Overview

• Solar Cooling
• Solar Collectors
• Solar Collector Performance
• Measurement and Monitoring Experiences
What is Solar Cooling?

How does Solar Cooling Work?

1. Solar Heat
2. Thermally-driven Cooling Process
3. Chilled Water
4. Conditioned Air

www.ausSCIG.org
Simple Operation Concept

MODE:

1. Demand ON
2. Collectors ON
3. Solar to load
4. Solar to storage
5. Dump OFF
6. Reverse storage
7. Collectors OFF
8. Storage empty
9. Auxiliary ON
10. Demand OFF

Collector field output

Heat-up system

From auxiliary (+Q_A)
From collector field (Q_C)
From storage (-Q_D)
From auxiliary (Q_A)

Demand (Q_L)

© CSIRO

Stine & Harrigan (1985)

Simple Solar Energy System

MODE:

1. Demand ON
2. Collectors ON
3. Solar to load
4. Solar to storage
5. Dump OFF
6. Reverse storage
7. Collectors OFF
8. Storage empty
9. Auxiliary ON
10. Demand OFF

Collector field

Constant-temperature control valve

Excess heat dissipation

Storage heat loss

Auxiliary heater

© CSIRO

Stine & Harrigan (1985)
Energy Losses in Solar Thermal Systems

Stine & Harrigan (1985)

Collector performance

Optical losses

Thermal losses

Component definition

Sub-system definition

System design

Resource assessment

Solar Insolation

Tracking

Reflection

Focusing

Transmittance

Absorbance

Convection

Radiation

Fluid transport

Storage

Power generation

System integration

Solar Collectors
### Solar Thermal Collectors

#### Type of Collector

<table>
<thead>
<tr>
<th>Type of Collector</th>
<th>Concentration Ratio</th>
<th>Typical Working Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plate collectors</td>
<td>1</td>
<td>≤70</td>
</tr>
<tr>
<td>High efficiency flat plate</td>
<td>1</td>
<td>60-120</td>
</tr>
<tr>
<td>collectors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed concentrators (non-imaging)</td>
<td>3-5</td>
<td>100-150</td>
</tr>
<tr>
<td>Parabolic trough collectors</td>
<td>10-50</td>
<td>150-350</td>
</tr>
<tr>
<td>Parabolic dish collectors</td>
<td>200-500</td>
<td>250-700</td>
</tr>
<tr>
<td>Central receivers</td>
<td>500-&gt;3000</td>
<td>500-&lt;1000</td>
</tr>
</tbody>
</table>

Source: Goswami 1999
Solar Collector Performance (Egypt)

Lupfert et al (2001)

Hourly Tracking and Alignment for a Day
Hourly Tracking and Alignment for a Year

- **Dual Axis Tracking**

- **Fixed with No Tracking**

- **NS Alignment with EW Tracking**

- **EW Alignment with NS Tracking**

Annual Tracking and Alignment

- Dual axis tracking (1.45 kWh/m²/y)
- NS alignment with EW tracking (1.27 MWh/m²/y)
- EW alignment with NS tracking (1.09 MWh/m²/y)
- Fixed with no tracking (0.93 MWh/m²/y)
### Transient Model of Chiller System Performance

<table>
<thead>
<tr>
<th>City</th>
<th>Sydney</th>
<th>Brisbane</th>
<th>Melbourne</th>
<th>Perth</th>
<th>Darwin</th>
<th>Adelaide</th>
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</thead>
<tbody>
<tr>
<td>Annual DNI</td>
<td>MWh</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Qsolar</td>
<td>MWh</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Annual cooling</td>
<td>MWh</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Utilisation h/y</td>
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<td></td>
<td></td>
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<tr>
<td>Utilisation d/y</td>
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<td>Utilisation %h/y</td>
<td></td>
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<tr>
<td>Utilisation %h/sun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual chiller efficiency</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual system efficiency</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **City**
  - Annual DNI
  - Qsolar
  - Annual cooling
  - Utilisation
  - Annual system efficiency

- **Values**
  - Sydney: MWh 83.5, 43.9, 27.2, 2042, 292, 23%
  - Brisbane: MWh 80.1, 43.6, 27.5, 2101, 295, 24%
  - Melbourne: MWh 77.9, 40.6, 24.8, 1979, 290, 23%
  - Perth: MWh 114.9, 61.8, 39.8, 2776, 334, 32%
  - Darwin: MWh 110.8, 62.1, 41.2, 2880, 333, 30%
  - Adelaide: MWh 109.2, 58.4, 37.2, 2638, 325, 30%
National Solar Energy Centre - Troughs

Australian Solar Collector Standards

- Test methods for solar collectors. Part 1: Thermal performance of glazed liquid heating collectors including pressure drop
  - AS2535.1:2007
- Solar water heaters – Domestic and heat pump – Calculation of energy consumption
  - AS4234-1994
- Solar and heat pump water heaters - Design and construction
  - AS/NZS 2712:2002
ASHRAE Thermal Efficiency Testing

- Methods of Testing to Determine the Thermal Performance of Solar Collectors
  - ASHRAE Standard 93-2003
- Covers
  - Liquid and air collectors
  - Indoor or outdoor testing
  - Concentrating and non-concentrating
    - “higher concentration ratios (near 3:1)”
  - Collector incidence angle modifier

ASHRAE Thermal Efficiency

Measurement
\[ \eta_g = \frac{m C_p (T_{out} - T_{in})}{A_g G_{bp}} \]

Analysis
\[ \eta_g = (A_a / A_g) F_R \left[ \tau\alpha \rho \gamma - (A_r / A_g) U_L \left( \frac{T_{in} - T_a}{G_{bp}} \right) \right] \]

ASHRAE Standard 93-2003
ASHRAE Thermal Efficiency Test Analysis

\[
\eta = \frac{(T_{in} - T_a)}{G (Aa / Ag) F_R (\tau \alpha), \rho \gamma}
\]

“Although a straight-line representation of the efficiency curve will suffice for many solar collectors, some collectors may require the use of a higher-order fit”

ASHRAE Standard 93-2003

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Day 2 – Solar Cooling Conference - 19/05/2009
Venue: CSIRO Energy Technology Auditorium, Newcastle
ASHRAE Thermal Efficiency

\[ y = -93.173x + 63.294 \]

\[ R^2 = 0.4169 \]

\[ y = -117.6x + 70.39 \]

\[ R^2 = 0.4924 \]

Australian Solar Cooling Interest Group (ausSCIG) Conference 2009
www.ausSCIG.org

Day 2 – Solar Cooling Conference - 19/05/2009
Venue: CSIRO Energy Technology Auditorium, Newcastle
NREL: ASHRAE Extension for Troughs

**Measurement**

\[ \eta_{th} = \frac{mC_p (T_{out} - T_{in})}{I \cdot \text{Area}} \]

**Analysis**

\[ \eta_{th} = \frac{Q}{I} = K \cdot M [A + B(\Delta T)] + C \frac{\Delta T}{I} + D \frac{\Delta T^2}{I} \]

- Measurement uncertainty
  - “… typically ± 2 to 5 percent”
  - “Minimising measurement uncertainty is not a trivial task”

Dudley (1994) and Lippke (1995)

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NREL Thermal Efficiency

![NREL Thermal Efficiency Graph](image)

- A=56.6
- \( R^2 = 0.504 \)
NREL Thermal Efficiency

![Graph showing thermal efficiency data with A=56.6]

© CSIRO

European Thermal Efficiency Test Analysis

• “Thermal solar systems and components – Solar Collectors”

• European Standard EN 12975-2

\[
\frac{Q_{\text{max}}}{A} = F^* K^* (\theta) G_\alpha + F^* K^* G_\gamma - c_1 \mu T_{\text{in}} - c_2 (T_n - T_u) + c_3 (E - \sigma T_u^4) - c_4 \frac{dT_u}{dt}
\]

Direct beam
Diffuse
Total horizontal
Conductive and convective heat loss
Forced convection heat loss
Radiation heat loss
Thermal fluctuation

© CSIRO

CEN (2001)
European Thermal Efficiency Test Analysis

Simplest Form

\[ Q = F' \tau \alpha_{en} G - c_1 (T_m - T_a) - c_2 (T_m - T_a)^2 \]

Fischer et al. (2006)

\[ \frac{Q}{A} = \eta_0 K_{th}(\theta) G_b + \eta_0 K_{th} G_d - c_1 (T_{avg} - T_a) - c_2 (T_{avg} - T_a)^2 - c_3 \frac{dT_{avg}}{dt} \]

Janotte et al. (2008)

\[ \frac{Q_{min}}{A} = F' K_{th}(\theta) G_b + F' K_{th} G_d - c_6 aG - c_1 (T_m - T_a) - c_2 (T_m - T_a)^2 - c_3 a(T_m - T_a) + c_7 (V_{\text{coeff}}) - c_5 \frac{dT_a}{dt} \]

Fischer et al. (2006) and Janotte et al. (2008)

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Measured and calculated heat gain

Fischer et al. (2006) and Janotte et al. (2008)
European Thermal Efficiency Test Analysis

Measured and calculated heat gain

\[ \text{Output} = \begin{cases} 0.945x + 26.804 & (\text{Fischer et al. (2006)}) \\ 0.9371x + 27.181 & (\text{Janotte et al. (2008)}) \end{cases} \]

\[ R^2 = 0.9455 \text{ (Fischer et al. (2006))} \]
\[ R^2 = 0.9393 \text{ (Janotte et al. (2008))} \]

Model Results

- **ASHRAE model**
  - collector efficiency at ambient temperature
    - 70% (63%)
    - \( R^2 = 0.49 \) (0.42)

- **NREL**
  - optical efficiency and selective coating absorptivity
    - 57%
    - \( R^2 = 0.50 \)

- **Fischer**
  - zero loss efficiency
    - 55% ±1
    - \( R^2 > 0.94 \)

- **Janotte**
  - collector efficiency factor
    - 49% ±1
    - \( R^2 > 0.95 \)
Comparison of Model Results

![Graph showing thermal efficiency vs. average temperature above ambient for ASHRAE, NREL, Fischer, and Janotte.]
Outlet Temperature: Low Temperature and Flow

NEP1 ON-sun 14Nov08

Temperature (°C)

Time of Day (h:m)

© CSIRO

Mixing: Low Temperature and Flow

Reynold’s Number

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Other Flow Rate Issues

- Initially used ambient pump flow calibration
- Flow rate varied with T, even when density considered
- No hot oil pump calibration service in Australia
- Flow calibration varied flow path, even though dP~1bar
- Intend to install coriolis flow meter

Temperature Sensors

- Initially used K-type thermocouples
  - A/D convertor in sun has cold-junction drift
- Changed to 4-wire Band-3 RTDs
  - but made incorrectly
- Changed to 4-wire Band-5 RTDs
  - NATA calibrated each RTD to its channel
Improve Temperature Measurement?

- ASHRAE specifies $dT \pm 0.1^\circ C$
  - How can this be measured over 20m?
- Using industrial A/D convertor for 3-wire RTD
  - At best $T \pm 0.1^\circ C$
- Tried differential $T$-type thermocouple
  - too much RF noise

Alignment and Tracking Accuracy

![Graph showing NEP2 Tracking Error 081210](image)
Standard vs Real Performance Measurement

- “Testing to Standards”
  - Short troughs where details can be perfected
- “Real performance measurement”
  - Equally valid but “less standard”

Summary

- Higher solar cooling **system** efficiencies will occur at higher temperatures
- Higher temperatures (quality) require more concentration
  - More collector area will give more heat (quantity)
- Collector specifications
  - Normally peak performance quoted
    - Efficiency at low temperature
    - Temperature at low efficiency
  - Performance at other times required
- No universal standard
  - “Consider the details”
Thank you