Development of a High Flux Solar Furnace Facility at CSIRO for Australian Research and Industry

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ABSTRACT

CSIRO has developed a concept proposal for the construction of an Australian High Flux Solar Furnace. The proposal is designed to meet the needs of both research and industry by providing the critical infrastructure required to develop and optimise technologies to exploit Australia’s high quality solar resource. The furnace would be hosted by CSIRO at the National Solar Energy Centre in Newcastle, and could be available for the first experiments within two years of project approval. The design will be developed in consultation with international solar experts to ensure that it is both state-of-the-art and relevant to the needs of local stakeholders.

The Australian High Flux Solar Furnace will allow Australian companies and researchers to explore the next generation of high temperature solar and thermal technologies. There are only a handful of such facilities worldwide and none in the southern hemisphere. The facility will also provide capability for high temperature materials development with potential application to many industries including higher temperature cycles for solar thermal power generation, metal production and ore smelting.

Keywords Solar furnace, concentrated radiation, flux, high temperature.

INTRODUCTION

Solar furnaces are advanced facilities which produce concentrated radiation fluxes more than 5000 times that of the sun (“5000 suns”), and surface temperatures over 2700 K. A solar furnace has two main optical elements. The first is a flat heliostat that tracks the sun and uniformly illuminates the second element – the concentrator - with reflected light. The concentrator consists of a number of very precise concentrating facets, which focus the energy onto a spot as small as 10 to 15 cm in diameter.

Two basic configurations are possible with a solar furnace, and each has advantages and disadvantages. In an on-axis design, the focal point is located between the heliostat and the concentrator, as shown in Fig. 1. This design has the advantage of having a symmetrical beam distribution away from the focal point, and can be uniformly attenuated by placing a louver shutter between the heliostat and concentrator. However, the approach has several disadvantages due to the location of the focus, and hence the experimental platform, between heliostat and concentrator – this blocks some of the light from the heliostat (placing constraints on the size of the experimental platform), and can be difficult to access as it is usually several metres above ground level.
In an off-axis design, the focal point is located away from the light path between heliostat and concentrator as shown in Fig. 2. This design avoids the issue of the experimental set-up blocking light from the heliostat and enables the focus to be located inside a building, which makes experimental set-up and monitoring far more convenient. The main disadvantage of this design is that the beam is asymmetric away from the focal plane. Furthermore, maximum optical performance cannot be achieved in an off-axis design.

**Fig. 1:** Two stage on-axis design as used at Sandia National Laboratories (USA) and Plataforma Solar de Almeria, Spain (PSA).

**Fig. 2:** Off-axis design of the DLR Solar Furnace near Cologne, Germany (Source: DLR, reproduced with permission).

**Fig. 3** shows the concentrator at the DLR Solar Furnace. In this case the concentrator is built of many smaller hexagonal facets. These are very precise concave facets which are 554 mm across the flats. The facets have a spherical curvature, and individual facets
have position specific focal lengths as might be inferred from Fig. 2 with the differing distances to the focus.

Fig. 3: Photograph showing hexagonal facets of concentrator, DLR furnace (Source: DLR, reproduced with permission).

Tab. 1 lists the known solar furnace facilities around the world. It is also reported that facilities are currently being constructed in Mexico and South Korea, although details are not available. There are no furnaces in the power range of 50-500 kW so this is potentially a good niche for an Australian solar furnace to fill.

Tab. 1: Solar furnace facilities (>10 kW) worldwide.

<table>
<thead>
<tr>
<th>Institute</th>
<th>Location</th>
<th>Power kW</th>
<th>On/Off Axis</th>
<th>Max conc.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROMES</td>
<td>France</td>
<td>1000</td>
<td>On Axis</td>
<td>10,000</td>
<td>PROMES-CSNR 2010</td>
</tr>
<tr>
<td>Uzbek Ac. Sciences</td>
<td>Uzbekistan</td>
<td>1000</td>
<td>On Axis</td>
<td>5,100</td>
<td>Abdurakhmanov &amp; Akbarov 1995</td>
</tr>
<tr>
<td>PSA</td>
<td>Spain</td>
<td>45</td>
<td>On Axis</td>
<td>3,000</td>
<td>Fernández- Reche et al. 2006</td>
</tr>
<tr>
<td>PSI</td>
<td>Switzerland</td>
<td>40</td>
<td>On Axis</td>
<td>5,000</td>
<td>Haueter et al. 1999</td>
</tr>
<tr>
<td>PSI</td>
<td>Switzerland</td>
<td>17</td>
<td>On Axis</td>
<td>4,000</td>
<td>Ries &amp; Schubnell 1990</td>
</tr>
<tr>
<td>DLR</td>
<td>Germany</td>
<td>25</td>
<td>Off Axis</td>
<td>5,500</td>
<td>Neumann &amp; Groer 1996</td>
</tr>
<tr>
<td>Sandia</td>
<td>USA</td>
<td>16</td>
<td>On Axis</td>
<td>5,000</td>
<td>Sandia 2006</td>
</tr>
<tr>
<td>WIS</td>
<td>Israel</td>
<td>15</td>
<td>On Axis</td>
<td>10,000</td>
<td>Levitan et al. 1989</td>
</tr>
<tr>
<td>NREL SERI</td>
<td>USA</td>
<td>10</td>
<td>Off Axis</td>
<td>5,000</td>
<td>Lewandowski et al. 1991</td>
</tr>
</tbody>
</table>
APPLICATIONS OF A SOLAR FURNACE

A solar furnace has a number of significant advantages compared to using a heliostat field and tower based experimental platform:

• Extremely precise control of concentration and uniformity of radiation
• Faster set up / tear down times for experiments
• More precise measurements of technical parameters using sensitive instruments rather than average engineering values in the field
• Superior control over emissions from experiments and the possibility of exhaust gas scrubbing for removal of undesirable species
• Ability to conduct experiments at intermediate power level for proof of concept testing under precise conditions before progressing to tower based experiments
• Smaller balance of plant equipment for the key processes

CSIRO has compiled a list of possible applications for its planned solar furnace. These are based on CSIRO’s and worldwide research into renewable and solar applications. A solar furnace is invaluable for the development of the following technologies:

• Solar electricity production from high temperature cycles using working fluids like supercritical steam, air or helium
• Stirling cycle evaluation and component design
• High temperature heat transfer fluids which can store solar energy as thermal energy at higher temperatures than are possible with current molten salt technologies
• Thermochemical processes for storage of solar energy in fuels
• Reforming of methane and other hydrocarbons
• Gasification of coal and petroleum coke
• Pyrolysis of biomass to provide feedstocks for renewable liquid fuels
• Water splitting cycles for renewable hydrogen production

It is also anticipated that the wider research community and Australian industry will gain significant benefit, especially for the development of processes and materials for the following areas:

• Industries that use high temperature processes e.g., smelting, blast furnaces
• High temperature materials e.g., refractory materials and ceramics
• Modification of material surfaces to obtain desirable properties e.g., passivating films
• Applications involving high concentrations of solar/electromagnetic radiation e.g., aerospace, military

Figure 4 shows two experiments conducted at the DLR solar furnace in Cologne.
Fig. 4: High temperature thermochemical experiment (left) and photochemical experiment (right) at DLR furnace (Source: DLR, reproduced with permission).

SITE CONSIDERATIONS: DIRECT IRRADIANCE

A major consideration in terms of locating a solar furnace is to ensure that the site is suitable. One criterion is direct normal irradiance because this is the energy source for a solar furnace: preferred sites for solar technology deployment would have daily direct irradiance energy (DNI) values above 6 kWh/m²/day.

However, high DNI is only one parameter that impacts the operation of a solar furnace. Far more important is convenient access for users and good support infrastructure with expert personnel, workshops and services. These considerations argue for the furnace being located in an existing research facility in or near a major metropolitan centre with good transport connections. Efficient operation in areas with DNI below 6 kWh/m²/day is possible through the optimisation of solar resource usage and experimental scheduling. The CSIRO site at Newcastle, NSW has been evaluated as it is currently a national leader for solar technology development with considerable existing expertise, excellent infrastructure, and is close to a major regional airport.

Irradiance from NASA Satellite Data

NASA publishes global maps and tabulated values of irradiance data. The resolution of these data is poor but they are useful for initial site assessment. Data for the proposed Newcastle site, close to the ocean, are shown in

Tab. 2, confirming that the location has somewhat lower DNI values than an ideal site.

Tab. 2: Solar irradiance data retrieved from NASA satellite measurements

<table>
<thead>
<tr>
<th></th>
<th>kWh/m² per Day</th>
<th>kWh/m² per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Normal Energy DNI</td>
<td>4.9</td>
<td>1790</td>
</tr>
<tr>
<td>Global Horizontal GHE</td>
<td>4.5</td>
<td>1624</td>
</tr>
<tr>
<td>Diffuse Horizontal DHE</td>
<td>1.7</td>
<td>610</td>
</tr>
<tr>
<td>Global Tilted to Latitude</td>
<td>4.9</td>
<td>1770</td>
</tr>
</tbody>
</table>
CSIRO Irradiance Measurements

While a useful guide, satellite data needs to be compared with and calibrated against ground-based measurements. CSIRO continually monitors solar irradiance at the Newcastle site as part of the site infrastructure. The average values over 1200 daily measurements between 2006 and 2009 are shown in Tab. 3. The mean values are slightly lower than the NASA data but correspond well. The available DNI at CSIRO (1570 kWh/m² per year) is significantly higher than DLR’s Cologne site (800 kWh/m² per year) but lower than the Plataforma Solar site in southern Spain (2100 kWh/m², Trieb et al. 2009).

<table>
<thead>
<tr>
<th></th>
<th>kWh/m² per Day</th>
<th>kWh/m² per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Normal Energy DNI</td>
<td>4.3</td>
<td>1570</td>
</tr>
<tr>
<td>Global Horizontal GHE</td>
<td>4.4</td>
<td>1606</td>
</tr>
</tbody>
</table>

DESIGN CONSIDERATIONS

This proposal has been developed to offer the most flexible solution to the demands of a wide range of possible experiments. An off-axis design is preferred as it enables:

- A dedicated experimental chamber which can be safely secured from other parts of the support buildings such as the control room;
- Precise control of the incident radiation using an attenuation louver between the concentrator and the experiment;
- Accurate measurement systems can be installed to determine the concentrated radiation profile;
- Simple experimental set-up and change out since the focus can be set up at 1.2 m (or so) above floor level; this is much easier than with an on-axis system or with a heliostat and tower field;
- Sophisticated and extensive monitoring equipment can be installed and protected from the incoming radiation and weather;
- Capture and treatment of fumes or gases emitted during the experiment;
- Dedicated systems for gas supply, extraction and analysis.

In addition, several options have been considered to tailor the furnace design to specific applications:

Linear Focus for Parabolic Trough Component Assessment

CSIRO is actively involved in a number of bids under the Australian Government’s Solar Flagships program, and it is likely to have a role of supporting the commercial project through component evaluation. An option for the solar furnace design is to have a mode in which a linear element of several metres in length can be uniformly irradiated. This is a challenging optical design problem as the furnace would at other times need to be capable of achieving a tight focus for different experiments. However, there are some advantages in using solar radiation rather than thermal energy from heating elements to assess receiver tube performance. Not only is the actual solar spectrum supplied, but energy is transferred by radiation only and not convection. Use of a solar furnace would also enable much finer control of the thermal load as it can be
measured and adjusted rapidly and accurately, without the thermal inertia associated with heating elements.

**Beam Down for Melt Process Evaluation**

Australia has an abundance of mineral wealth and sunshine, and these resources are often co-located. Solar processing of ores and concentrates is therefore an area of great interest. One of the challenges with these processes is that the formation of a melt phase requires irradiation of the experiment from above. These experiments have been conducted in other solar furnaces through the use of a third mirror close to the focal point. The first problem with this solution is that additional losses occur in the third mirror. This may be overcome with an optical design as shown in Figure 5.

![Optical design of a solar furnace for smelting experiments](image)

Fig. 5: Optical design of a solar furnace for smelting experiments

Regardless of the chosen design a solar furnace will have the following major components:

- Heliostat
- Concentrator
- Beam Attenuator
- Experiment area/table/jig
- Beam diagnostics system
- Control system
- Building and infrastructure

The CSIRO Solar Furnace Project is in its conceptual phase based on the following specifications:

- Beam Power: 100 to 200 kW
- Peak Irradiance: 5 MW/m² at DNI=1000 W/m² (5000suns)
- Beam on/off Time: <1sec
- Full power operating time: solar noon ±3 hours
- Other features: exposure at focal distance ±0.5m
At this stage, there is insufficient design information to estimate the cost of the proposed facility.

SUMMARY

CSIRO has developed a proposal to construct an advanced Solar Furnace delivering about 100 to 200 kW of concentrated sunlight with intensities of up to 5000 suns to various kinds of experiments. The furnace would build on overseas experience in the design and operation of earlier facilities to develop a world leading facility. The furnace could provide a cost effective and realistic platform for experiments, which can be conveniently conducted at ground level. The proposed facility would employ an off-axis design, enabling the focal point to be located in a dedicated experimental chamber. This greatly simplifies many aspects of experimentation with concentrated solar energy compared with the use of a heliostat field and tower or dish system. Potential applications include:

- Solar electricity production from high temperature and Stirling cycles
- Materials and components for high temperature solar thermal power generation – higher temperatures are widely recognised as essential to increasing the efficiency of solar thermal energy to electricity
- Development of novel material for high temperature heat transfer and thermal energy storage
- Thermochemical processes for storage of solar energy in fuels, including reforming and gasification of hydrocarbons, solids and biomass
- Thermochemical water splitting cycles for renewable hydrogen production
- High temperature heat transfer fluids and thermal energy storage
- Accelerated life testing and exposure to extreme radiation
- Concentrated solar energy for minerals and metals processing

REFERENCES


ACKNOWLEDGEMENTS
This work was funded by the CSIRO Energy Transformed Flagship, Solar Thermal Power stream led by Wes Stein.

BRIEF BIOGRAPHY OF PRESENTER
Dr Jim Hinkley is a chemical engineer with over 20 years experience in research and operations roles in a various industries from mineral beneficiation to the assessment of particulate emissions from coal fired power stations. Over the last six years, he has worked at CSIRO to develop concentrating solar thermal technologies for solar steam reforming of methane and hydrogen production from solar thermochemical water splitting. Dr Hinkley has strong links with overseas researchers through participation in a number of international research programs and initiatives, and has spent 3 months at the German Aerospace research centre (DLR) as a visiting scientist.