SOLAR COOLING TECHNOLOGIES

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Overview on physical ways to convert solar radiation into cooling or air-conditioning. Processes marked in dark grey: market available technologies which are used for solar assisted air-conditioning. Processes marked in light grey: technologies in status of pilot projects or system testing.
CLOSED-CYCLE SYSTEMS
Absorption (WET) and adsorption (DRY) cycles are examples. They produce chilled water that can be used in combination with any airconditioning equipment such as an air-handling unit, fan-coil systems, chilled ceilings, etc.

•Common Wet Systems:
Water (H2O)– Lithium Bromide (LiBr) Systems
Ammonia (NH3)– Water (H2O) Systems

•Common Dry Systems:
Water-Zeolite, Water – Silica Gel, Methanol-Activated Carbon, Ammonia-Activated Carbon, etc.

OPEN-CYCLE SYSTEMS
Desiccant Systems (Wet and Dry) are the main types. The term “open” cycle is used to indicate that the refrigerant is discarded from the system after providing the cooling effect, and new refrigerant is supplied in its place in an open-ended loop.
WET ABSORPTION SYSTEMS

Typical coefficient of performance (COP) for large single-effect machines are 0.7 to 0.8. Double-effect absorption systems, with typical operating COPs of 1.0 to 1.2 are also available. Current R&D efforts are focusing on three- and four-effect systems, with a COP of 1.7 to 2.2.

For solar-assisted systems, it is important to select the appropriate solar collector type to meet the temperature needs of the cooling machine. Systems with high COPs need higher operating temperatures.

Most commercially available absorption chillers range in capacity from medium (40 to 100 kW) to high (300 kW and above). However, given the increasing cooling demand in residential and small size building applications, a growing market exists for low cooling capacity equipment (i.e. less than 10 kW to 40 kW).

Some firms are offering systems in the small ranges, especially suitable for solar energy applications: examples - Broad (China), Rotartica (Spain), Yazaki (Japan).

In India, Thermax offers “Half-Effect” systems for low hot water input temperatures of about 60 C. There are other companies also which supply absorption cooling systems.
DRY ABSORPTION SYSTEMS

Today, adsorption or solid-sorption chillers have a higher efficiency than absorption chillers at low driving temperatures (defined as the average temperature of the heating fluid between inlet and outlet of the heating system).

The advantage is that their internal cycle does not have any moving parts (no pumps, no electrically driven valves). Also, crystallization cannot occur, as in the case of LiBr/H2O absorption chillers.

However, due to their intermittent operation (periodic cycle), they require more effort in system design and operation control.

In addition, compared to absorption machines, they are larger, heavier, and more expensive per kW cooling capacity.

Only a few manufacturers make the systems, limiting equipment choices. The COP of commercially available systems is 0.55 to 0.65, depending on operating conditions.

More suitable for smaller capacity domestic, mobile and portable applications.
COP-curves of sorption chillers and ideal thermodynamic limit (Carnot)

chilled water temperature: 9 °C
cooling water temperature: 28 °C
POSSIBLE COMBINATIONS OF SOLAR THERMAL AND SORPTION REFRIGERATION TECHNOLOGIES

- air collector
- flat plate collector
- evacuated tube collector

Solar collector efficiency vs. generation temperature (°C)

- Adsorption
- Double effect absorption
- Single effect absorption
- Desiccant cooling
Distribution of the specific collector area (collector area in m² of installed cooling capacity in kW) for different technologies.
When the Hot Water reduces the temperature from 88°C to 60°C, the capacity of the Adsorption Chiller stays in 90% and 43% in case of the absorption chiller. This shows a stable output from the Adsorption Chiller.
## COMPARISON OF DIFFERENT TECHNOLOGIES

<table>
<thead>
<tr>
<th>Systems</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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</table>
| Absorption| • Only one moving part (pump) with possibly no moving part for a small system  
           | • Low-temperature heat supply is possible                                      | • Low COP                                                                      |
|           |                                                                            | • It cannot achieve a very low evaporating temperature                        |
|           |                                                                            | • The system is quite complicated                                              |
| Adsorption| • No moving parts (except valve)                                           | • High weight and poor thermal conductivity of the absorbent                   |
|           | • Low operating temperature can be achieved                                | • Low operating pressure requirement makes it difficult to achieve air-tightness|
|           | • Thermal Coefficient of Performance (COP) is quite high compared to other heat operating systems | • Very sensitive to low temperatures especially the decreasing temperature during night-time |
|           |                                                                            | • It is an intermittent system                                                 |
| Desiccant | • Environmentally friendly, water is used as the working fluid             | • It cannot function properly in a humid area                                  |
|           | • Can be integrated with a ventilation and heating system                   | • It is not appropriate for an area where water is scarcity                    |
|           |                                                                            | • Requires maintenance due to moving part in a rotor wheel                     |
Some of the work done by the author at R & AC Lab of IIT Madras

**WET SYSTEMS**
- Multi-Effect Systems for performance improvement (Water-LiBr)
- Multi-Stage Systems for performance improvement (Water-LiBr)
- Multiple Heat Sources at Different Temperature Levels (Water-LiBr)
- Heat Pump – Chillers for both Heating and Cooling (Water-LiBr)
- New Working Fluids (R22 or R134a with Organic Solvents)
- Pumpless / Transfer Tank to eliminate the Mechanical Pump
- Heat and Mass Transfer in Falling Film Absorbers

**DRY SYSTEMS**
- Metal Hydride based Systems for Portable Cooling and Automotive Airconditioning
- Heat and Mass Transfer in Solid Sorption Beds / Optimization and Design

**DESICCANT BASED SYSTEMS**
- Rotary wheel based silica – gel systems
- LiBr-Water based liquid desiccant systems
- Solid and liquid desiccant + vapour compression hybrids
Simulation of Solid Sorption Cooling Systems

- Adsorber Configuration
- Refrigerant Vapour
- Adsorbent Bed
- Fins / Separators
- Heat Transfer Fluid

Diagram showing the configuration of a sorption cooling system with adsorber beds, fins, and separators.
Performance of Sorption Bed; Carbon (FX400)-Methanol

1. Chilling Temperature : 0 °C
2. Cooling Fluid Temperature : 30 °C
3. Adsorption Bed Pressure : 4000 Pa
4. Desorption Bed Pressure : 21000 Pa
5. Desorption Temperature : 85 °C
Performance of Sorption Bed; Carbon (FX400)-Methanol (contd..)

Concentration vs time (Sorption cooling cycle)

Concentration vs time (Desorption)

Specific heat variation in the bed

Reaction rate and Concentration variations (Refrigeration Cycle)
Performance of Carbon (FX400)-Methanol Cooling Cycle

The Carbon methanol cycle
Optimal Performance of Carbon (FX400)-Methanol Cooling Cycle

Parameters studied
1. COP
2. Cooling Power
4. Pressure

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>COP</th>
<th>Cooling (KJ/Kg)</th>
<th>Time (Sec)</th>
<th>Power (W/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.41</td>
<td>137.3</td>
<td>6500</td>
<td>21.1</td>
</tr>
<tr>
<td>20</td>
<td>1.21</td>
<td>117.2</td>
<td>5800</td>
<td>20.0</td>
</tr>
<tr>
<td>25</td>
<td>0.99</td>
<td>94.9</td>
<td>5300</td>
<td>17.9</td>
</tr>
<tr>
<td>30</td>
<td>0.75</td>
<td>70.6</td>
<td>4500</td>
<td>15.7</td>
</tr>
</tbody>
</table>
Heat and mass recovery processes greatly improve the performance of the system as apparent in COP of the system. Heat recovery results in a 10-21% increase in the COP of the system, but the SCP remains the about the same and also reduces in some cases. Mass recovery results in an 11-19% increase in COP, and the SCP increases by 9-20%. Heat and mass recovery processes together result in improvements in COP of 16-40% and SCP of 14-34%.
Four-bed Metal Hydride system with combined recovery

Hydrogen flow lines
Mass recovery line with valve
Heat recovery line with valve
Heat flow

HT Alloy A: Zr0.9 Ti0.1CrFe (1000 g/reactor)
LT Alloy B: Zr0.7 Ti0.3 CrFe (900 g/reactor)
Variation of COP with $T_h$ for different cases

$T_m = 30^\circ C$
$T_c = 0^\circ C$

- Combined recovery
- Heat recovery cycle
- Mass recovery cycle
- Basic cycle
Variation of COP with $T_m$ for different cases

- $T_h=90^\circ C$
- $T_c=10^\circ C$

- Combined recovery cycle
- Heat recovery cycle
- Mass recovery cycle
- Basic cycle

Intermediate temperature, $T_m$: °C

COP
Design, Analysis and Optimization of Sorption Beds

- Liquid Cooled Hydrogen Storage Device with Embedded Heat Exchanger Tubes
- Hydrogen Storage Device with Plate Fins
- Hydrogen Storage Device with Radial Fins
Computational Models used in COMSOL Multiphysics™

- **Liquid Cooled Storage Device**
  - Number of elements = 22165
  - Computational time = 180 s

- **Air Cooled Storage Device with Radial Fins**
  - Number of elements = 14689
  - Computational time = 1740 s

- **Air Cooled Storage Device with Plate Fins**
  - Number of elements = 35155
  - Computational Time = 2100 s
Minimization of Total Weight

Example

Data
Charging capacity = 2 kg
Charge level = 80 %
Charge time = 300 s
Supply pressure = 15 bar
Coolant Temperature = 300 K
L/D ratio = 2 – 4
Hydriding alloy = LaNi₅

Results
Radius of container \( r_1 \) = 154 mm
Radius of HX tube \( r_2 \) = 5.5 mm
Radius of filter \( r_3 \) = 1.5 mm
Pitch distance \( s \) = 22 mm
Total no. of HX tubes = 163
Total no. of filters = 282
Length of device \( L \) = 986 mm
L/D of device = 3.2
\( A_{sc}/V_c \) of device = 1.182 cm²/cm³
Total system weight \( W_t \) = 370 kg
Results on Air Cooled Devices with Radial Fins

Effect of external fins on rate of hydride formation inside tubular storage device with fins kept within the air stream during absorption at different time intervals ($b=5\text{ mm}$, $p=15\text{ bar}$, $T_f=300\text{ K}$)

Effect of air temperature on hydride concentration (weight %)

Formation of hydride inside tubular storage device with fins kept within the air stream during absorption at different time intervals ($b=5\text{ mm}$, $p=15\text{ bar}$, $T_f=300\text{ K}$)
Results on Air Cooled Devices with Tube Bundle

Temperature profile of air and concentration profile of hydride bed for the finned-tube metal hydride storage device at different time intervals (p=15 bar, T_f=300 K, s/d=2, b=5.5 mm, u= 1 m/s)

Variation of hydride density at leading and trailing cross sections at different bed thicknesses
CFD Based Study of Solid Sorption Beds

Physical model of the problem
Velocity vector and Concentration distribution at different times

(a) t = 1500 s

(b) t = 2000 s
Velocity vector and Concentration distribution at different times

(c) $t = 2500$ s

(d) $t = 3000$ s
Pictorial view of the experimental set up for coupled reactor studies
(1) HT hydride reactor (2) LT hydride reactor (3) Hydrogen reservoir/receiver (4) High pressure cylinder (5) HT thermostatic bath (6) LT thermostatic bath, (F1, F2) Gas flow meters, (BP) Bypass, (P1, P2) Pressure gauges
Specifications of the Sorption Cooling System

Hydride pair (HT/LT) : ZrMnFe/MmNi_{4.5}Al_{0.5}
Mass of ZrMnFe : 700 g
Mass of MmNi_{4.5}Al_{0.5} : 800 g
Cycle time : 3 to 12 minutes
Heat source temperature : 110 to 130°C
Heat sink temperature : 25 to 30°C
Cold temperature : 5 to 15°C
Cooling COP : 0.2 to 0.35
Solar thermal air conditioning system in India in Ahmedabad operating since February, 2006.
The 25 TR (88 kW cooling) Vapor Absorption Machine is powered by hot water generated through 98.4 kW of high efficiency heat pipe evacuated tube solar collectors. The total carpet area air-conditioned is 227 m².

Annual Mean COP: 0.856
DESIDCANT COOLING SYSTEMS

These are useful when latent heat load is larger than the sensible heat load. Thermal energy input is needed to regenerate the desiccant.

Advantages of desiccant cooling systems:

• Environment friendliness
• Significant potential for energy savings  Electrical energy requirements are about 25% of the conventional V-C refrigeration system.
• Source of input thermal energy are diverse viz solar, waste heat and natural gas.
• IAQ is improved due to higher ventilation rates and the capability of desiccants to remove air pollutants.
• Operation at near atmospheric pressures ensures their construction and maintenance to be simple.
• Desiccant systems can be used for summer/ monsoon air conditioner as well as winter heating when regeneration energy can be used for heating.
Solar Liquid Desiccant System at IIT Madras

- Regenerator
- Solution to Solution Heat Exchanger
- Solution to Cooling Tower
- Pre Cooler
- Pre Heater
- Absorber
- Dry Air from Cooling Tower
- Solution
- Hot Water
- Cold Water

Flow Path:
- Solution from Solar Tank
- Humid Air from Regenerator
- Solution to Solution Heat Exchanger
- Solution to Cooling Tower
- Dry Air from Cooling Tower
- Solution
- Hot Water
- Cold Water

Direction:
- Air
- Solution
- Hot Water
- Cold Water
MAJOR PARTS.
ABSORBER
REGENERATOR
SOLUTION HX
PRECOOLER
PREHEATER
AUXILIARY-FITTINGS
The Regenerator
The Solar Panels

FLAT PLATE COLLECTOR FIELD
15 COLLECTORS PARALLEL IN 2 ROWS
### RANGES OF OPERATING PARAMETERS

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>PARAMETER</th>
<th>RANGE</th>
<th>MEAN VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>HOT WATER TEMPERATURE, °C</td>
<td>60 - 80</td>
<td>80</td>
</tr>
<tr>
<td>2.</td>
<td>HOT WATER FLOW RATE, m³/h</td>
<td>0.4 - 0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>3.</td>
<td>RETURN AIR FLOW RATE, m³/s</td>
<td>0.12 - 0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>4.</td>
<td>REGENERATION AIR FLOW RATE, m³/s</td>
<td>0.18 - 0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>5.</td>
<td>SOLUTION FLOW RATE, l/h</td>
<td>125 - 225</td>
<td>225</td>
</tr>
<tr>
<td>6.</td>
<td>COOLING WATER FLOW RATE, m³/h</td>
<td>0.4 - 0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>7.</td>
<td>COOLING WATER TEMPERATURE, °C</td>
<td>28 - 32</td>
<td>28</td>
</tr>
</tbody>
</table>

Note:- Each parameter is varied in 5 equal steps over the given range and the results are shown in the figures which follow. While one parameter is varied, the other parameters are kept constant at the mean value.
• Cooling capacity increases with all input parameters except the cooling water temperature.

• Effect of solution flow rate is not significant on cooling capacity.

• Effect of return air flow rate is the most significant on cooling capacity.

Effect of Parameters on (virtual) Cooling Capacity (kW)
• Quantity of water vapour absorbed increases with parameters except cooling water temperature.

• Effect of regeneration air flow rate and cooling water flow rate is not significant on water vapour absorbed.

• Effect of return air flow rate is the most significant on water vapour absorbed.

**Effect of Parameters on Water Vapour Absorbed (kg/hr)**
• Increase in hot water temperature the COP remains same.

• Increase in hot water flow rate increases heat input so COP decreases.

• Increase in return air, regeneration air and cooling water flow rate the COP increases since cooling capacity increase with same heat input.

• Increase in solution flow rate the COP initially increase and then reduce. Effect of return air flow rate is most significant on COP.

**Effect of Parameters on (virtual) COP of the System**
Integration, prototype development, and performance evaluation of solar collection devices with heat based cooling technologies in the capacity range < 10TR

Project Sponsored by MNRE

Investigators: Sanjeev Jain & Subhash Mullick; IIT Delhi
Contact: sanjeevj@mech.iitd.ac.in

MAIN OBJECTIVES:
To develop prototype of a membrane based solar desiccant cooling systems for air-conditioning applications
To develop prototype of a solar collector cum regenerator
To carry out detailed experimental investigations and long term performance studies on the prototypes
Desiccant Dehumidifier Core

- Cross flow of air and desiccant
- No direct contact between the desiccant and the air stream
- Series of double channeled sheets to prevent carryover of liquid in air stream (Sealing?)
- Liquid to wet the sheet completely to ensure maximum area for air/liquid interaction

An inside view of the contactor
Typical Performance

![Graph showing typical performance of dehumidifier effectiveness against LiCl solution concentration.]
Fabricated Solar Collector-cum-regenerator
CONCLUDING REMARKS

Significant Research and Developmental works are being done by the author on various aspects of Solar cooling technologies.

All the three technologies, i.e. Wet Absorption, Dry Solid Sorption and also Liquid- and Solid Desiccant Dehumidification, are being studied.

Main emphasis is on the Thermodynamics, and Heat & Mass Transfer studies. Integration with Solar Energy Collection and Thermal Energy Storage Sub-Systems are also being done.

All these studies are yielding data for Optimal Thermal Design of Solar Cooling Systems for a variety of applications.

The author is the Chairman of the Solar Thermal Projects Advisory Committee and also the Chairman of the Solar Cooling Expert Committee of the MNRE; and may be contacted for collaboration in specific areas (ssmurthy@iitm.ac.in).
THANK YOU VERY MUCH