- Adsorption chiller

- Office
  - 3000 m²
2. Single /double effect
LiBr-water absorption chiller

2. Single /double effect LiBr-water absorption chiller (80°C-95°C for solar cooling with fossil fuel as backup)
2.1. System schematic

(1) High pressure generator

(2) Low pressure generators (falling film-single effect pool boiling-double effect)

(3) Condenser

(4) Absorber

(5) Evaporator
热水/直燃单双效吸收式冷热水机组

热水 hot water
加热热水 heated water
冷凝器 condenser
蒸发器 evaporator
吸收器 absorber
冷却水 cooling water
高发 high temp. generator
低温热交换器 low temp. exchanger
高温热交换器 high temp. exchanger
仅适用燃料 only suitable the fuel
Example 1: Solar driven single/double effect absorption cooling system with Fresnel collector
Fresnel solar collector
Solar cooling in Shanghai Electric Co.

◆ 550 m² Fresnel solar collector; (150 ~ 200°C)
◆ Salt thermal energy storage (PCM, 146°C)
◆ Double/Single effect absorption chiller (100kW)
**Single/double LiBr-water chiller**

<table>
<thead>
<tr>
<th></th>
<th>double effect</th>
<th>Single effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling capacity</strong></td>
<td>134 kW</td>
<td>91 kW</td>
</tr>
<tr>
<td><strong>Hot water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>11.0 m³/h</td>
<td></td>
</tr>
<tr>
<td>Inlet/Outlet Temp.</td>
<td>150 /140 °C</td>
<td>105/95 °C</td>
</tr>
<tr>
<td><strong>Cold water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>23.0 m³/h</td>
<td></td>
</tr>
<tr>
<td>Inlet/Outlet Temp.</td>
<td>12/7 °C</td>
<td>12/8.4 °C</td>
</tr>
<tr>
<td><strong>Cooling water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>44 m³/h</td>
<td></td>
</tr>
<tr>
<td>Inlet/Outlet Temp.</td>
<td>31/36 °C</td>
<td>31/35.3 °C</td>
</tr>
</tbody>
</table>
Performance analysis

- Under sunny days, double effect mode from 10am - 14 pm
- Single effect mode for the other time.
- Daily average COP is about 0.8
- Cooling production for 6-8 hours
Example 2: Single/double effect LiBr-water Chiller (Changle hotel, Shandong)
## Chiller Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas firing driven cooling power</td>
<td>1280 kW</td>
<td>Solar driven cooling power</td>
<td>320 kW</td>
</tr>
<tr>
<td>Gas firing driven heating capacity</td>
<td>1066 kW</td>
<td>Temperature for heating output</td>
<td>55-60°C</td>
</tr>
<tr>
<td>Chilled water temperature (in-out)</td>
<td>12-7°C</td>
<td>Chilled water flow rate (in-out)</td>
<td>220 t/h</td>
</tr>
<tr>
<td>Chilled water pressure drop</td>
<td>90 Pa</td>
<td>Cooling water temperature</td>
<td>32-37°C</td>
</tr>
<tr>
<td>Cooling water flow rate</td>
<td>343 t/h</td>
<td>Cooling water pressure drop</td>
<td>69 Pa</td>
</tr>
<tr>
<td>Hot water temperature (in-out)</td>
<td>90-84°C</td>
<td>Hot water flow rate</td>
<td>61 t/h</td>
</tr>
<tr>
<td>Hot water pressure drop</td>
<td>70 Pa</td>
<td>Power of refrigerant pump</td>
<td>0.75kW</td>
</tr>
<tr>
<td>Low pressure generating pump power</td>
<td>0.75 kW</td>
<td>High pressure generating pump power</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>Low pressure generating pump power</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Operation of the system

Location:
Changle, Shandong 36.69°N, 118.83°E

Application:
Heating, cooling and hot water supply for a 5 star hotel
Operating data of the system

Energy saving:
The hybrid energy system saved 50.3% of the gas consumption for the whole year operation (2012.10 ~2013.9).
Daily performance taken recently

COP for solar cooling range from 0.5 to 0.6
3. The 1.n effect LiBr-water absorption chiller

3. The 1.n effect LiBr-water absorption chiller (90°C-135°C)
3.1. The 1.n effect absorption cycle

(i) Single effect

(ii) 1.n effect

(iii) Double effect
3.2. Schematic of 1.n effect cycle

(i) Schematic of the cycle
(ii) thermodynamic calculation
3.3. Schematic of chiller

Rated condition for design:

\[ T_{\text{gen}} = 125^\circ \text{C} \]
\[ T_{\text{con}} = 40^\circ \text{C} \]
\[ T_{\text{abs}} = 35^\circ \text{C} \]
\[ T_{\text{eva}} = 5^\circ \text{C} \]

Concentration distribution:

\[ X_{\text{HA}} = 45.73\% \]
\[ X_{\text{ABS}} = 55.28\% \]
\[ X_{\text{HG}} = 60.10\% \]
### 3.4. Design of the chiller

<table>
<thead>
<tr>
<th>Heat exchanger form</th>
<th>Calculated power (kW)</th>
<th>Heat transfer area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG</td>
<td>50.8</td>
<td>7.84</td>
</tr>
<tr>
<td>HA</td>
<td>22.7</td>
<td>5.52</td>
</tr>
<tr>
<td>LG2</td>
<td>22.7</td>
<td>6.68</td>
</tr>
<tr>
<td>LG1</td>
<td>15.1</td>
<td>4.65</td>
</tr>
<tr>
<td>CON</td>
<td>38.2</td>
<td>4.61</td>
</tr>
<tr>
<td>ABS</td>
<td>62.9</td>
<td>14.24</td>
</tr>
<tr>
<td>EVA</td>
<td>50.0</td>
<td>9.59</td>
</tr>
<tr>
<td>SHX</td>
<td>29.6</td>
<td>4.25</td>
</tr>
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</table>

**Cooling power: 50 kW**
## 3.5. Performance testing

![Diagram of the system with temperature and cooling power data](image)

<table>
<thead>
<tr>
<th>$T_{\text{gen}}$</th>
<th>$T_{\text{ch1}}$ (°C)</th>
<th>$T_{\text{ch2}}$ (°C)</th>
<th>$T_{\text{c1}}$ (°C)</th>
<th>$T_{\text{c2}}$ (°C)</th>
<th>Cooling power (kW)</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.01</td>
<td>12.46</td>
<td>9.38</td>
<td>31.17</td>
<td>34.94</td>
<td>35.90</td>
<td>0.69</td>
</tr>
<tr>
<td>100.17</td>
<td>10.19</td>
<td>7.45</td>
<td>32.53</td>
<td>35.85</td>
<td>31.97</td>
<td>0.71</td>
</tr>
<tr>
<td>102.71</td>
<td>12.71</td>
<td>9.85</td>
<td>28.13</td>
<td>32.10</td>
<td>39.12</td>
<td>0.73</td>
</tr>
<tr>
<td>104.45</td>
<td>16.35</td>
<td>13.23</td>
<td>29.78</td>
<td>34.22</td>
<td>45.53</td>
<td>0.78</td>
</tr>
<tr>
<td>110.89</td>
<td>15.04</td>
<td>10.69</td>
<td>32.45</td>
<td>37.19</td>
<td>43.53</td>
<td>0.85</td>
</tr>
<tr>
<td>115.77</td>
<td>14.65</td>
<td>10.45</td>
<td>30.88</td>
<td>35.08</td>
<td>49.03</td>
<td>1.01</td>
</tr>
<tr>
<td>119.88</td>
<td>13.46</td>
<td>9.00</td>
<td>27.55</td>
<td>31.85</td>
<td>52.06</td>
<td>1.08</td>
</tr>
</tbody>
</table>
4. CaCl$_2$/AC-ammonia adsorption refrigerator

4. CaCl$_2$/AC-ammonia adsorption refrigerator
(100$^\circ$C - 140$^\circ$C)
4.1. System schematic

CaCl₂/AC-ammonia

2 adsorbers
2 condensers
2 evaporators
4 valves

A: Adsorber
C: Condenser
E: Evaporator
V: Valve
Heat pipe heating is used
4.2. Prototype

10.6 kg composite adsorbent (CaCl$_2$ 8.5kg)

140 °C heat source,  
28 °C cooling source,  
-12.5 °C evaporating temperature

$Q_e$=3.74 kW  
COP=0.26  
SCP=440.0 W kg$^{-1}$

Size: 1.85 ×0.85 ×1.05
4.3. Performance test

28 °C cooling source and -12.5 °C refrigeration temperature
5. Ammonia water absorption ice maker with perfect internal heat recovery

5. Ammonia water absorption ice maker with perfect internal heat recovery (140°C - 170°C)
5.1. Problems and solutions

Ammonia water absorption ice-making system on fishing ship

**Drawbacks:**
- Low COP (construction defect)
- Large bulk (large distillation column and heat exchangers)
- Requirement of anti-swaying (ship swaying leads to deterioration of absorption and purification processes)

**Solutions:**
- Improve internal heat recovery (pinch analysis)
- Compact heat exchangers (small scale heat and mass transfer)
- Heat and mass exchangers design without free liquid surface
5.2. Ice maker construction

1. Normal operating without effect of ship swaying
2. Compact and miniaturization
3. Better heat and mass recovery
4. Condensation and absorption cooling completed with the strong solution
5. Heat released in one plate heat exchanger

Design conditions:
T_g: 160 °C
T_a: 34 °C
T_c: 34 °C
T_e: -30 °C
Cooling capacity: 40kW
5.3. Small scale heat exchanger

Outside Diameter: 2.5 mm
Inside Diameter: 1.7mm

User side size: 1.7m*1.1m*0.85m
Desorption side size: 1.6m*0.64m*0.56m
5.4. Photos and stable operation

User side

Desorption side

1. Stable operation for a long time
2. Flue gas temperature variation just has a little effect on generation
Table 5. The results of different operating conditions.

### 5.5. Results of different conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>Flue gas inlet (°C)</td>
<td>542</td>
<td>480</td>
<td>497</td>
<td>498</td>
<td>560</td>
<td>492</td>
</tr>
<tr>
<td>Flue gas outlet (°C)</td>
<td>265</td>
<td>208</td>
<td>226</td>
<td>237</td>
<td>308</td>
<td>245</td>
</tr>
<tr>
<td>Ammonia after rectification (°C)</td>
<td>36.8</td>
<td>34.8</td>
<td>36.1</td>
<td>38.5</td>
<td>39.3</td>
<td>39.4</td>
</tr>
<tr>
<td>Absorber (°C)</td>
<td>23.9</td>
<td>25.1</td>
<td>26.2</td>
<td>28.0</td>
<td>28.7</td>
<td>30.4</td>
</tr>
<tr>
<td>Evaporation (°C)</td>
<td>-21.7</td>
<td>-20.2</td>
<td>-19.4</td>
<td>-18.7</td>
<td>-18.5</td>
<td>-16.6</td>
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<tr>
<td>Condensation (°C)</td>
<td>24.3</td>
<td>26</td>
<td>26.9</td>
<td>29.0</td>
<td>29.9</td>
<td>31.1</td>
</tr>
<tr>
<td>Cooling capacity (kW)</td>
<td>29.6</td>
<td>30.2</td>
<td>27.6</td>
<td>26.6</td>
<td>30.5</td>
<td>26.8</td>
</tr>
<tr>
<td>COP</td>
<td>0.52</td>
<td>0.56</td>
<td>0.55</td>
<td>0.50</td>
<td>0.52</td>
<td>0.53</td>
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</table>
6. Conclusions

<table>
<thead>
<tr>
<th>Working pair</th>
<th>Driven temperature</th>
<th>Evaporation temperature</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modular adsorption chiller</td>
<td>Silica gel- water</td>
<td>55 -90 °C</td>
<td>5°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Modular design, cost saving</td>
</tr>
<tr>
<td>Single/double effect absorption chiller</td>
<td>LiBr-water</td>
<td>85 -95°C / 135-150°C</td>
<td>5°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Continuously and steady operating</td>
</tr>
<tr>
<td>Adsorption refrigerator</td>
<td>CaCl₂/AC-ammonia</td>
<td>100 -140 °C</td>
<td>-5~ -20 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High efficiency, stability</td>
</tr>
<tr>
<td>1.n effect absorption chiller</td>
<td>LiBr-water</td>
<td>90 -135°C</td>
<td>5°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Variable effect, large working temperature range</td>
</tr>
<tr>
<td>Absorption ice maker</td>
<td>water- ammonia</td>
<td>140-170°C</td>
<td>-30°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>perfect internal heat recovery</td>
</tr>
</tbody>
</table>
Solar PV Powered HVAC & R?

Split room AC
VRV
Centrifugal chiller
Solar PV cooling

PV air conditioning becomes more competitive with the PV cost goes down.
Solar PV DC powered Inverter centrifugal chiller
光伏直驱变频离心机

普通光
伏空调

光伏组件

光伏逆变器

直流

交流

普通空调

格力光伏直驱变频离心机

格
利
光
伏
空
调

光伏组件

光伏组件

省设备
省转换

省设备
省转换

直流
Solar PV DC powered Inverter centrifugal chiller
光伏直驱变频离心机

电池阵列

光伏空调

空调+发电  市电+光伏  光伏发电

电池阵列

汇流单元  配电单元

直流母线

空调变频器

AC/DC
Solar PV DC powered Inverter centrifugal chiller
光伏直驱变频离心机

电池阵列

光伏空调
市电+光伏
光伏发电

空调+发电

光伏空调
市电+光伏
光伏发电

380V 供电

空调变频器

直流母线

AC
DC

DC
AC
Solar PV DC powered Inverter centrifugal chiller
光伏直驱变频离心机
光伏直驱变频离心机

电池阵列

汇流单元 配电单元

光伏空调 空调+发电 市电+光伏

光伏发电

光伏空调

空调+发电

市电+光伏

市电

380V

直流母线 空调变频器

DC AC
Solar Energy

for the bright future of mankind!
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