UC Solar Leads in Solar Thermal Science

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Summary

• Fundamental limitation for solar concentration
• Solar Thermal Research at UC Solar
  • The Arpa-E project
  • The XCPC project
    • The drum drying project
    • Evaporation Project
    • Mongolia project
  • The CEC combined heat and power project
• The Solar desalination project.
  • Current DOE Desal project
Thermodynamic limit on concentration

- From $\lambda_{\text{max sun}} \sim 0.5 \mu$ we measure $T_{\text{sun}} \sim 6000^\circ (5670^\circ)$

Without actually going to the Sun!

- Then from $\sigma T^4$ - solar surface flux $\sim 58.6 \text{ W/mm}^2$
  - The solar constant $\sim 1.35 \text{ mW/mm}^2$
  - The second law of thermodynamics
  - $C_{\text{max}} \sim 44,000$
  - Coincidentally, $C_{\text{max}} = 1/\sin^2 \theta$
  - This is evidence of a deep connection to optics
Limits to Concentration

\[
\frac{1}{\sin^2 \theta} \quad \text{Law of Maximum Concentration}
\]

Earth: Sun Example

\[
l_2 = \left(\frac{r_1}{r_2}\right)^2 l_1 \quad \text{Inverse Square Fall-off of Flux (Gauss's Law)}
\]

\[
\sin(\theta) = \frac{r_1}{r_2} \quad \Rightarrow \quad \frac{l_1}{l_2} = \frac{1}{\sin^2 \theta}
\]

\[
C l_2 \leq l_1 \quad (2\text{nd Law of Thermodynamics})
\]

Maximum Concentration \( C = \frac{1}{\sin^2 \theta} = 46,000 \)
The general concentrator problem

Concentration $C$ is defined as $A_2/A_3$

What is the “best” design?
Characteristics of an optimal concentrator design

1\textsuperscript{st} law efficiency: energy conservation
\[ q_{12} = q_{13} \Rightarrow P_{12} = P_{13} \]

2\textsuperscript{nd} law efficiency:
\[ A_1 P_{12} = A_1 P_{13}, \text{but } A_1 P_{13} = A_3 P_{31} \]

The concentration ratio C:
\[ C = \frac{A_2}{A_3} \]
\[ A_3 = \frac{A_1 P_{12}}{P_{31}} \]

The maximum concentration ratio
\[ C_{\text{max}} \text{ corresponds to minimum } A_3 \]

C is maximum IFF \( P_{31} = 1 \)

Recall that for maximum thermodynamics efficiency
\[ A_1 P_{12} = A_1 P_{13} = A_3 \]

Then \( A_2 P_{21} = A_3 \)
\[ C_{\text{max}} = 1/P_{21} \]
A more useful geometry for a parabolic trough thermal concentrator is a tubular receiver.

Concentration relation
\[ \frac{\sin \phi}{\pi \sin \theta} \]

Maximum value
\[ \frac{1}{(\pi \sin \theta)} \]
at 90° rim angle.

Falls short of the fundamental limit by a factor \( \pi \)!

\[ C = \frac{D}{2 \pi r \sin \theta} = \frac{\sin \phi}{\pi \sin \theta} \leq \frac{1}{\pi \sin \theta} \leq \frac{1}{\pi} C_{\text{fund}} \]
Record Breaking Exergy from Sunlight
1. TEAM

University of California, Merced

- Roland Winston, PhD
  - Co-Principal Investigator
  - Professor, Solar Optics

- Lun Jiang, PhD
  - Post-Doc, Hybrid Receiver
  - Project Leader

- Bennett Widyolar
  - Grad Student, Concentrating
  - Experimental System

- Jonathan Ferry
  - Grad Student, Solar Cell Testing

> Jiba Dahal
  - Grad Student, Vacuum System

> Melissa Ricketts
  - Grad Student, Optics
  - Design & Simulation
University of California, Berkeley

1. TEAM

- Eli Yablonovitch, PhD
  - Professor, Solid State Physics

- Gregg Scranton
  - Grad Student, Solar Cell Fabrication
1. TEAM

Gas Technology Institute

- Aleksandr Kozlov, PhD
  - Principle Investigator
  - Thermal Storage, Heat Transfer

- David Cygan
  - Project Management

- Hamid Abbasi
  - Project Management

- Joseph Pondo
  - Thermal System Testing

> Sandeep Alavandi
  - Thermal System Analysis

> Joseph Rabovitser, PhD
  - System Modelling

> Alek Tang
  - T2M, Licensing
Comparison of Nonimaging and conventional at 1:1 scale

- 3X smaller tube area means lower radiative loss at same T
Absorber

\[ \cos \phi = \frac{r \theta}{A_2/2} \]

\[ \sin \phi = \frac{A_1/2}{r} \]

Primary Concentrator

Secondary Concentrator

Glass Tube

Secondary Aperture

Secondary Reflector

Minichannels

Solar Cells

InGaP Spectral Efficiency

GaAs Spectral Efficiency

Direct Beam ASTM G173 Spectrum

Dual-Junction InGaP/GaAs PV + Thermal Junction

Approaches 59% Solar Conversion with 36% thermal fraction.

41% spectrum

23% spectrum

1000 Wavelength λ (nm)

2000

2500

2/3 Camot @ 608 C
Emissivity Testing of Selective Coatings At Temperature

\[ I \times V = A\varepsilon\sigma T_{abs}^4 \]
Coating undergoing 100 hours continuous testing at 650 °C
The graph shows the relationship between thermal efficiency and average particle temperature. The data points are labeled with dates:

- 8/31/2017
- 11/17/2017
- 9/25/2017
- 10/19/2017
- 11/14/2017

The equation of the trend line is given as:

\[ y = -6 \times 10^{-7}x^2 + 6 \times 10^{-5}x + 0.6325 \]

The coefficient of determination, \( R^2 \), is 0.867.
Filling the Hopper
Filling the Hopper
At Dirksen Senate Office Bldg aides to Sen Tammy Duckworth 3.14.18
Next Stop USG!
The external compound parabolic concentrators (XCPC)
The XCPC uses non-imaging optics to track the sun, while the XCPC hardware remains stationary.
The XCPC

• With CEC & private donor support, researchers at UC Merced have designed, tested and demonstrated the External Compound Parabolic Concentrator (XCPC), a novel non-tracking solar thermal collector for industrial process heat (100º-250ºC)
Solar Cooling

- 4 year demonstration
- 160 N/S XCPC collectors produce 20 kWth
- Power a 6.5 ton 2e absorption chiller
- Expanded to working IT trailer for 2015 tests
Solar cooling performance (sunny day)
Solar cooling performance (cloudy day)
Drum Drying

- XCPC collectors generate heat to mineral oil heat transfer fluid
  - 100-150 C
- Drum dryer uses steam (100-130 psig) to heat exterior surface of the drums.
- Retrofitted existing steam powered double drum dryer to use direct flow of mineral oil.
Evaporation

- XCPC collectors can provide heat (150 °C) to power commercial evaporators
  - Up to 90% waste stream volume reduction
  - 6-13 GPH evaporation
  - Test using heat transfer oil instead of steam or a natural gas burner
- Test effectiveness in processing valley waste streams:
  - RO discharge
  - Industrial and food processing waste streams
  - Agricultural drainage
Boiler Pre-heating in The UAE

CROSS COMPOUND PARABOLIC CONCENTRATOR

- Produces solar heat up to 250°C
- Uses evacuated absorber tubes to reduce heat losses
- Concentrating design without moving parts
- Developed in partnership with University of California, Merced
- Larger-scale system in operation at Al Khaleej Sugar factory in Jebel Ali

EMSOL
Masdar

A Sustainable Company
XCPC boiler pre-heating at sugar refinery plant in Dubai, UAE
XCPC Steam Generation in Beijing
XCPC Heating in Mongolia
(space, water, cooking, toilet)
Bennett in Ulan Bator
Initial Testing

310 °C

-14 °C
Project Launch
XCPC in Mongolia

UlaanBaatar, Mongolia - 5 kW Fully Off-Grid Space Heating
Solar array outside ger @ BogdKhan Resort, UB – May 2015
A Novel Low-Cost, High-Efficiency Solar Powered Micro-CHP System for Electricity, Hot Water, and Space Heating

• Hybrid PV/T Collector Generates
  • Electricity
  • Hot water (60 °C)

• Operates at same efficiency as solar PV panel and generates solar heat with minimal additional cost
Combined Heat and Power (CHP) for Domestic / Commercial Hot Water

Path of Light Ray in PVT Collector

Transmission ($\tau$)

Absorption ($\alpha$)

Reflection ($\rho$)

Glass tube

Solar Cells

Minichannel Heat Pipe Absorber

Reflective coating

Diagram showing the components and path of light rays in a PVT collector.
5 Flow-Through Tube Array

5 Heat-Pipe Tube Array

Illusion produced by flowline optics
Full Flow Through Tube Tests w/ Glass

Flow Through - On Sun Tests

14.07% Efficiency by cell area
11.87% Efficiency by Aperture
MPP @ 6.9 V

17.19% Efficiency by cell area
MPP @ 7 V

11.52% Efficiency by cell area
MPP @ 7.2 V
Topic Area 2: Low-cost solar thermal heat
The Internal Compound Parabolic Concentrator (ICPC)—A Novel Low Cost Solar Thermal Collection System for Desalination Processes

ICPC Collector

Direct-Contact Phase Change Thermal Storage

24/7 Low-Cost Dispatchable Solar Thermal for Desalination
Metal Absorber: Good heat transfer

Vacuum: Reduced heat loss

Metal-Glass Seal: New options for low cost (All aluminum)

Heat Pipe: Low-cost absorber material (aluminum + acetone)
- $7/m^2 aperture
- Thermal “superconductor”
  - Easy to install / replace tubes and remove heat

ICPC Optics / Reflector: $C_x = 1$

ICPC Collector
- Metal-glass Seal
- Integrated Reflector
- Heat Pipe Absorber
- Simple Collector Assembly

Low-cost, High-efficiency, Portability
Collector Efficiency Comparison
(1000 W/m² Global, 150 W/m² Diffuse, T_a = 25 °C)

- Flat Plate Collector (HelioDyne GOBI)
- Evacuated Tube Collector (SunRain)
- Evacuated Tube Collector with CPC Reflector (Linuo Ritter)
- Evacuated Flat Plate (TVP Solar)
- Micro Linear Fresnel (Chromasun MCT)
- Parabolic Trough (NEP Polytrough 180D)
- Internal Compound Parabolic Concentrator (ICPC)

120 °C Working Temperature
Target Solar Collector Operating Range

Thermal Efficiency (\eta)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

0 25 50 75 100 125 150 175 200
T_m - T_a
Cost reductions

- Glass tube
- Silver reflector coating
- Aluminum minichannel heat pipes
- Low cost metal-glass seal
Thank you