Solar cooling –
Status and perspectives

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Outline

- Introduction/background
  - The need for cooling…
  - Main alternatives, electric or heat driven
- Possible technologies
  - Heat driven systems
  - Electrically driven systems

Why solar cooling?

- Demand for cooling is typically in phase with availability of solar energy.
- AC-systems may lead to peak in electricity demand. Good for the grid if this load is removed.
- Low running costs.

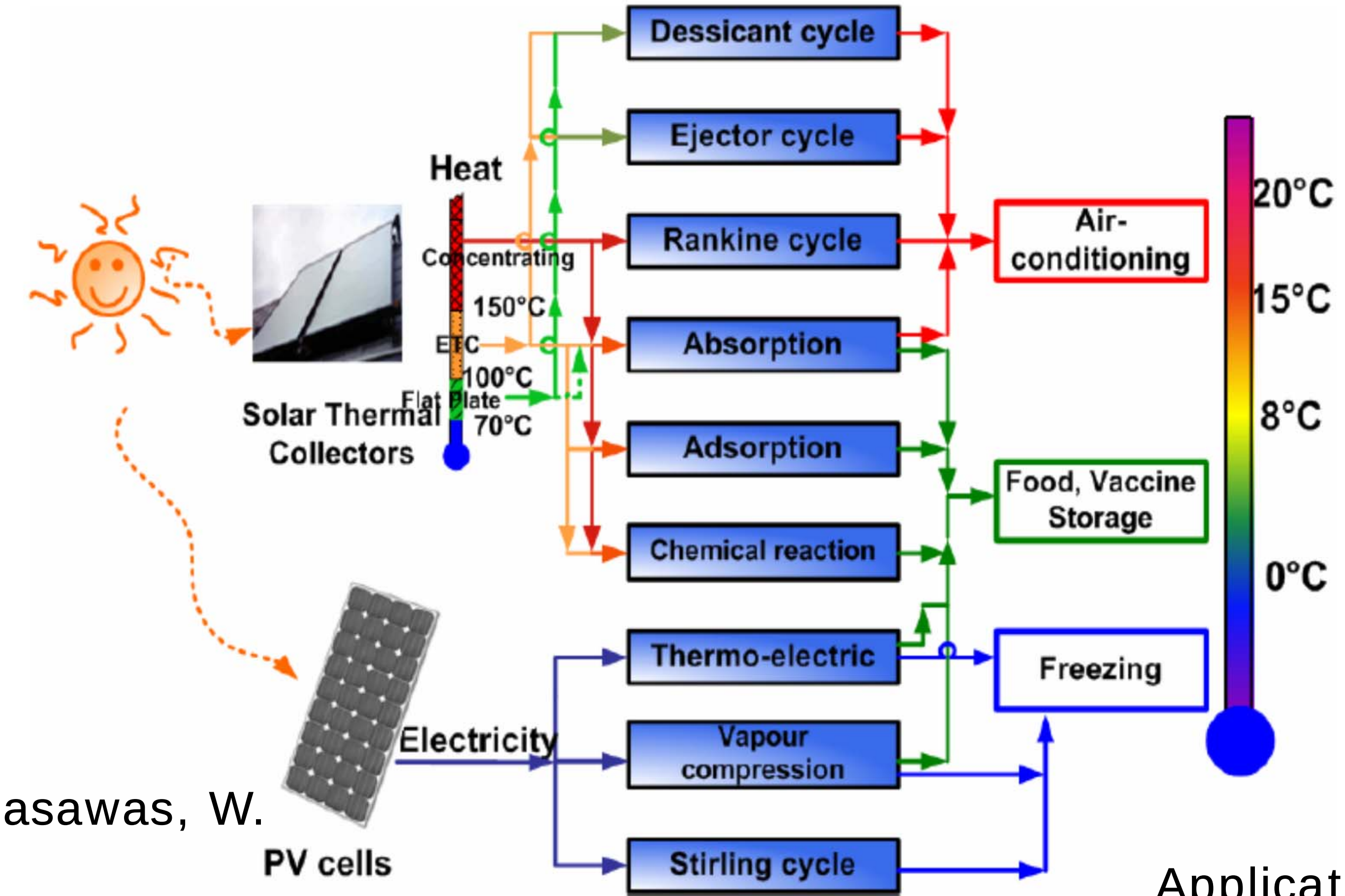
Why not solar cooling?

- Availability: Cooling may be required also when solar energy is not available. Requires then alternative system, or storage.
- Low efficiency.
- High first cost.

Solar cooling comes at a high first cost – try to limit the cooling demand!

- The design of the building, including size, direction and type of windows, shadings, thermal mass of the structure, thermal insulation, etc. should be considered as a means to minimize the need for active cooling, i.e. air conditioning.

Main options for solar cooling



Pridasawas, W.

Applications for PV-based cooling increases with decreasing cost.

Historical review of cooling from heat

- 1823: John Leslie shows that it is possible to make ice with an absorption- or adsorption process.
- 1850’s: Carré brothers develop absorption processes for cooling
- 1870’s: Albel Pifre and Augustin Mouchot demonstrate solar driven absorption machines for ice production.

Figure 8-2 *John Leslie (1766-1872), professor of mathematics at Edinburgh, Scotland, experimented with absorption and vacuum refrigeration beginning about 1815 (from the Smithsonian Institution, Division of Engineering and Industry).*

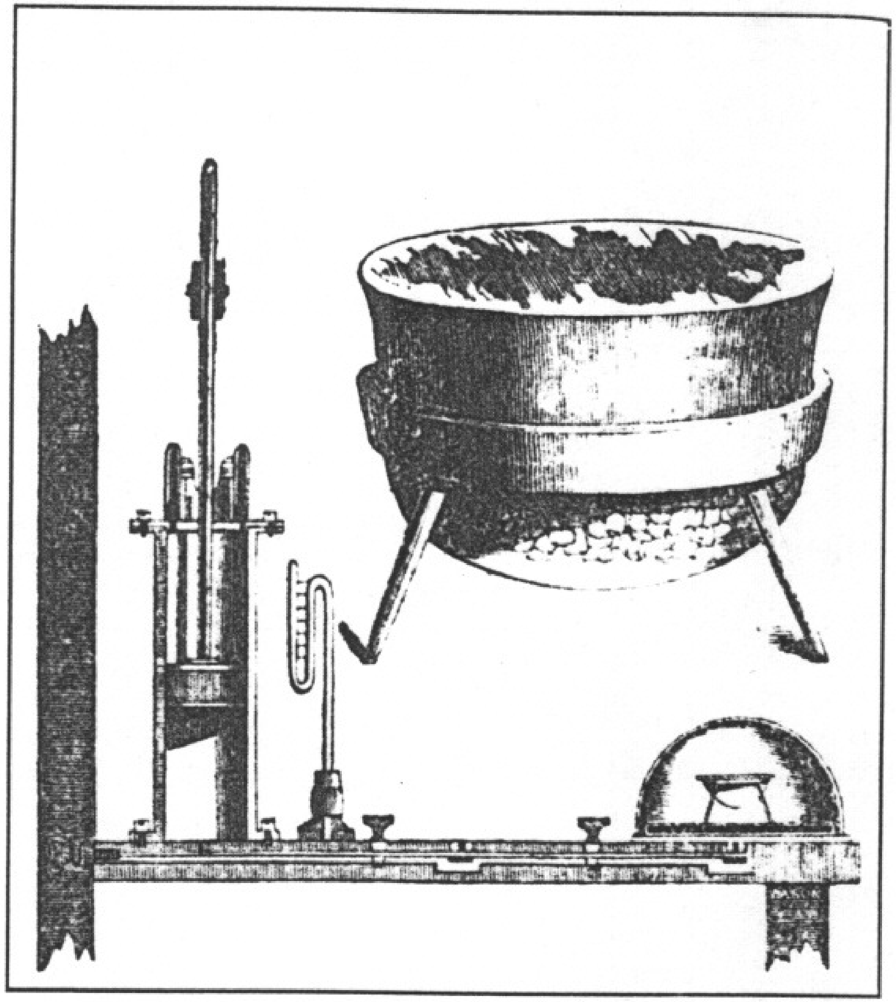


Figure 8-3 *John Leslie's absorption and vacuum freezing device, 1823. A dish of water is suspended above a flat tray of sulfuric acid under a sealed glass bell jar. The air pump at left is used to draw a vacuum on the jar. The water boils at a temperature below freezing, not only due to the action of the air pump, but also due to the absorbing effect of the acid, which absorbs water vapor, permitting an even greater vacuum. Leslie later discovered that parched oatmeal was a better absorber than sulfuric acid. The oatmeal had an added advantage of being reusable—it could be regenerated by heating on a stove or in the sun (from* Mechanic's Magazine, *1823, p. 313).*

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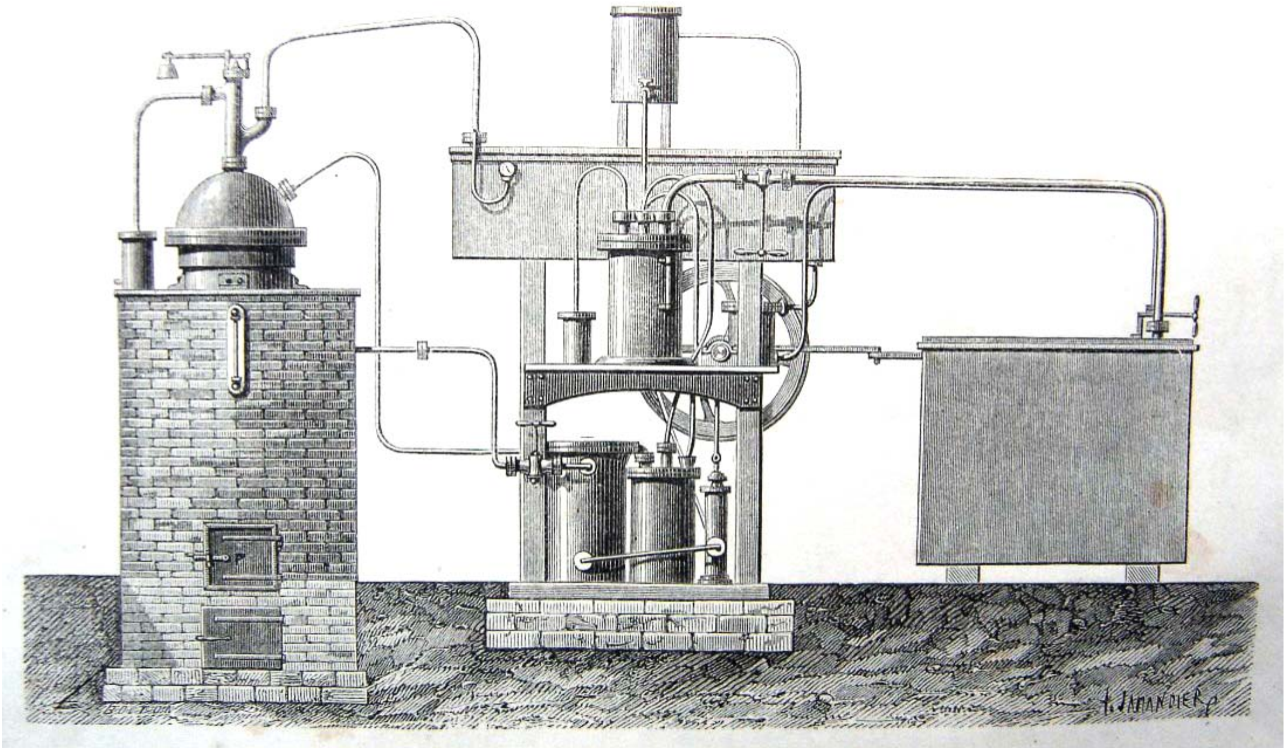
Ferdinand Carré's absorption machine (1858)



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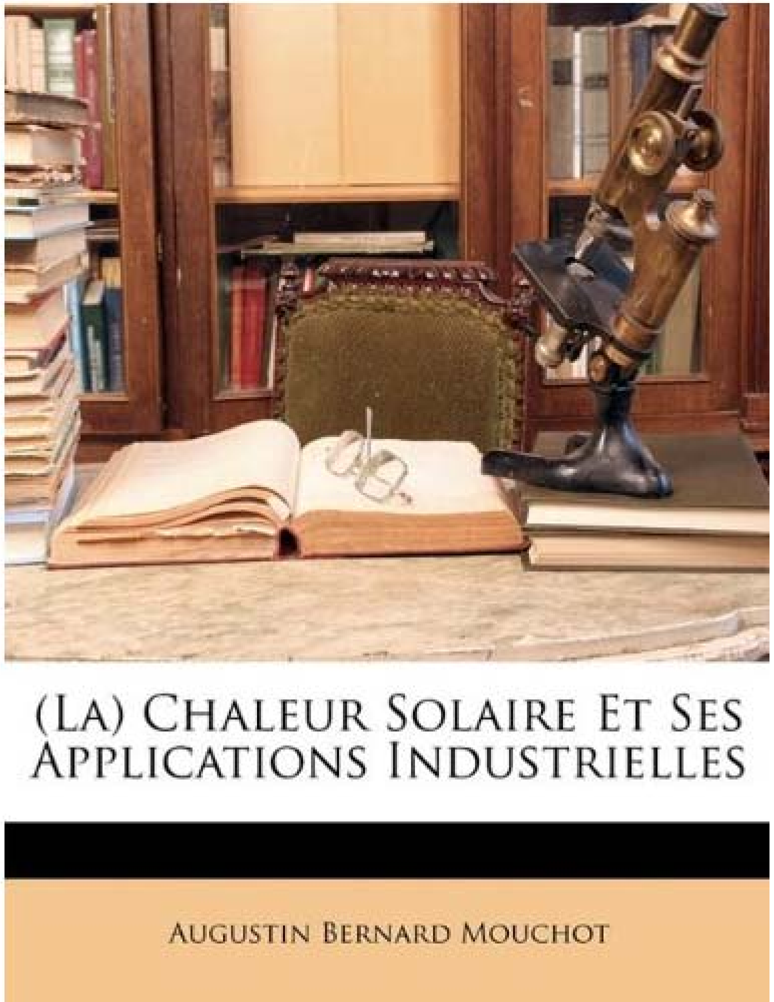
”Solar cooling and its industrial applications”



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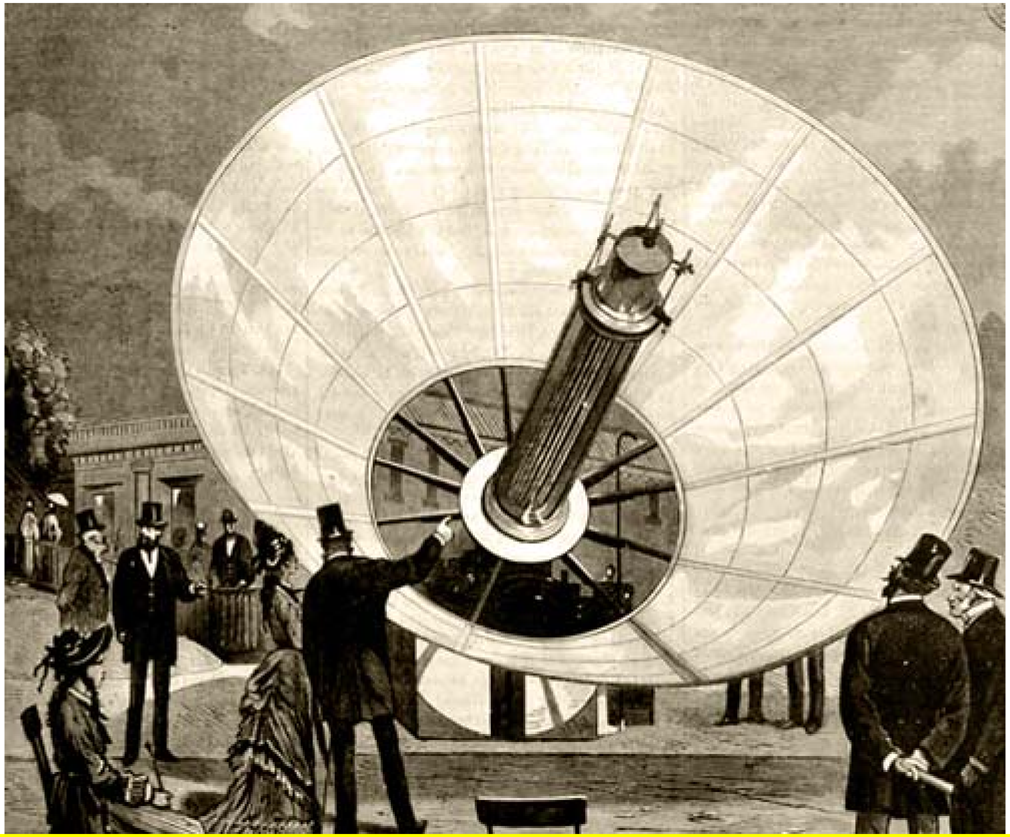
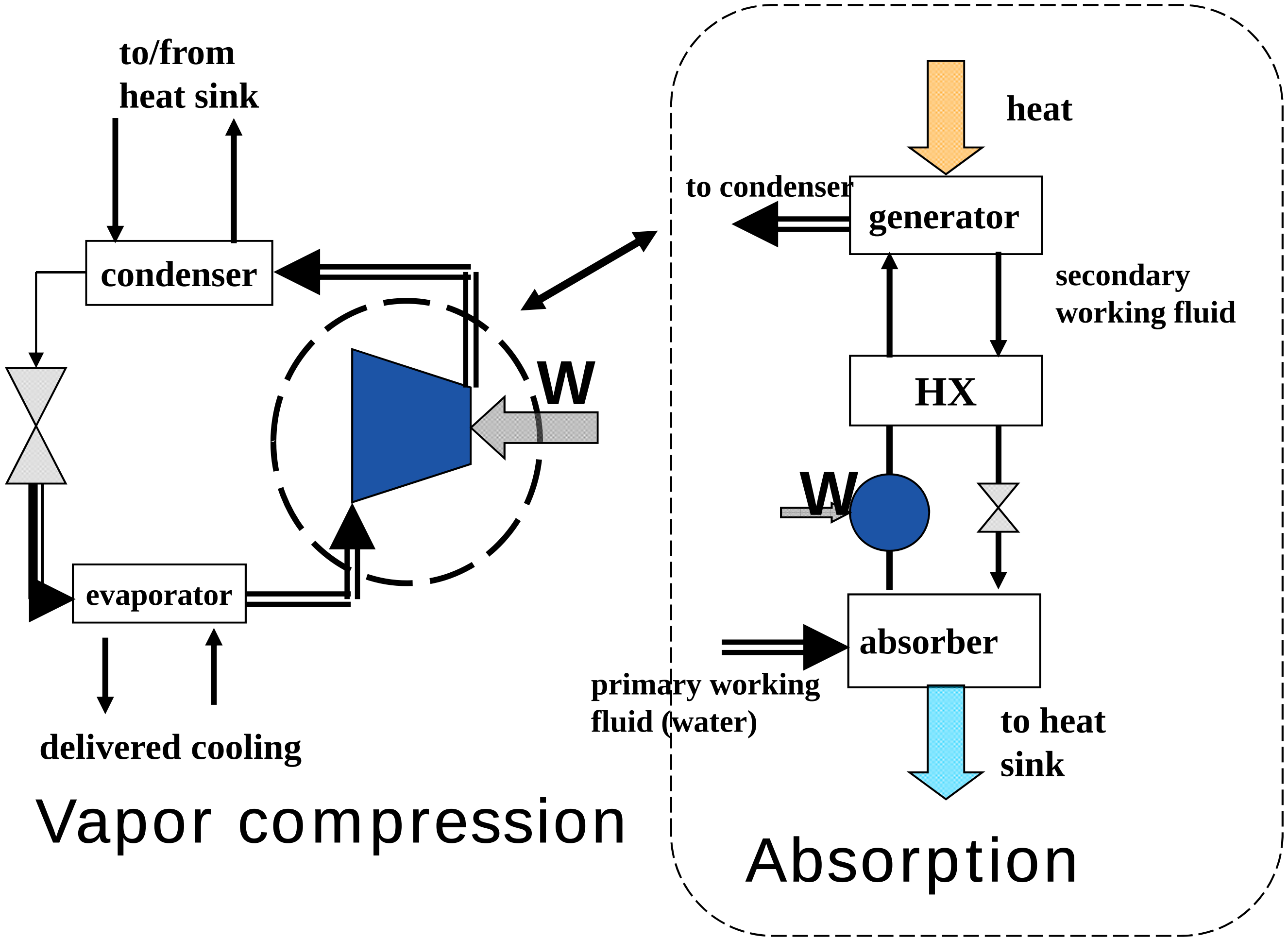
- Augustin Mouchot won the gold medal at the World Exhibition in Paris 1878 for his solar driven ice machine.



“Unfortunately, the falling price of coal, driven by efficiencies of transport and free trade agreements with Britain, meant that Mouchot’s work would soon be deemed unnecessary and his funding was cut soon after his triumph at the Universal Exhibition.”

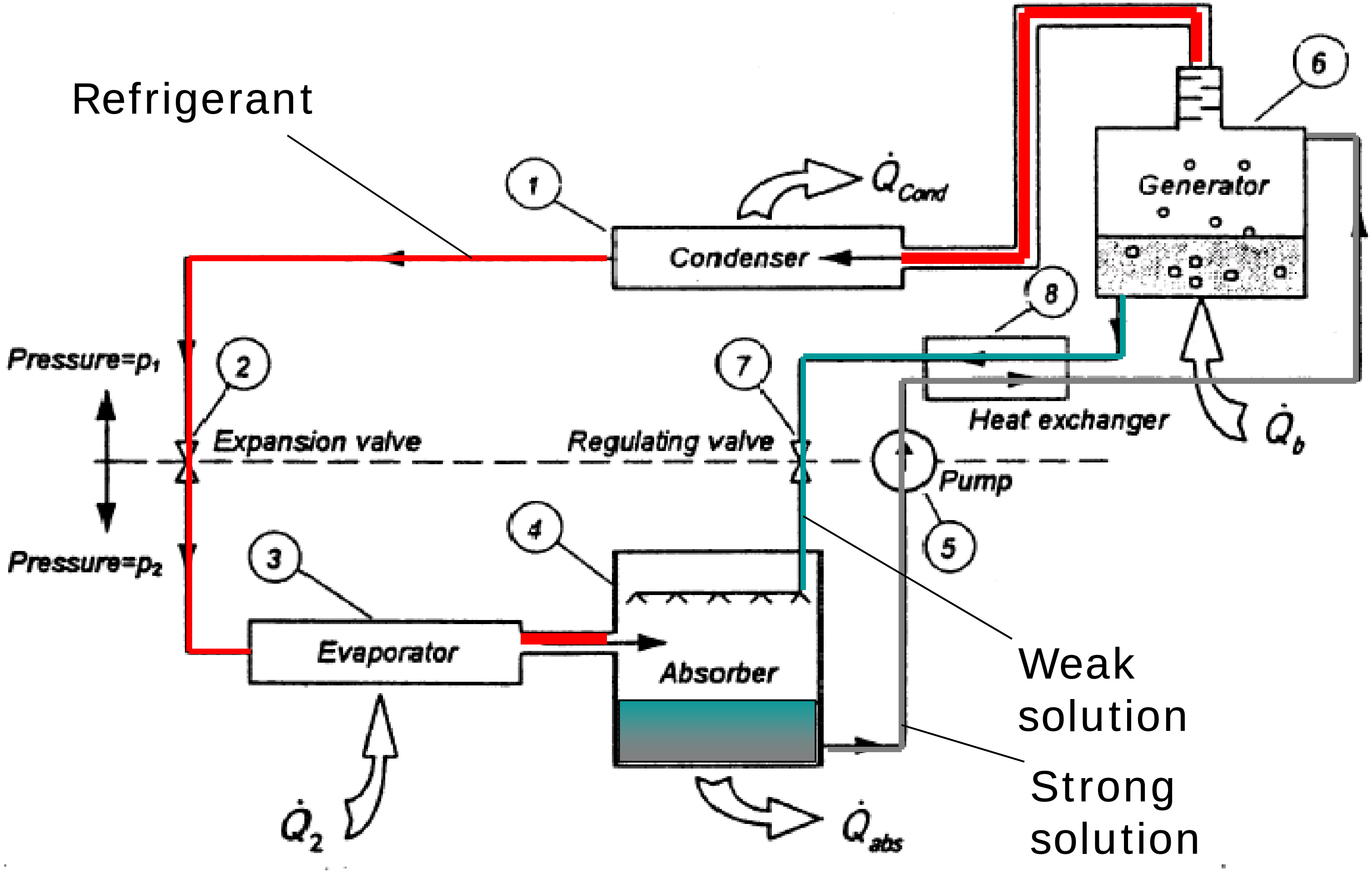
Review of technologies

Principle for a thermally driven absorption machine



Source: Viktoria Martin, KTH

Carré’s absorption process



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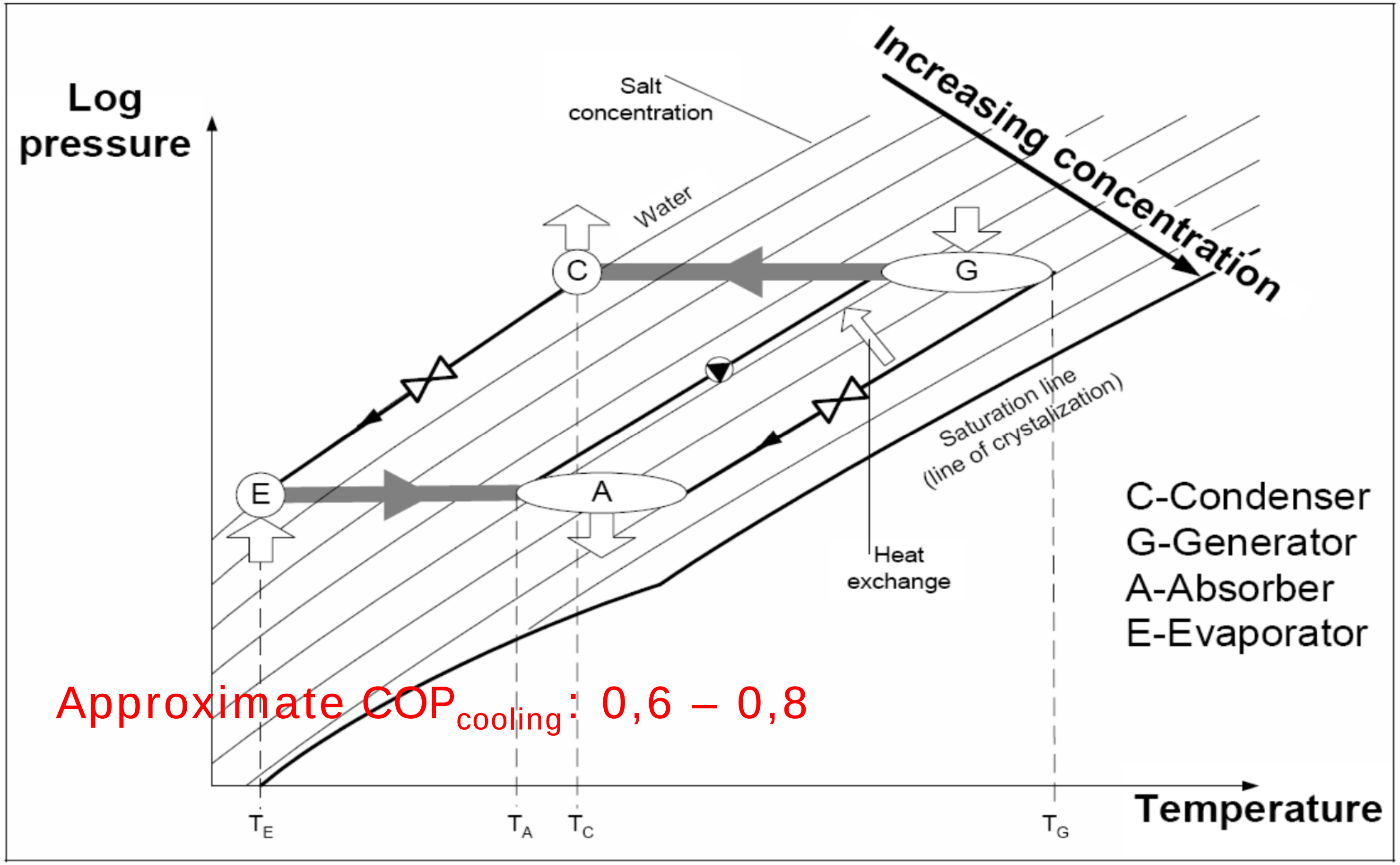
Working fluids – pros and cons

Fluids	Ammonia / Water	Water / LiBr
Properties		
Heat of evaporation	Good	Excellent
Pressure level	High	Very low
Freezing point	Good (i.e. low)	Bad (0°C)
Poisonous	Yes	No

Based on: Viktoria Martin, KTH

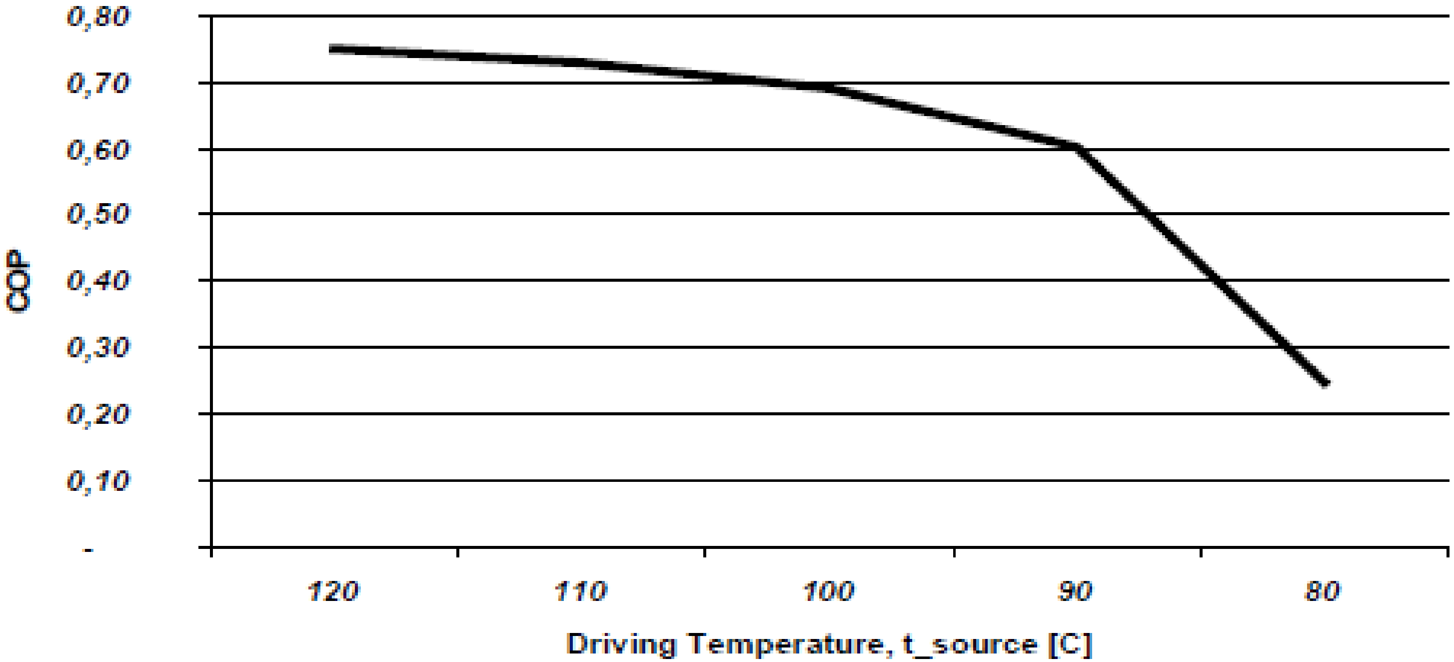
Singel effect absorption system (LiBr-water)



Approximate $COP_{cooling}$: 0,6 – 0,8

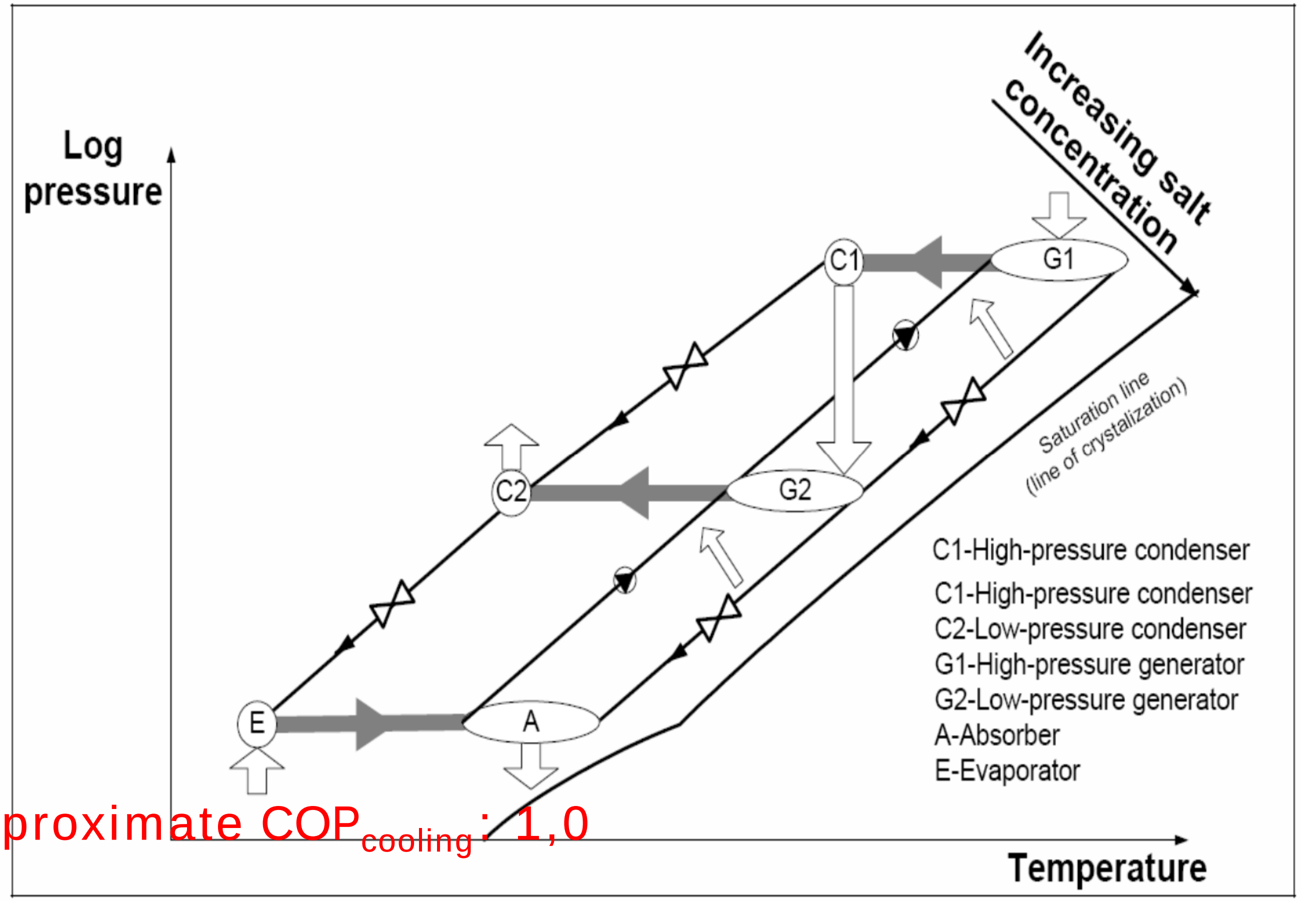
Source: Rydstrand et al., Heat Driven Cooling, Swedish District Heating Association, Report No. FoU 2004:112, 2004.

Approximate $COP_{cooling}$ vs driving temperature for absorption processes



Source: Viktoria Martin, KTH

Double Effect Absorption system



Approximate $COP_{cooling}$: 1,0

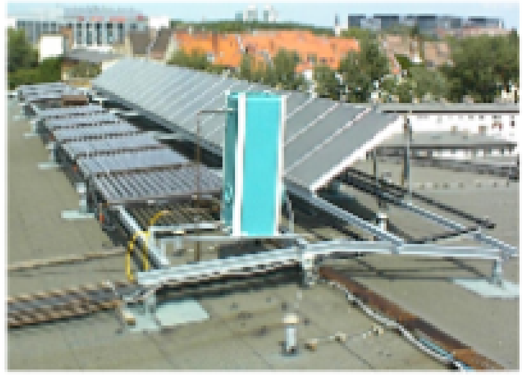
Source: Rydstrand et al., Heat Driven Cooling, Swedish District Heating Association, Report No. FoU 2004:112, 2004.

Technical University Berlin

Solar Cooling of Buildings

A worldwide increasing demand for air-conditioned offices, hotels, private households and also, e.g., stables is already causing power supply systems to work to capacity in summer months. Heat driven sorption chillers offer a real solution to this growing problem. Those working with low driving temperatures are especially advantageous as they can be run with solar thermal energy, profiting from the simultaneity of cooling demand peak load and availability of solar thermal energy.

However, presently there are only a few solar chillers installed in Europe and there is almost no absorption chiller with a small cooling capacity below 30 kW commercially available.



Solar collector field and cooling tower at Phönix SonnenWärme AG (Berlin Treptow)

To fill this gap a 10 kW absorption chiller, designed for low driving temperature with the working fluid pair water/LiBr, was developed and built together with ZAE Bayern and Phönix SonnenWärme AG. The focus was on good part load behaviour and compact design.

Since August 2003 the first prototype is used to cool the Phönix SonnenWärme AG offices. Laboratory tests under different well defined steady-state and transient conditions

Specification of the chiller

Working pair H_2O/LiBr

Coefficient of performance 0.76

Cooling capacity 10 kW
chilled water in/out 18/15°C
flow rate 2.9 m^3/h

Driving heat capacity 13.2 kW
hot water in/out 75/65.3°C
flow rate 1.2 m^3/h

Rejected heat capacity 23.2 kW
cooling water in/out 27/34.7°C

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- Phönix SonnenWärme: LiBr/vatten absorption refrigeration plant.
- 10 kW cooling at 75°C/27°C and 18°C cooling water out.
- COP: 0,78

- Photo: A. Kühn.

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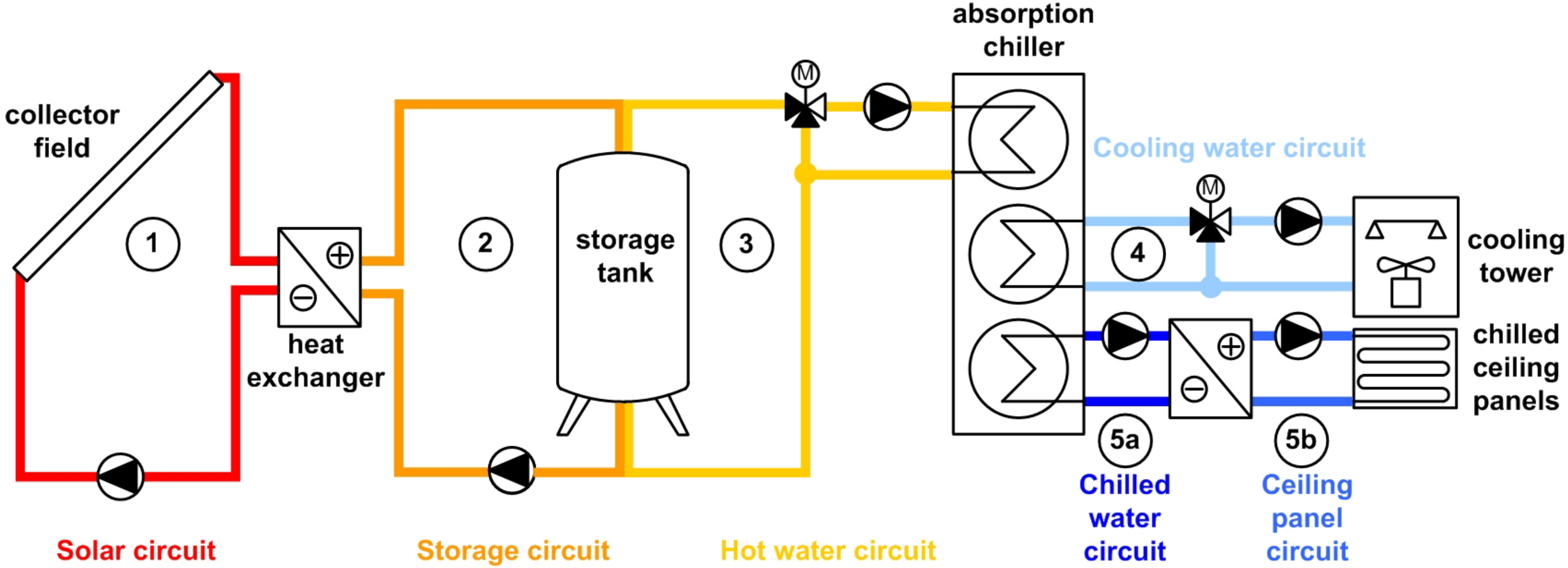
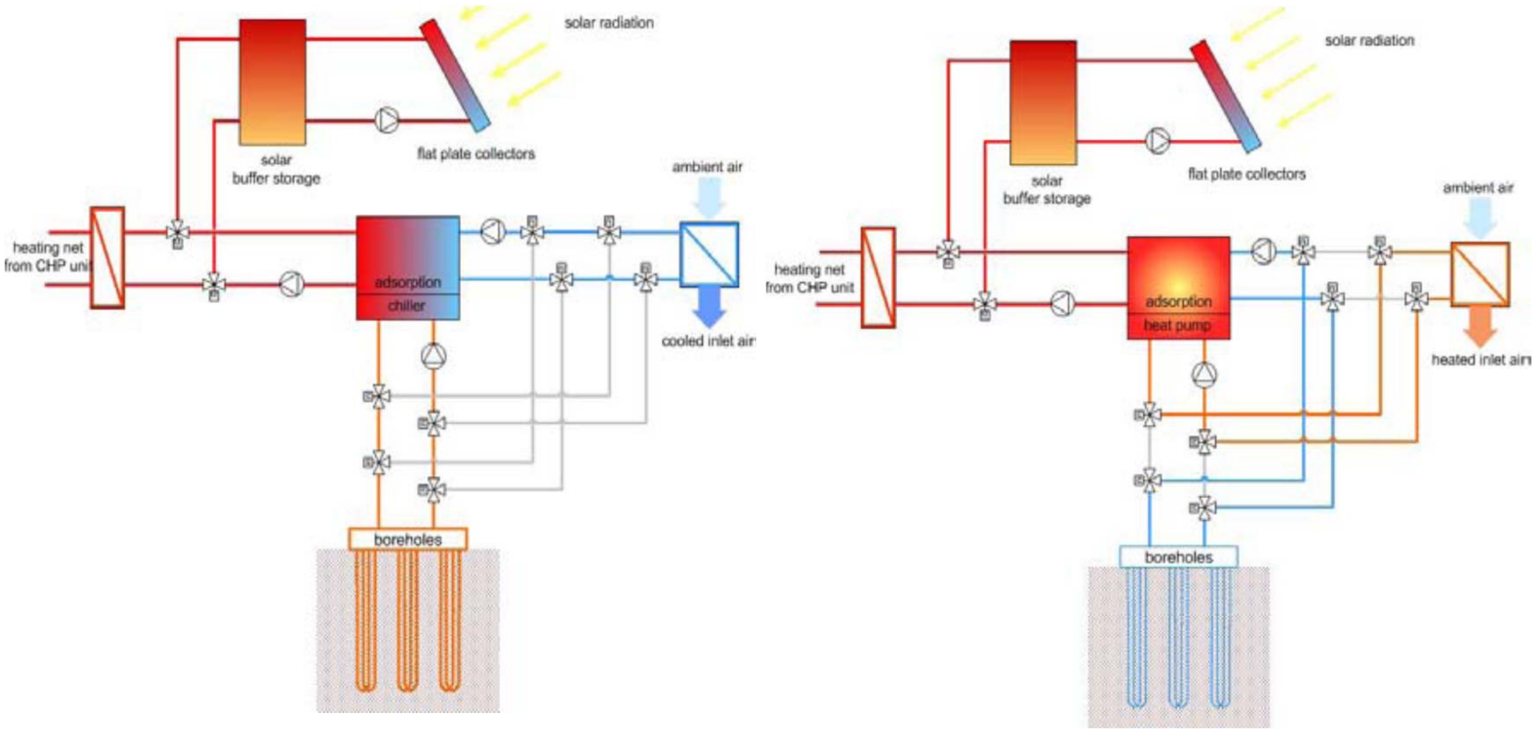
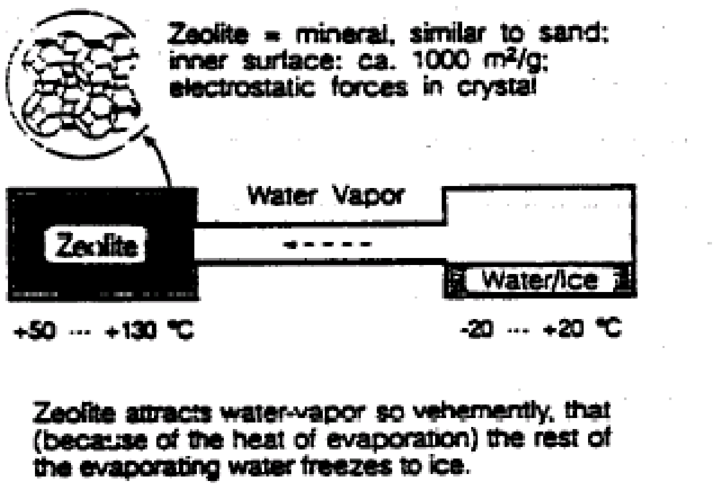


Combined Solar Heating and Cooling – developments at Fraunhofer ISE

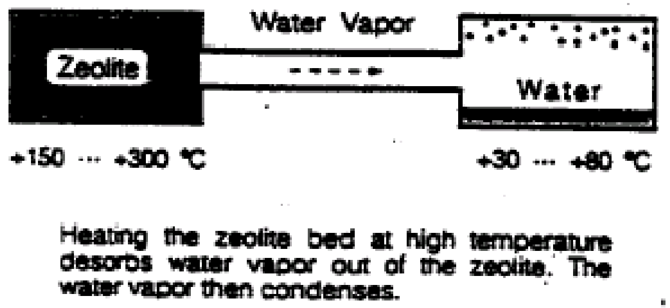


Nunez et al, Eurosun 2008, Paper no. 448

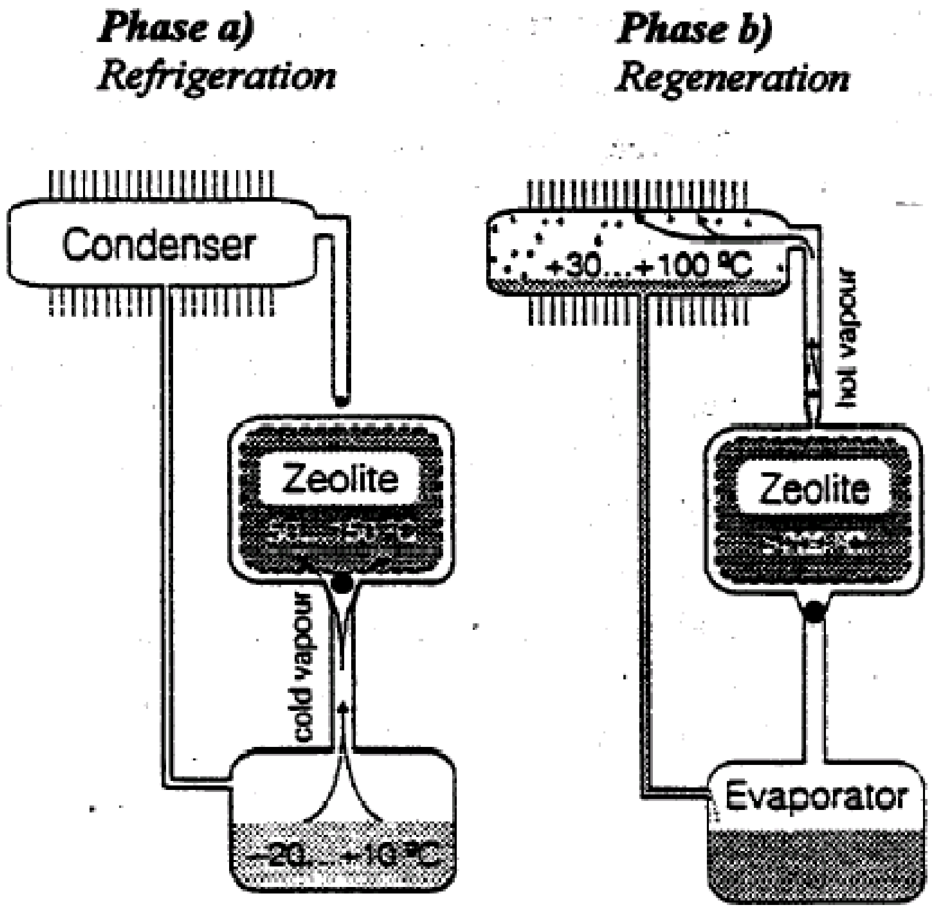
Adsorption system – intermittent



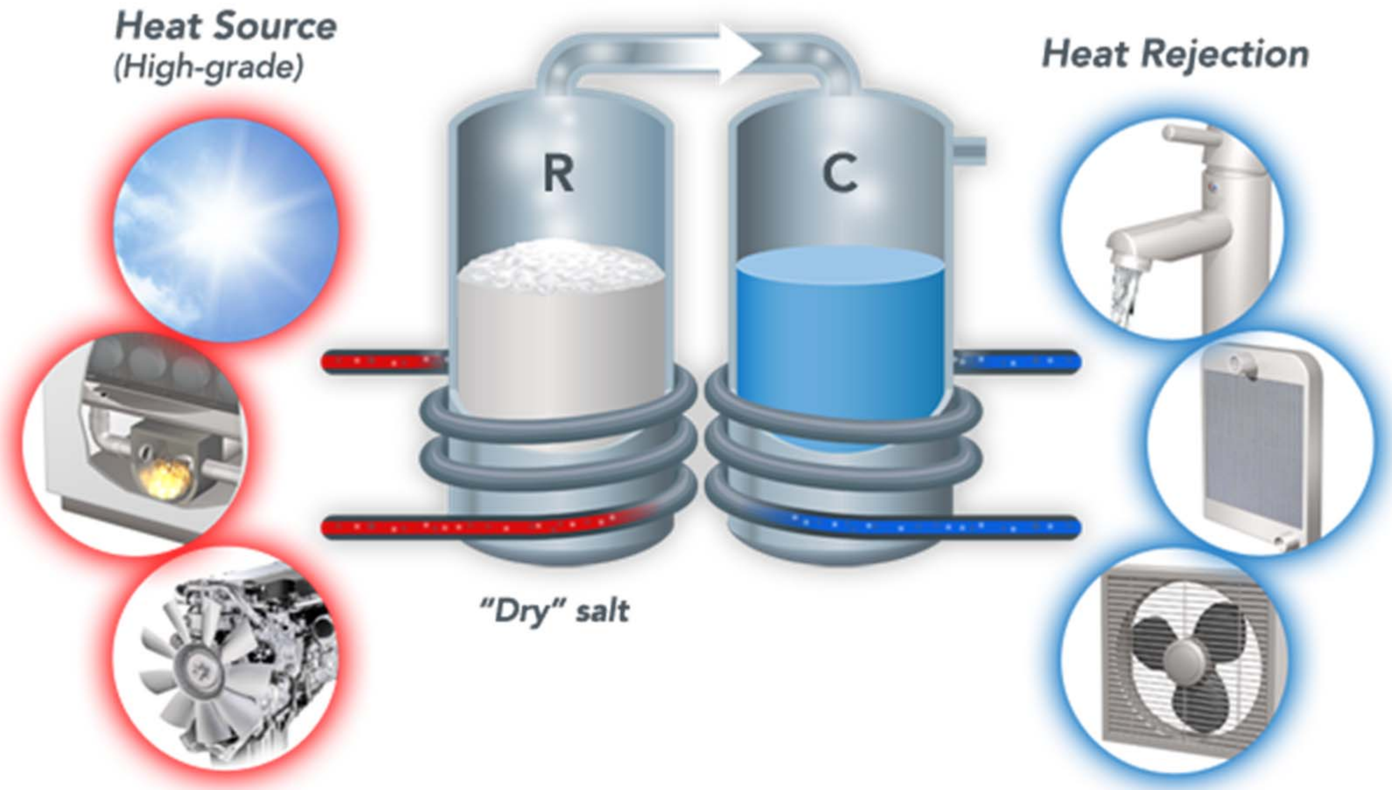
Phase a): Adsorption = *Refrigeration*



Phase b): Desorption = *zeolite regeneration*

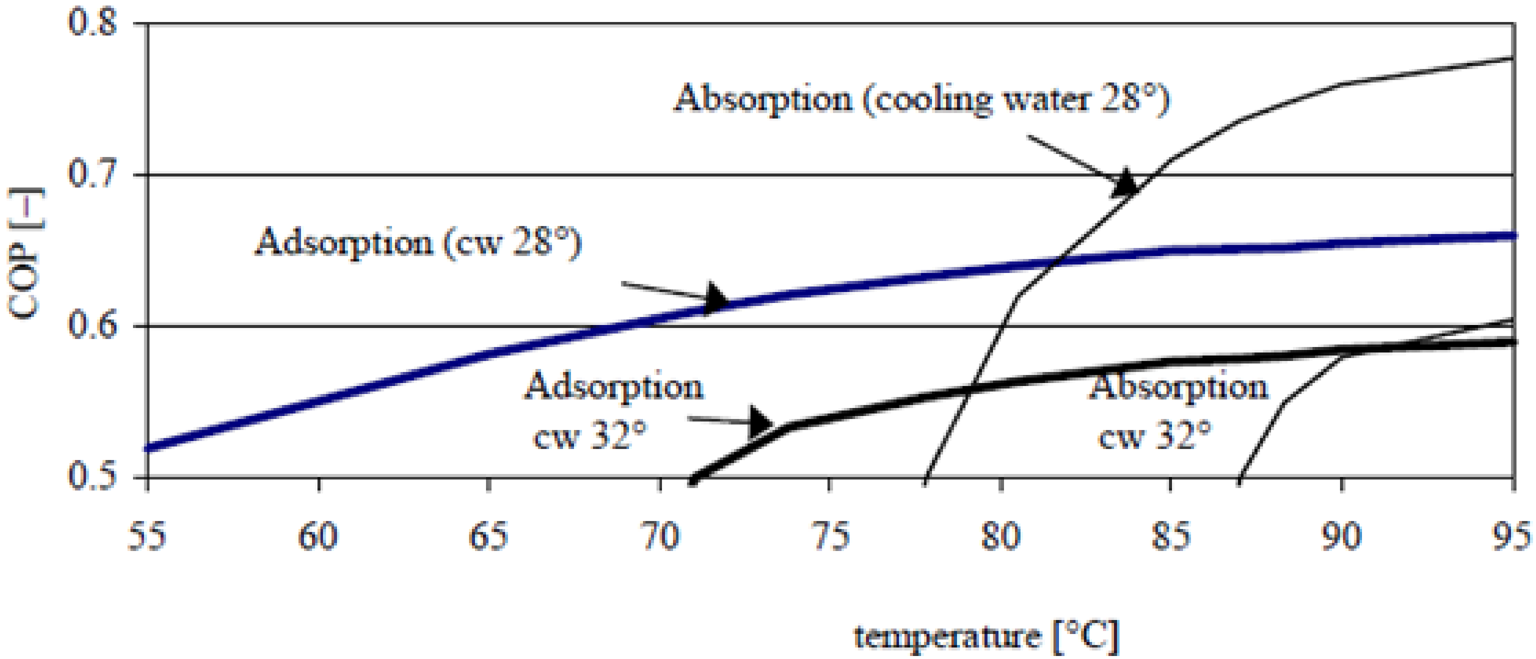


Adsorption system – intermittent



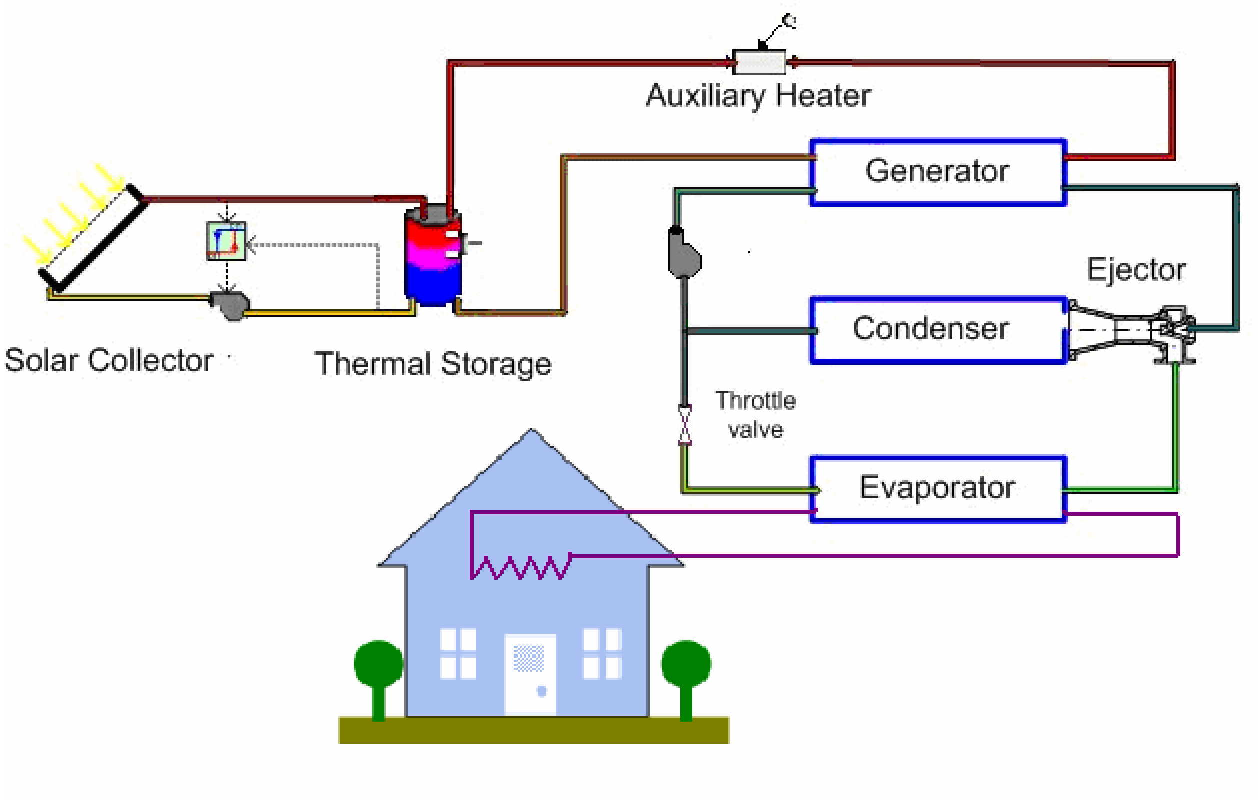
Source: Climatewell

Expected COPcooling for absorption and adsorption processes at different heat source temperatures



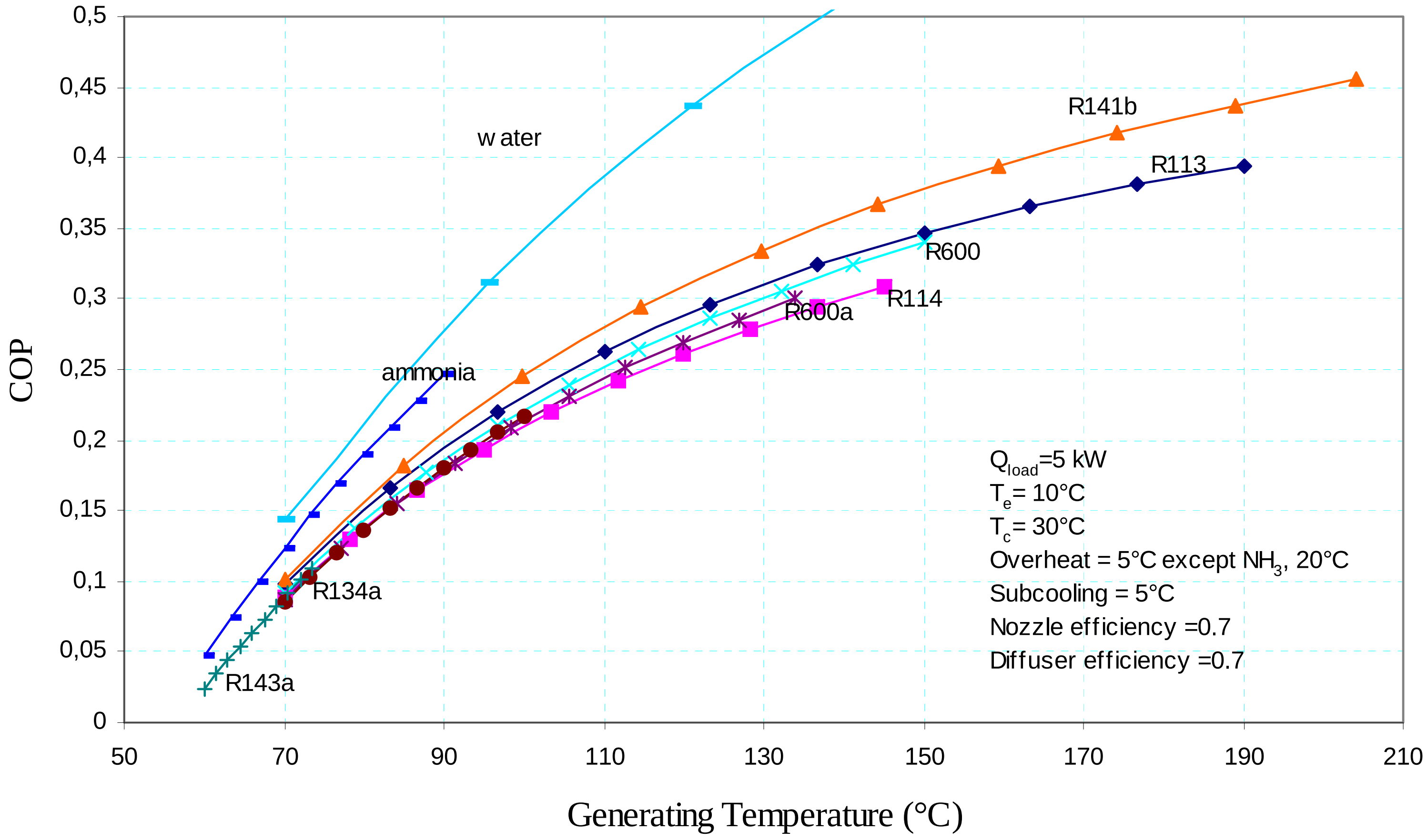
Source: *Technical Investigation of Absorption Cooling For Northern Ireland - A Nicol*

Ejector cooling systems

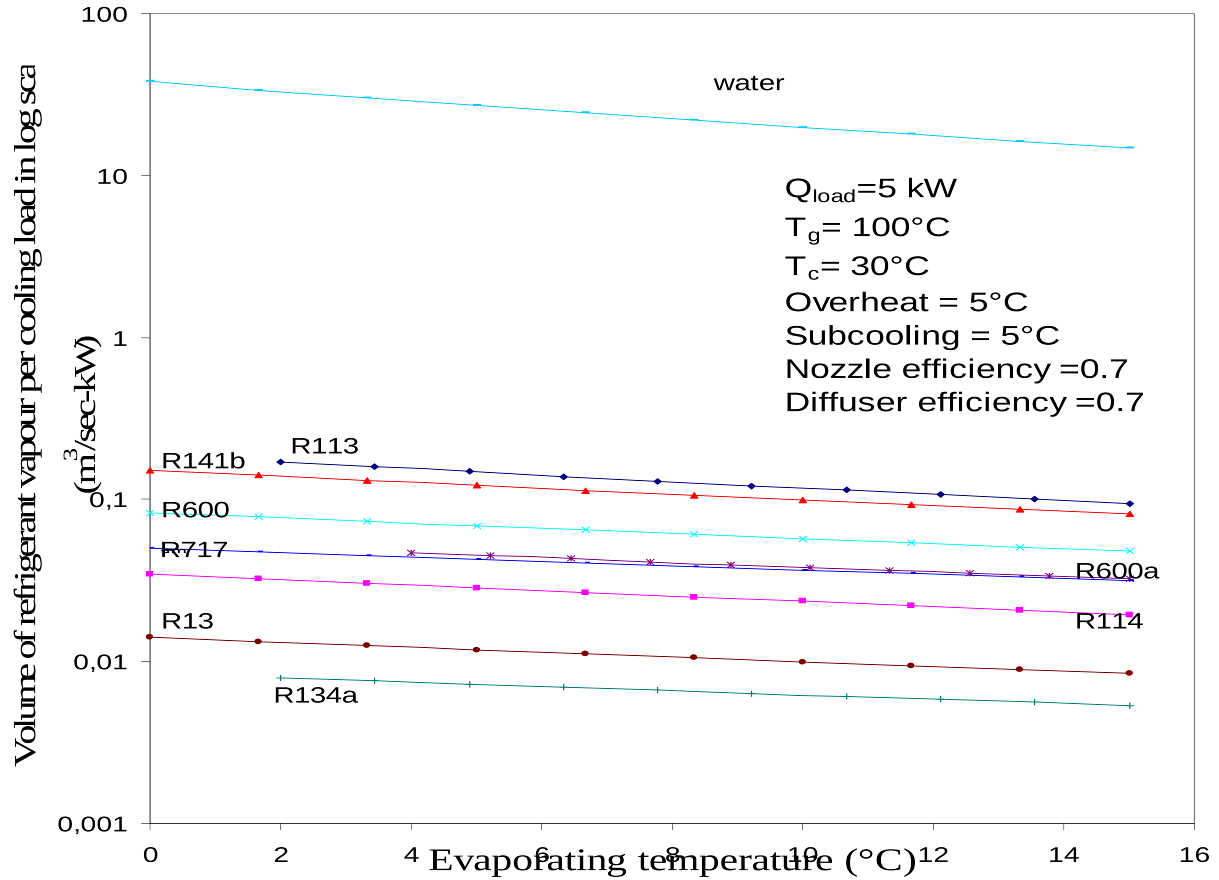


Pridasawas, W.

$COP_{cooling}$ for the ejector process at a condensing temperature of 30 °C using different refrigerants



Volyme flow of gas per kW cooling for different refrigerants at varying evaporation temperatures.
Note the logarithmic scale.



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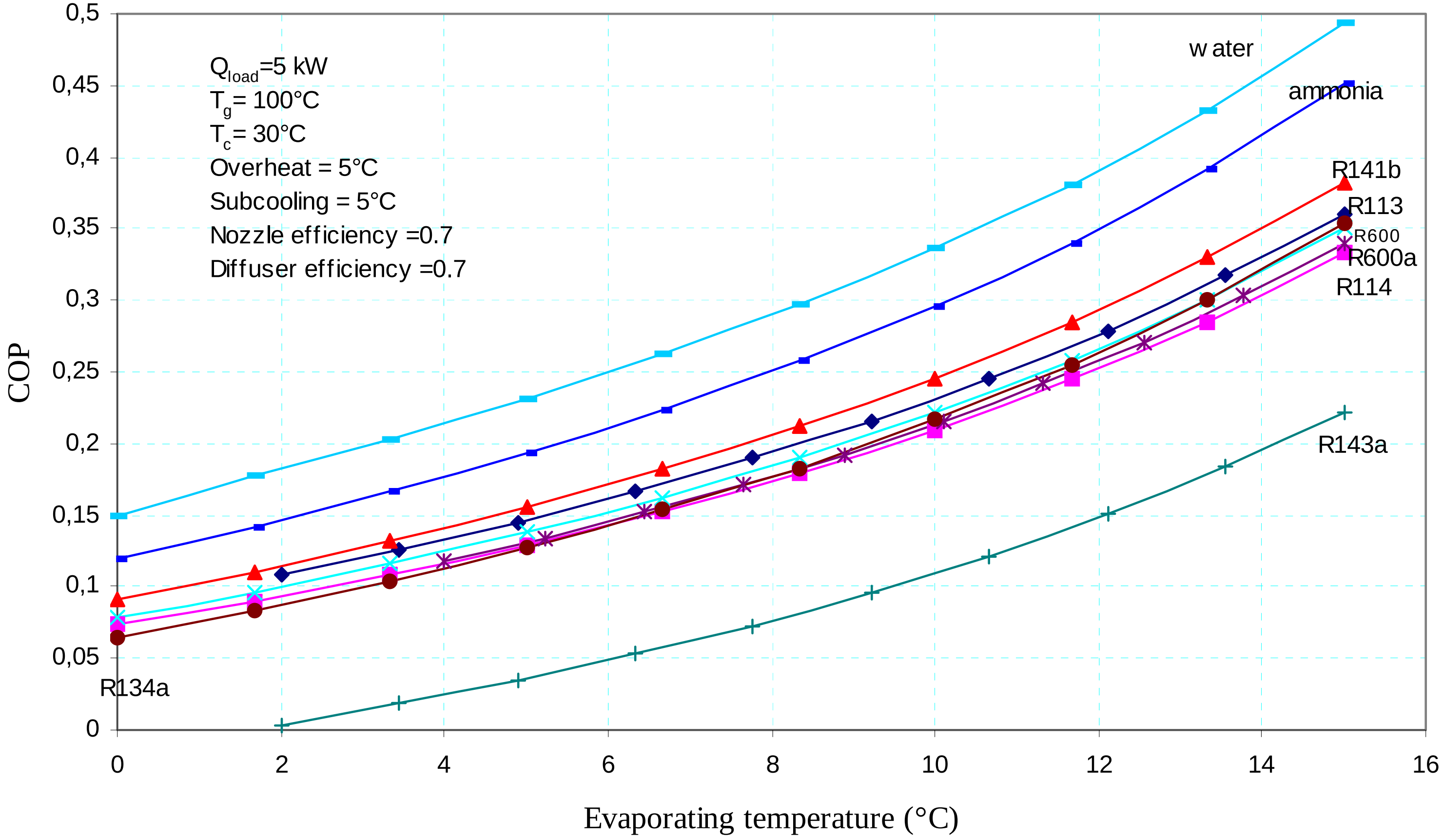
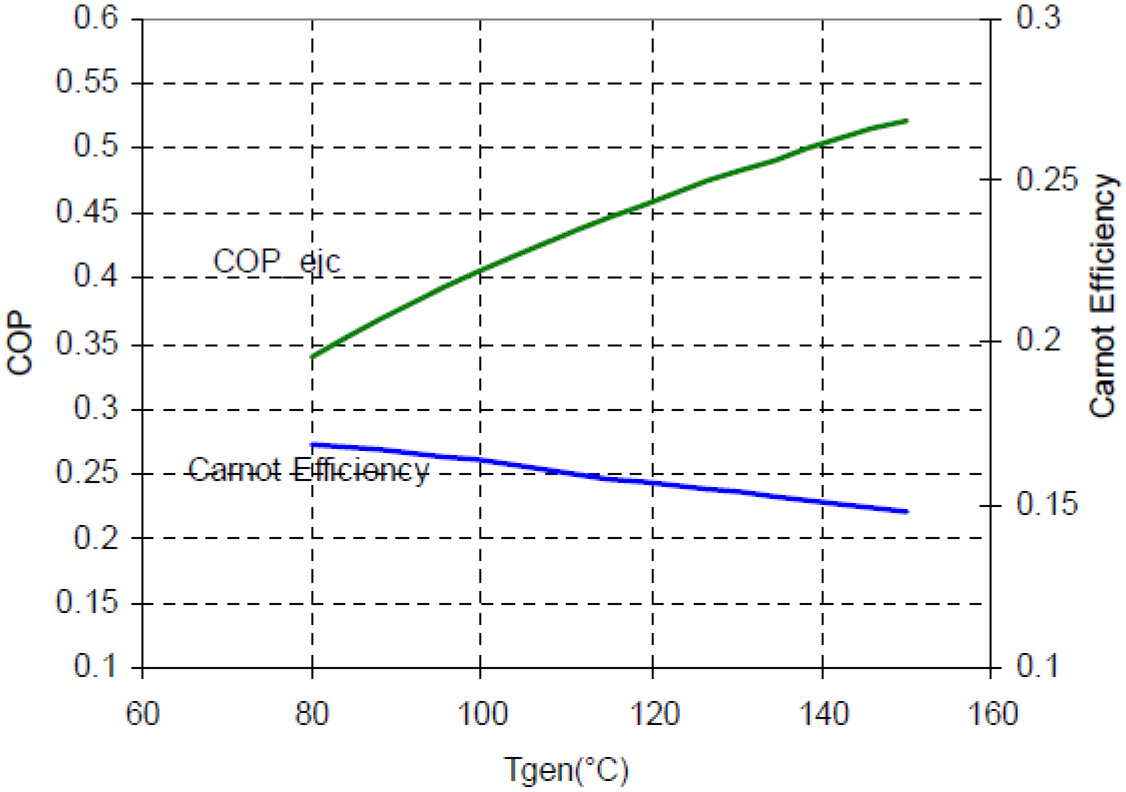
Influence of the evaporation temperature on the COPcooling of the ejector cycle.



COP and Carnot Efficiency of an ejector system at 10°C of Te and 30°C of Tc



Pridasawas, W.

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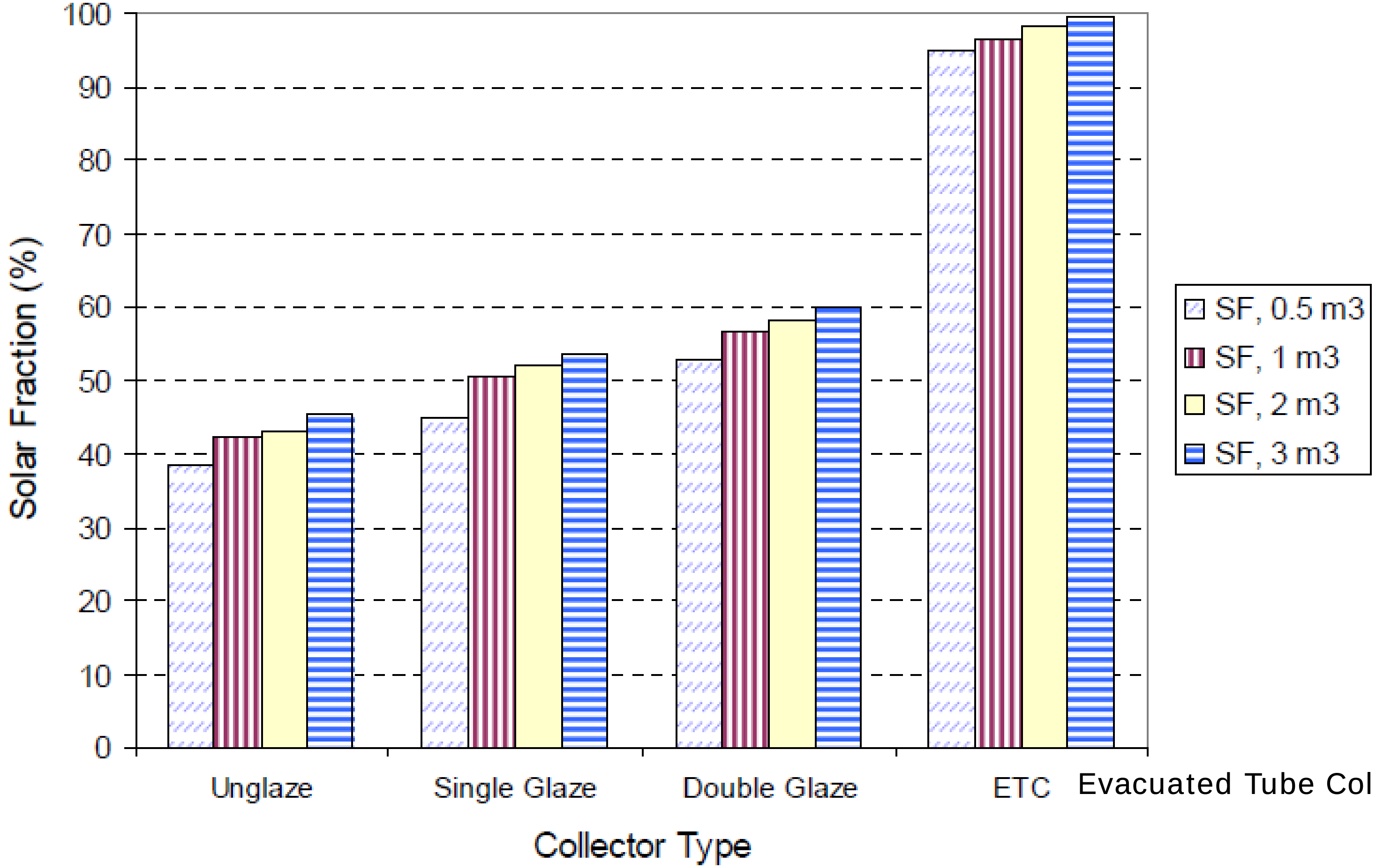
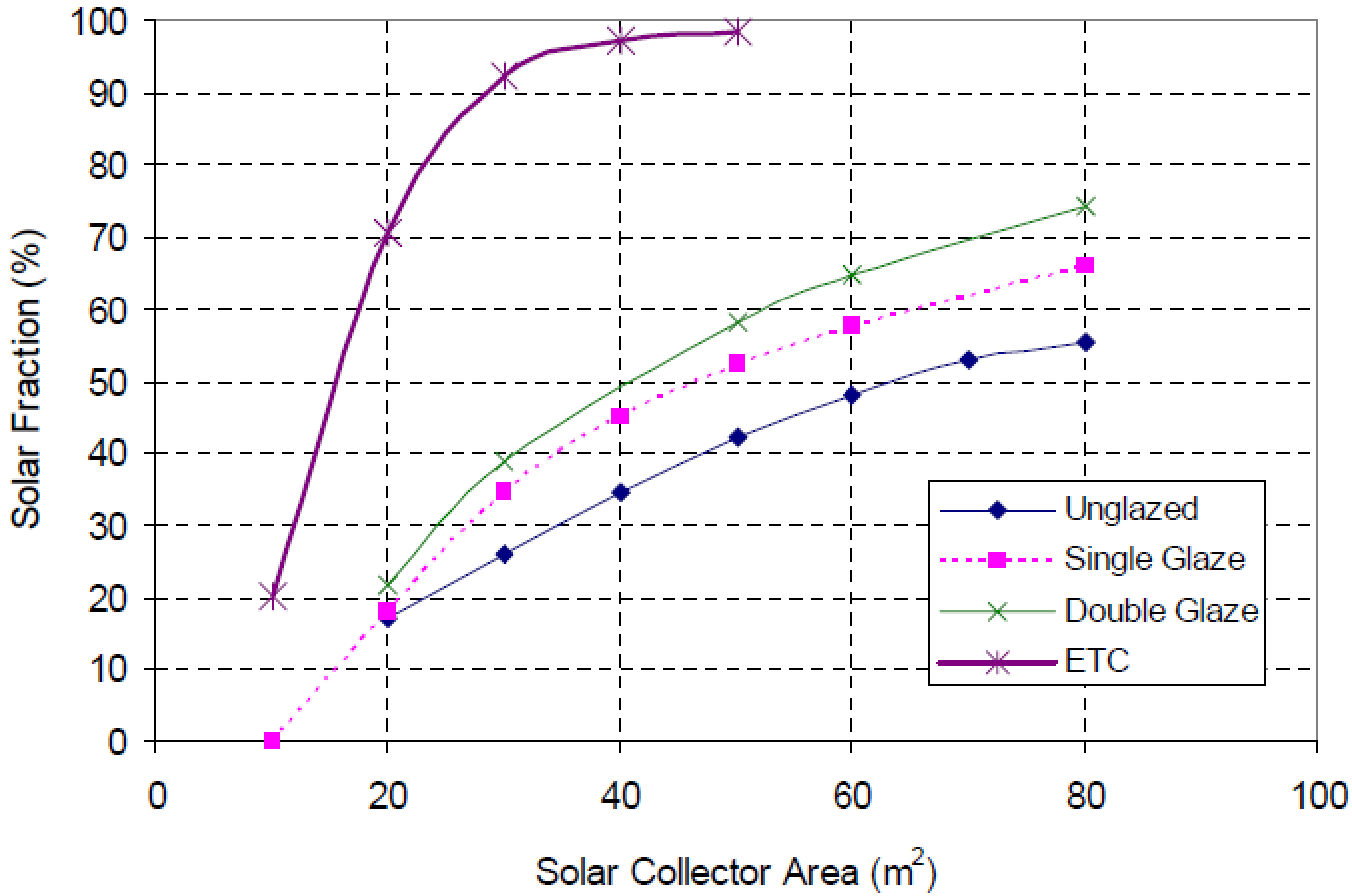
Ejector process: Effect of Storage Tank Size for Different Types of Solar Collectors at 50 m^2

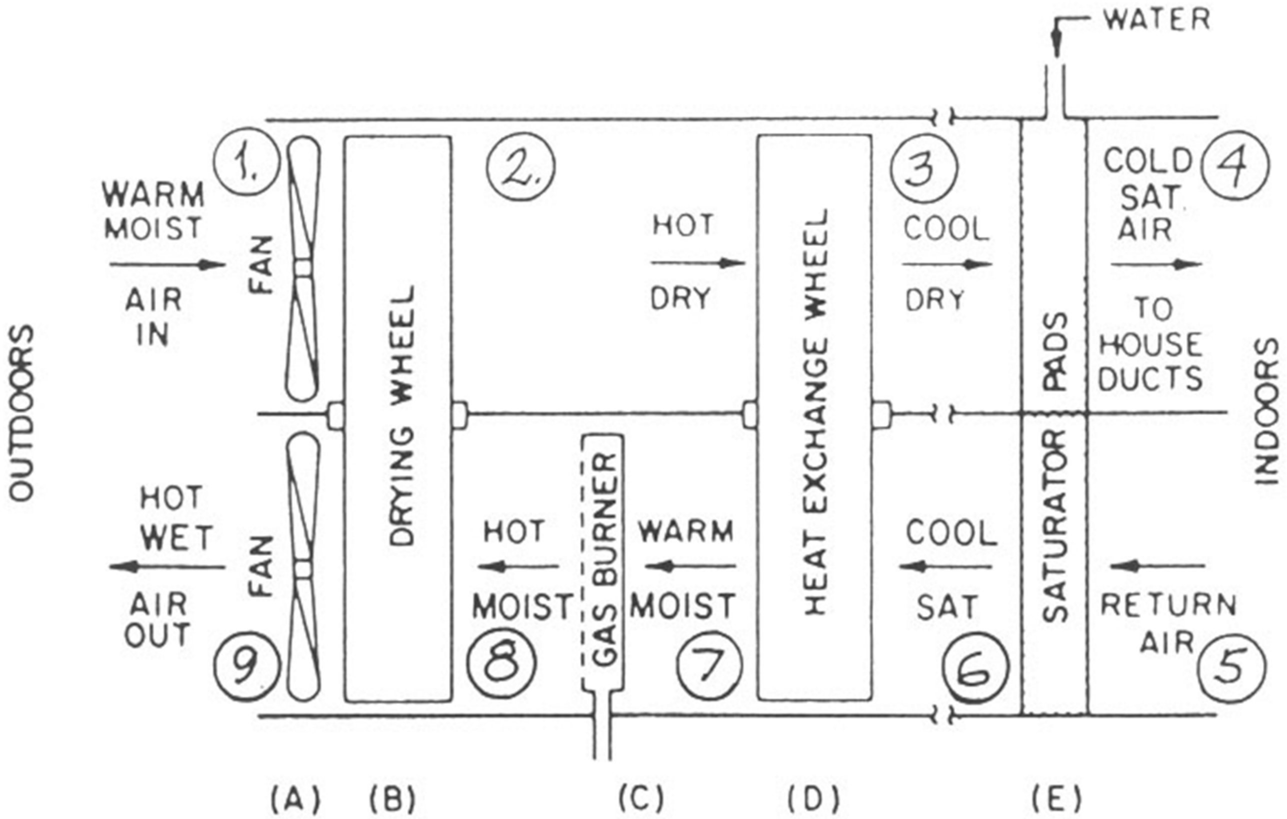


Evacuated Tube Collector

Solar Fraction for Different Types of Solar Collectors and Solar Collector Areas. Storage Tank Volume 2 m^3



Munters/Lizzy-process, type of desiccant cooling



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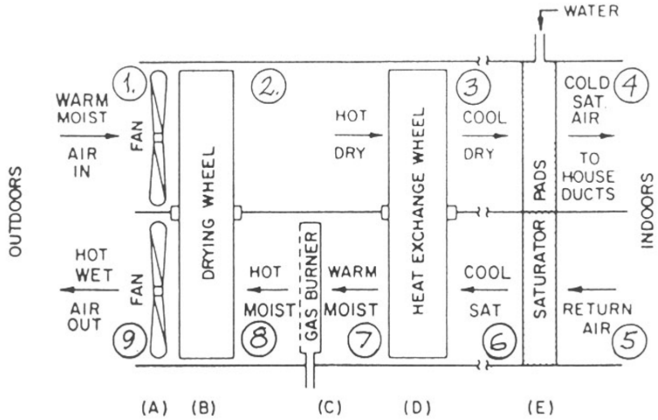
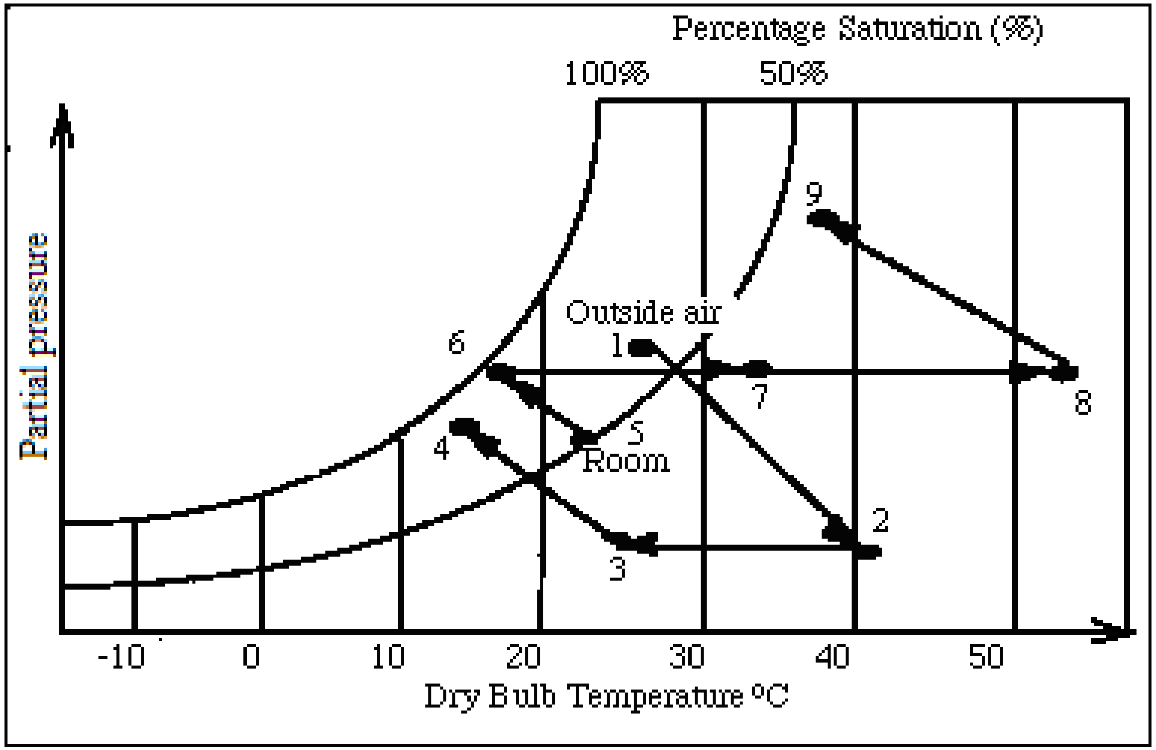
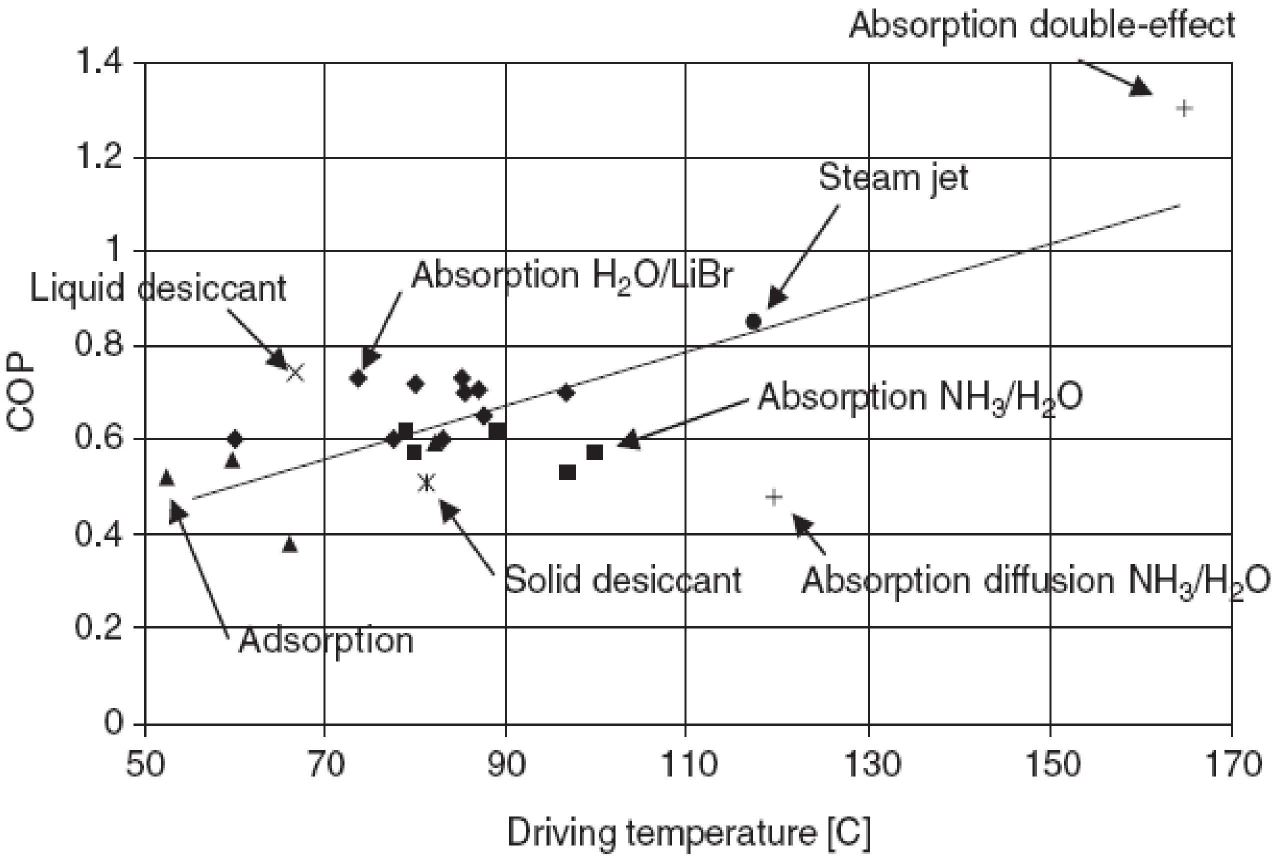
Munters/Lizzy-process, type of desiccant cooling



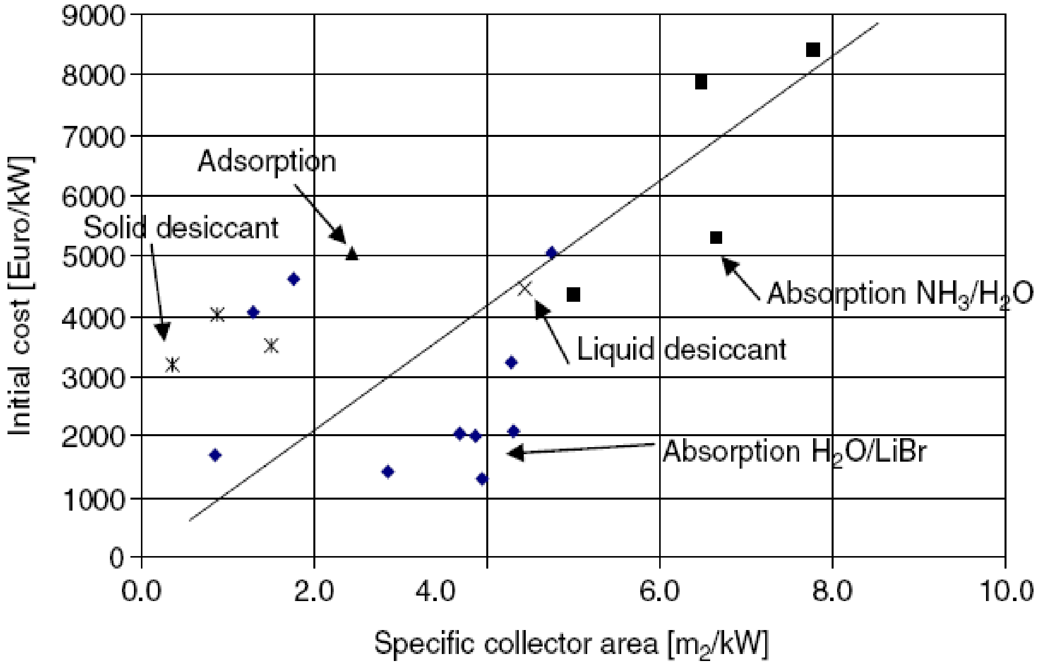


Comparison of $COP_{cooling}$ for different technologies for solar cooling



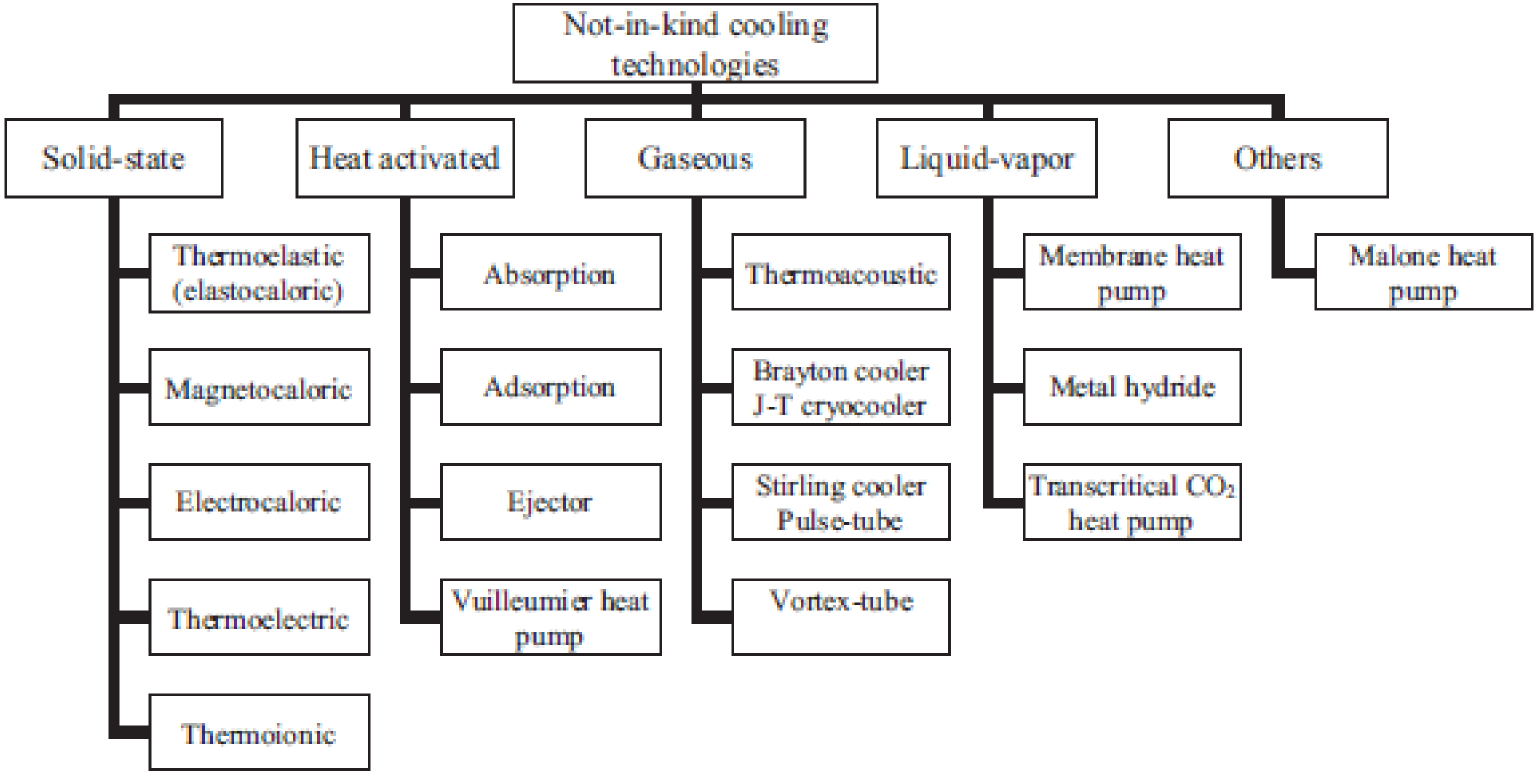
Balaras et al, Renewable and Sustainable Energy Reviews, 2007

Estimate of the system cost for solar driven processes.

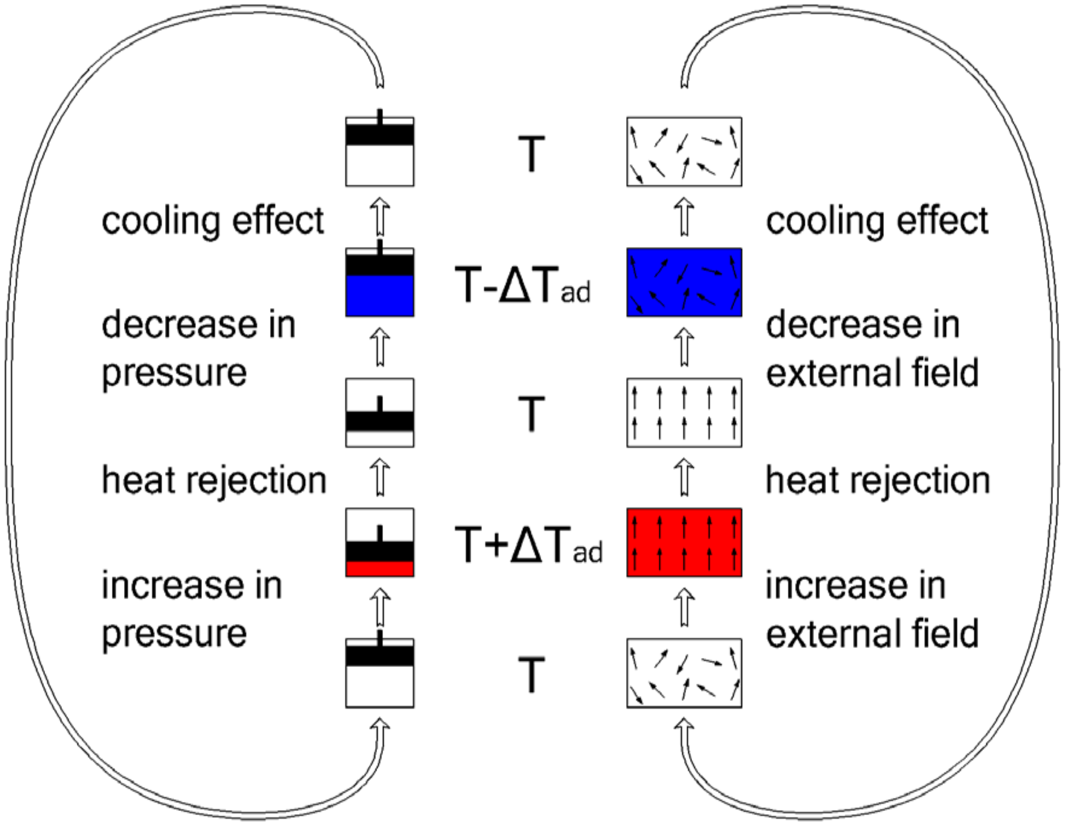


Balaras et al, Renewable and Sustainable Energy Reviews, 2007

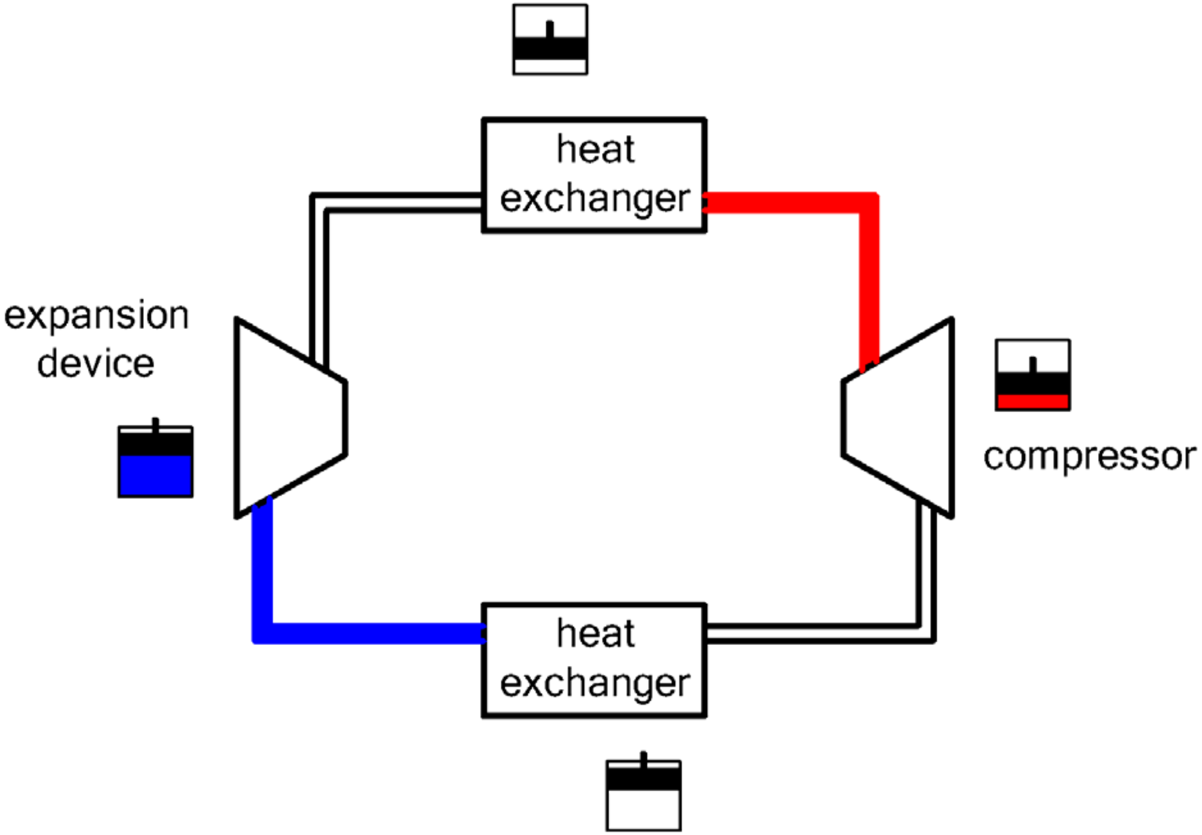
How about NIK (not in kind) technologies?



Magnetocaloric process



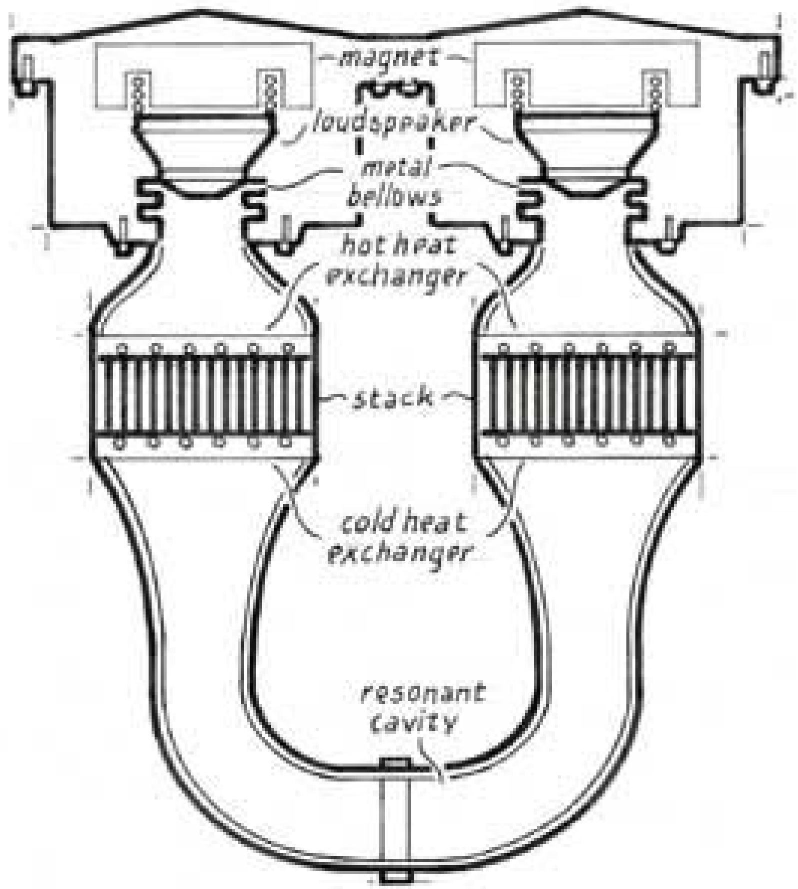
Reversed Joule-Brayton cycle (air-cycle)



Thermoacoustic refrigerator

- The Power of Sound » American Scientist.mht

- Capacity: 400W
-
- Min. temp. 0°C
  - (limited by risk of freezing)
- Carnot Efficiency: 17%

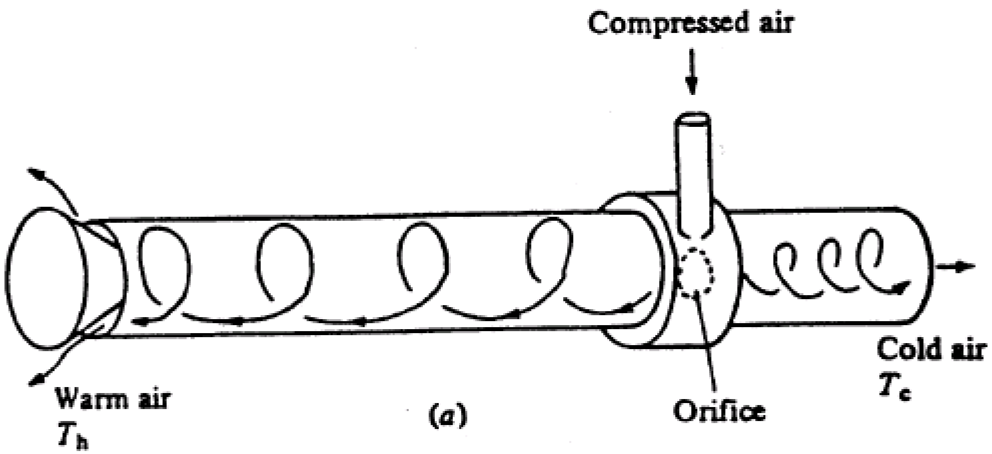


Stirling cycle

- Can achieve very low temperatures
- Has best relative performance at large temperature lifts
- Ideal Stirling cycle has the same COP as the Carnot cycle

Stirling-cooler

Hilsch Tube/Ranque Vortex Tube



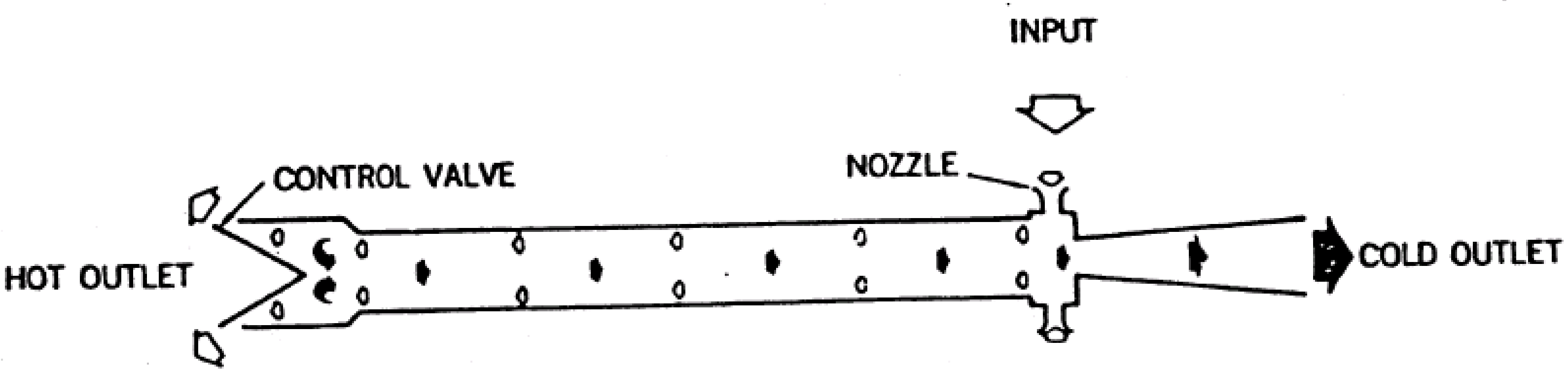


Figure 4.31. The principle of a Hilsch, or Ranque vortex tube.

Gifford – McMahon cooler

- Very low efficiency
- Very low capacities
- Very low temperatures
  - Single stage 30K
  - Two stage 10 K

Peltier process

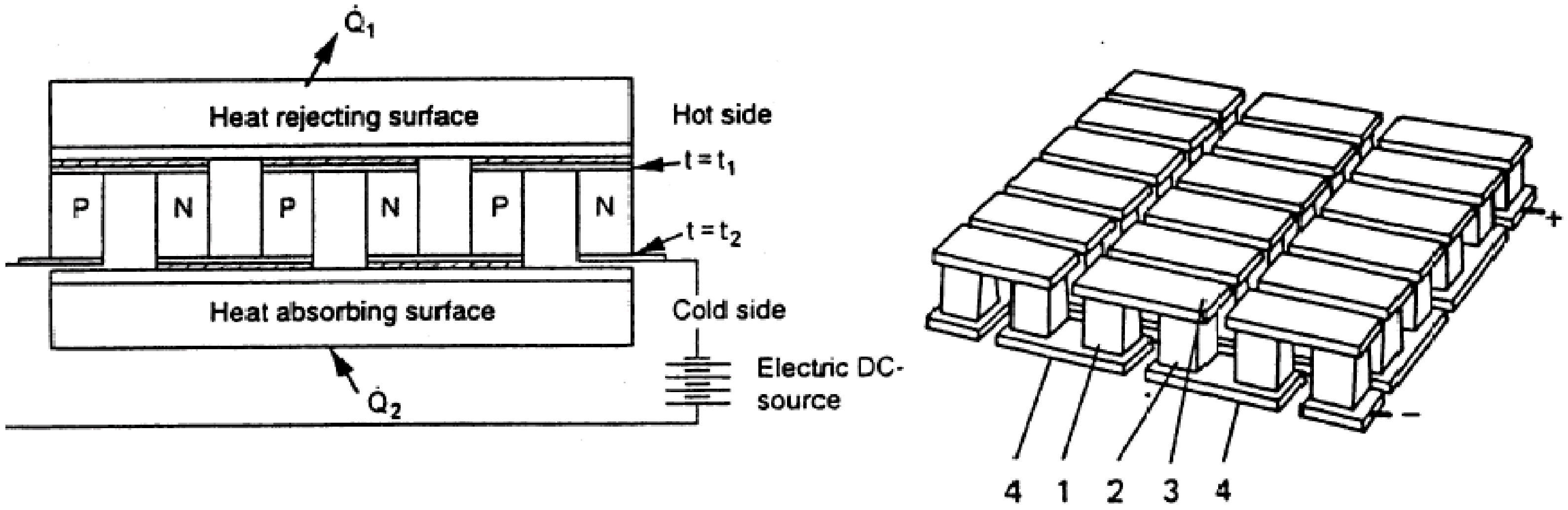
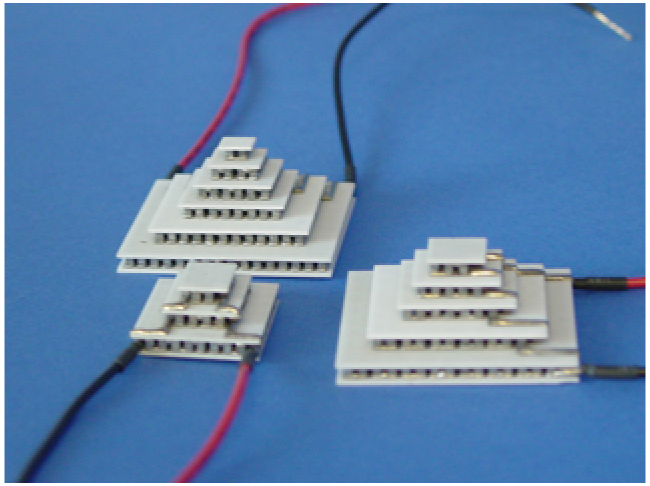


Figure 4.44. Scheme of a Peltier refrigerator. To the left are shown three pairs of Peltier elements electrically in series. To the right a commercial arrangement of a "Peltier block" is shown (no 1 and 2 are "N" and "P"-doped semiconductor materials; no 3 and 4 are electrical conductors made out of copper).

Peltier cooling



Rubber band cooling

Stretching causes heating

http://www.youtube.com/watch?v=Z6-CiSyI9oE

Rubber band cooling

Releasing causes cooling

http://www.youtube.com/watch?v=Z6-CiSyI9oE

Map of Not In Kind cooling technologies

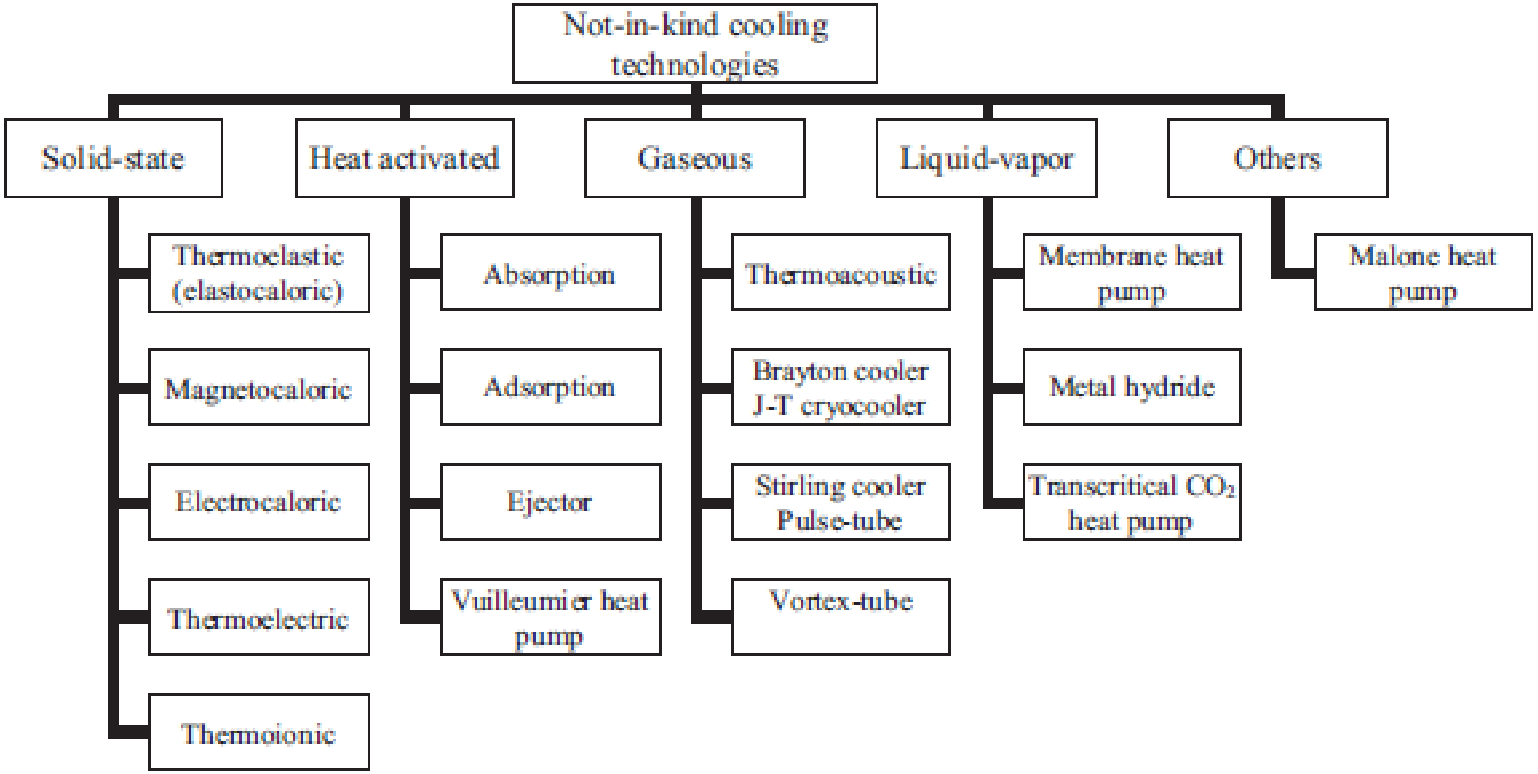


Fig. 1 – Various categories of not-in-kind cooling technologies.

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journal homepage: www.elsevier.com/locate/ijrefrig

Not-in-kind cooling technologies: A quantitative comparison of refrigerants and system performance

Suxin Qian [a], Dennis Nasuta [b], Adam Rhoads [b], Yi Wang [c], Yunlong Geng [c], Yunho Hwang [a,*], Reinhard Radermacher [a,b], Ichiro Takeuchi [c]

[a] Center for Environmental Energy Engineering, Department of Mechanical Engineering, University of Maryland, 4164 Glenn L. Martin Hall Bldg., College Park, MD 20742, USA
[b] Optimized Thermal Systems, Inc., 5000 College Park Avenue, Suite 3105, College Park, MD 20740, USA
[c] Department of Material Science and Engineering, University of Maryland, 1242 Jeong H. Kim Engineering Building, College Park, MD 20742, USA

Table 1 – Brief summary of the NIK cooling technologies in this study.

Technology	R&D status[a]	Cost/ complexity[a]	Refrigerant	Work input form	Possible heat recovery method	Possible work recovery method
Vapor compression (baseline)	Mature	Low	R410A	$\int p dv$	Suction-line heat exchanger	Expander
Elastocaloric	R&D, recently started	Moderate	Ni—Ti	$\int \sigma d\varepsilon$	Thermowave heat recovery	Multi-bed symmetri design
Magnetocaloric	Advanced R&D	High	Gd	$\int \mu_0 H dm$	Active magnetic regenerator	Multi-bed rotary be design
Electrocaloric	R&D, recently started	Moderate	P(VDF-TrFE-CFE)	$\int E dD$	Passive external regenerator	n/a
Thermoelectric	Well established, on-going materials research	Moderate	Bi—Sb—Te	n/a	n/a	n/a
Stirling	Manufacturing issues	Moderate	Helium	$\int p dv$	Regenerator	Piston
Brayton	Manufacturing issues	Moderate	Air	$\int p dv$	Recuperative heat exchanger	Turbine

[a] Based on Bansal et al. (2012) and Goetzler et al. (2014).

- “...Since the evaporation–condensation process is highly reversible, only the magnetocaloric materials and ideal gas under a Stirling cycle are competitive to the baseline....”
- “...The magnetocaloric cooling system is the only NIK technology superior to the baseline.....”

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Gulf Organisation for Research and Development

International Journal of Sustainable Built Environment

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Review

Status of not-in-kind refrigeration technologies for household space conditioning, water heating and food refrigeration

Pradeep Bansal*, Edward Vineyard, Omar Abdelaziz

Building Equipment Program, Oak Ridge National Laboratory (ORNL), One Bethel Valley Road, P.O. Box 2008, Oak Ridge, TN 37831-6070, USA

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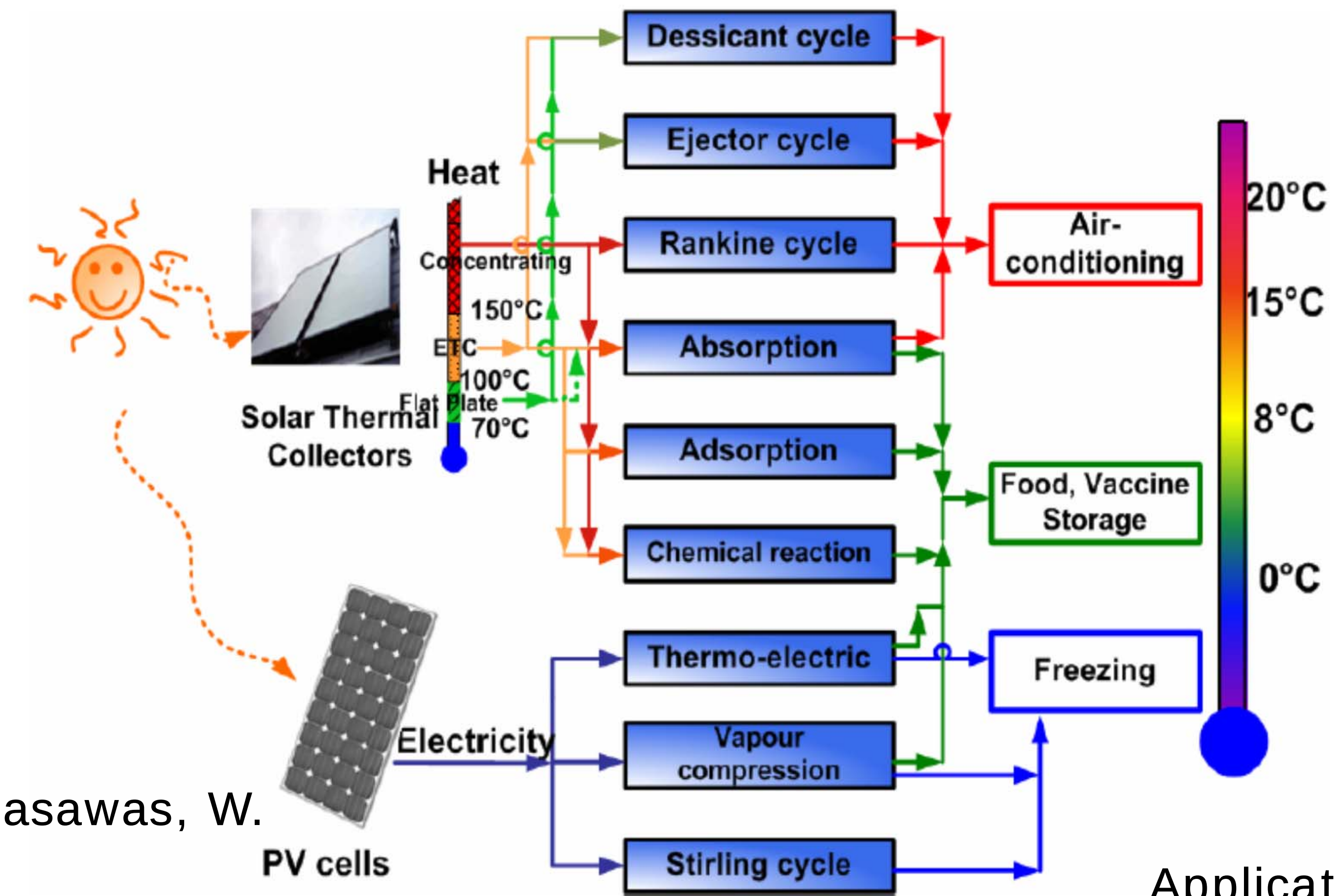
Elastocaloric	R&D, recently started	Moderate	Ni—Ti	$\int \sigma d\varepsilon$	Th
Magnetocaloric	Advanced R&D	High	Gd	$\int \mu_0 H dm$	Ac
Electrocaloric	R&D, recently started	Moderate	P(VDF-TrFE-CFE)	$\int E dD$	Pa
Thermoelectric	Well established, on-going materials research	Moderate	Bi—Sb—Te	n/a	n/
Stirling	Manufacturing issues	Moderate	Helium	$\int p dv$	Re
Brayton	Manufacturing issues	Moderate	Air	$\int p dv$	Re

[a] Based on Bansal et al. (2012) and Goetzler et al. (2014).

Main options for solar cooling



Pridasawas, W.

Applications for PV-based cooling increases with decreasing cost.

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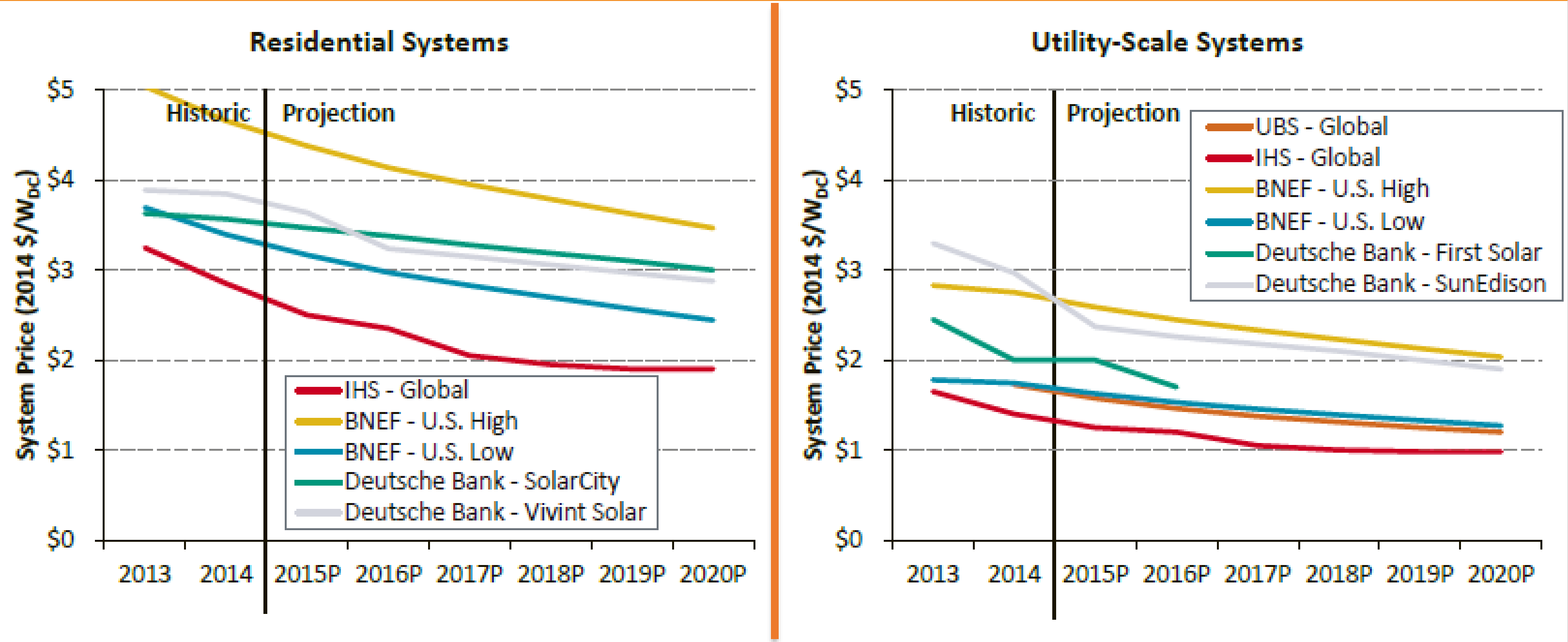
How about PV-driven vapor compression systems?

Analyst Estimates (2013-14) and Projections (2015–2020) of Average System Price



- Analysts expect the system prices of both utility-scale and distributed systems to continue to fall in the near future
  - Residential systems are expected to reach \$1.5/W - \$3.0/W and utility-scale systems are expected to reach \$1.00/W - \$1.75/W by 2020
  - Analysts project that from 2014-2020, system prices will fall 16%-33% for residential systems and 26%-36% for utility-scale systems, or between 3%-12% per year.

Decrease in PV prices will make PV-driven solar cooling more competitive

Advantages of PV-driven solar cooling:

- Well developed technology
- Components produced in large numbers
- Excess electricity can be stored in batteries or sent to the grid
- The system can be run wholly or partly from the grid when solar energy is not sufficient

Disadvantages

- High cost for PV (but decreasing)
- Low combined efficiency of PV plus vapor compression – large surface area needed

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Conclusions

- Several different cooling technologies are possible for solar cooling for air conditioning purposes. The most frequently used types have been discussed here.
- With continued decrease of the price of PV-panels, it has been concluded that in the near future, vapor compression systems driven by PV will require the lowest capital investment.
- For thermally driven systems, it has been concluded that for small- to medium sized systems, single- or double effect absorption systems based on water/lithium bromide are the most promising solution