Reflectance & Absorptance

Table 3.1. Types of solar thermal collectors and their typical temperature range

<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 collector</td>
<td>1</td>
<td>≤70</td>
</tr>
<tr>
<td>High efficiency flat plate collector</td>
<td>1</td>
<td>60-120</td>
</tr>
<tr>
<td>Fixed concentrator</td>
<td>3-5</td>
<td>100-150</td>
</tr>
<tr>
<td>Parabolic trough collector</td>
<td>10-50</td>
<td>150-350</td>
</tr>
<tr>
<td>Parabolic dish collector</td>
<td>200-500</td>
<td>250-700</td>
</tr>
<tr>
<td>Central receiver</td>
<td>500-&gt;3000</td>
<td>500-&gt;1000</td>
</tr>
</tbody>
</table>

Figure 3.12. Schematic diagram of solar collector.

Optical Concentration Ratio, \( CR_o = \frac{I_r}{I_a} = \frac{\text{solar flux received}}{\text{solar flux at aperture}} \) takes into account optical losses

Geometric Concentration Ratio, \( CR_a = \frac{A_r}{A_a} \)
Figure 3.17. Evacuated-tube solar energy collectors: (a) flat plate; (b) concentric tubular; (c) concentrating; (d) vacuum bottle with slip-in heat exchanger contacting rear surface of receiver.
Energy Balance (Flat Plate Collector)

\[ I_{c} \cdot A_{c} \cdot T_{s} \cdot \alpha_{s} = \frac{dE}{dt} + \Delta E_{\text{fluid}} \]

- \( I_{c} \cdot A_{c} \): Rate of sensible heat accumulation/loss in collector
- \( T_{s} \cdot \alpha_{s} \): Effective solar transmittance of the collector covers
- \( \frac{dE}{dt} \): Solar insolation

\[ \Delta E_{\text{fluid}} = m \cdot C_{p} \cdot AT \]

- \( m \cdot C_{p} \cdot AT \): Rate of useful energy delivered to fluid

\[ \eta_{c} = \frac{\Delta E_{\text{fluid}}}{I_{c} \cdot A_{c}} \]

- \( \eta_{c} \): Rate of useful energy delivered to fluid divided by total incident solar energy

Flat Plate Collectors
- Liquid-type
- Air-type

- Glazing:
  - Transmits shorter wavelength solar radiation, but blocks longer wavelengths from absorber
  - Reduces convective heat transfer losses
  - Most common material is glass

Tubular Collectors (Fig 3.17, 6k&k)

- Evacuated-Tube Collectors
  - Minimize losses
  - Proposed in 1909; 2 concepts still sold today
  - Internal reflectivity serves as pseudo-concentrator

Concentrators

Optical concentration ratio, \( CR_{o} = \frac{I_{a}}{I_{a}} \)

Geometric concentration ratio, \( CR_{g} = \frac{A_{o}}{A_{r}} \)
\[ \rho = \text{reflectance} \]
\[ \tau = \text{transmittance} \]
\[ \alpha = \text{absorptance} \]
\[ \epsilon = \text{emittance} \]

\[ \epsilon_\lambda(\theta, \phi) = \frac{I_\lambda(\theta, \phi)}{I_{b,\lambda}} \]
\[ \phi = \text{azimuthal angle} \]
\[ \theta = \text{polar angle} \]

\[ \epsilon = \frac{1}{4\pi} \int_0^\infty \epsilon_\lambda \, E_\lambda \, d\lambda \]

\[ \alpha_\lambda(\theta, \phi) = \frac{I_\lambda(\theta, \phi)}{I_{i,\lambda}(\theta, \phi)} \]
\[ \alpha(\theta, \phi) = \int_0^\infty \alpha_\lambda(\theta, \phi) \, I_{i,\lambda}(\theta, \phi) \, d\lambda \]

\[
\text{not just a surface property} \]
\[ \text{can design selective surfaces which absorb radiation from one source at a greater rate than from another source} \]

\(\rho\) can be specular or diffuse.
Solar - Thermal Conversion

Solar Radiation converted to heat → low temp → flat plate → hot water
high temp → thermal reservoir for power cycle

Solar - Thermal Central Receiver Systems
- Large field of heliostats (reflecting mirrors) → redirect solar energy flux to a central receiver
- Heliostats individually controlled to follow sun
- Heat absorbed by working fluid
- Typically has storage for nighttime & cloudy periods
- High peak power needs excess power bypassed to thermal storage & greatest solar incidence

Solar - One - 10 MWe (peak) pilot plant in Mojave Desert
- Operational in mid-1982

LOCA → damage to receiver

Receiver → subject to peak energy flux of 300-700 kW/m² (eq. 12-15)
- Base: spillage → reflectors miss central receiver
  - Tracking errors / control system errors
  - Wind effects
  - Steering backlash
  - Reflection → energy scattered back by receiver
  - Convection → natural & wind-driven (forced)
  - Radiation → emittance by receiver
  - Conduction → heat conduction through structural members, etc.

Design optimization is critical:
- Larger receiver has less spillage, but greater radiation & convection losses
- Smaller cavity has less convection & radiation losses, but greater conduction losses

Cavity ~ 90% efficient (more costly & complex) → Solar One, 240 tonnes each
External ~ 80% efficient
Working Fluids: (Steam)

(2) Liquid Metals (Na)
- High heat transfer coefficient
- Boiling point 1580°F (860°C)
- Melting point is 98°C (210°F)
- Thus, require freeze protection
- Chemically active -> requires cover gas such as Ar
- 5400°C (1000°F) as single phase
- To steam generator
- Low pressure

(3) Molten Salts
- Low pressure system
- High volumetric heat capacities
- Melting point 140-220°C (290-430°F)

(4) Gases (CdCl₂)
- Often > 840°F (450°C)
- Low pressure losses
- Low heat capacities -> requires large flow
- Increasing pressure increases both heat capacity & flow losses
- Brayton cycle or steam generator

(5) Oils (Thermol 66 & Carokna HT-43)
- Low corrosion
- Flammable decomposing
- Suffer pyrolic damage (decompose at high temp)
- Operated in only a narrow-temp range
- 740 to 315°C (1400-600°F)
- Steam generator
Figure 8.1. Solar furnace used by Lavoisier in 1774. Illustration courtesy of Bibliotheque Nationale de Paris. Lavoisier, *Oeuvres*, vol. 3.

Figure 8.2. Parabolic collector powered a printing press at the 1878 Paris Exposition.
Figure 8.3. Irrigation pumps were run by a solar-powered steam engine in Arizona in the early 1900s. The system consisted of an inverted cone that focused rays of the sun on the boiler.

With the increasing availability of low-cost oil and natural gas, interest in solar energy for power production waned. Except for C.G. Abbott, who exhibited in 1936 a 1/2-hp solar-powered engine at an International Power Conference in Washington, D.C. and in 1938 in Florida, an improved, somewhat smaller version with a flash boiler, there was very little activity in the field of solar power between 1915 and 1950. Interest in solar power revived in 1949 when, at the centennial meeting of the American Association for the Advancement of Science in Washington, D.C., one session was devoted to future energy sources. At that time, the potentials as well as the economic problems of solar energy utilization were clearly presented by Daniels [7]. Some important conferences that considered solar power generation were held by UNESCO in 1954, the Association for Applied Solar Energy in 1955, the U.S. National Academy of Sciences in 1961, and the United Nations in 1961. In addition, a research and development program was supported by the National Aeronautics and Space Administration to...
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SOLAR THERMAL ELECTRIC: PARABOLIC TROUGH
TYPES OF SOLAR ENERGY POWER PLANTS

Parabolic Trough Solar Field
Solar Collection Assemblies

As the Earth rotates, the solar collectors need to be adjusted to optimize the angle of the sun to the collection surface. The mirrors are adjusted about once every minute.
**Figure 3.25.** Focusing of parallel rays of light using circular mirrors with different rim angles.

**Figure 3.26.** Concentration by parabolic reflector for a beam (a) parallel to the axis of symmetry, and (b) at an angle to the axis.

- **Compound parabolic concentrator (CPC)**
- **Non-imaging concentrator**

**Figure 3.34.** Ray trace diagrams of the tubular CPC collector at three values of incidence angle: (a) normal incidence, (b) intermediate, and (c) the limit of acceptance. (Courtesy of W. McNew, Argonne National Laboratory.)

- **fewer optical losses**
Early Argonne Design

External reflector CPC coupled to evacuated dewar-type absorber with spectrally selective coating
The measured values are about 5 percentage points below the performance predicted by raytrace results.

Figure 3.36. Measured optical efficiency of a PTC in north-south and east-west orientations [65]. Adapted from Kreider [43].
Figure 3.38. Examples of commercially developed multifaceted and stretched membrane paraboloidal concentrators: (a) multifaceted mirror.

Figure 3.38. (continued) (b) Stretched single membrane (Schlaich Bergermann & Partner (Germany)).

optical concentration ratio,

\[ CR_o = \frac{J_r}{J_a} \]

geometric concentration ratio,

\[ CR = \frac{A_{concentrator}}{A_{absorber}} \]

\( CR_o \) gives true concentration because it accounts for the optical losses due to reflection & refraction.

\( CR_o \) unrelated to receiver area & thus provides no information on thermal losses which are proportional to area.

\[ Q_u = \%_c I_c A_a - U_{c(T_c-T_a)} A_r \]

\[ \eta_{optical} = \frac{Q_u}{\text{solar radiation}} \]

\[ \%_c = \frac{Q_u}{I_c A_a} = \% - \frac{U_{c(T_c-T_a)}}{I_c} \frac{1}{CR} \]
Combined-Cycle Systems

Combined cycles are those using a combination of Brayton- and Rankine-cycle-type powerplants with the gas turbine of the Brayton cycle occupying the high-temperature end and exhausting to the steam generator of the Rankine cycle (Sec. 8-8).

Figure 13-25 shows a combined-cycle with a two-shaft gas turbine and a solar central-receiver system. Atmospheric air is compressed by the compressor into a high-temperature receiver where it is heated to perhaps 1500°F (815°C). It then expands through the compressor turbine and through the power turbine, which drives an electric
Figure 13-19 Point-focus distributed-type concentrators: (a) thin plastic film reflecting panels by Boeing, Inc. (b) Fresnel-lens concept by E-Systems Corporation [125].
Solar Water Pumping System

Figure 3-21  Solar powered water pumping station
SOLAR THERMAL ELECTRIC: DISH STIRLING ENGINE
SOLAR THERMAL ELECTRIC: CENTRAL RECEIVER
SOLAR THERMAL ELECTRIC: CENTRAL RECEIVER
Figure 13-18 Overall view of Solar One, a 10-MW(e) (peak) central-receiver pilot powerplant near Barstow, California.

Figure 13-10 Optimum heliostat field shapes oriented for the northern hemisphere: (a) small plant < 100 MW(t) and (b) large plant > 5000 MW(t). Dimensions in multiples of receiver-tower height $H$ [118].
Figure 13-7 Schematic of a solar-thermal central-receiver system powerplant.

to the storage system, instead of to the receiver, where it vaporizes for use in the turbine. Proper valving in the system allows operation in either mode.

Because solar-thermal electric plants are most likely to be located in hot arid areas where land is plentiful (for the large heliostat field) and where the sun’s energy is plentiful and dependable, but where cooling water is scarce, the condenser was most probably cooled by a dry-cooling tower. Such towers are less effective and reduce in Rankine cycle efficiency but require practically no makeup water.

In the next five sections, the major subsystems of the central-receiver concept will be presented, with many of the design features and data obtained from the Solar One plant experience. Solar One is a 10-MW(e) (peak) pilot plant located in the Mojave Desert in California that went into operation and testing in mid-1982 (Sec. 13-
Figure 8.18. Flow of heat-transfer fluid through the SEGS VIII and IX plants (Adapted from [8]).

Figure 13-13 Typical central receivers: (a) four-aperture cavity type and (b) external type [118].
The Heliostat Field

The *heliostat field* supplying a central receiver, also called the *collector subsystem*, has a shape that must be optimized to suit the topography of the area and the power level of the plant. The field may be on a flat terrain, on the side of a hill, etc. In the northern hemisphere, the noontime sun is always south of the central-receiver tower, so a north field is usually most cost-effective because its cosine loss (below) is least.

For small plants, of less than 100 MW of thermal-energy input, a totally north field is optimum (Fig. 13-10a). As plant size increases, the field becomes larger and many heliostats are farther from the tower. The atmosphere around the plant attenuates the reflected radiation from the most distant north heliostats. The receiver input can then be improved by relocating the distant heliostats to the east and west of the tower and, as plant size increases further, to the south of it (Fig. 13-10b). In such cases, the additional cosine loss is less than the atmospheric attenuation loss from the distant north heliostats.

![Diagram of a typical glass-heliostat system](image1)

Figure 13-8 A typical glass-heliostat system, rear view *(McDonnell Douglas.)*

![Diagram of a typical plastic heliostat system](image2)

Figure 13-9 A typical plastic heliostat system *(Boeing.)*
Figure 8.20. Schematic of Solar Two central-receiver plant configuration (Adapted from [8]).

Figure 8.21. Schematic of the Shenandoah Solar Total Energy Project [8].