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A review of high temperature solar driven reactor technology: 25 years of experience in research and development at the Paul Scherrer Institute

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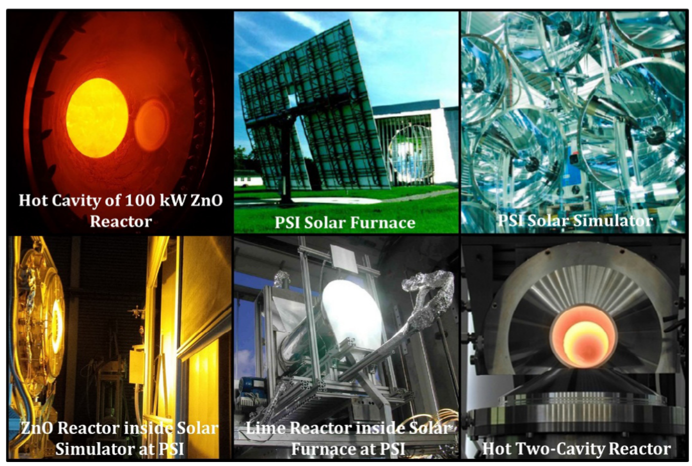
HIGHLIGHTS

- Five solar reactor development projects presented in detail.
- Solar reactors for fuel production and high temperature materials processing.
- Continuous operation of solar reactor technology above 2000 K and 4000 kW/m^2.
- 25 years of research and development in solar reactor design and demonstration.
- Deployment of solar reactor technology to scales as high as 300 kW.

GRAPHICAL ABSTRACT

Solar facilities and reactors at the Paul Scherrer Institute.



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ABSTRACT

High temperature fuel production and thermal material processing driven by concentrated solar energy has the potential to significantly reduce the fossil fuel dependence of our current energy economy. Critically important to the utilization of solar power to drive a high temperature thermal or thermochemical process is the solar receiver and reactor. In this review article, the full scope of the development process for a solar receiver and reactor is considered, beginning with fundamental materials science and ending with large scale demonstration projects. As representative examples, and spanning over 25 years of solar reactor research and development by the Solar Technology Laboratory at the Paul Scherrer Institute, five projects have been selected and are presented in detail: H_2O and CO_2 splitting via the Zn/ZnO thermochemical cycle brought to the 100 kW level, carbothermal reduction of ZnO demonstrated at the 300 kW level, gasification of carbonaceous waste materials proven at the 150 kW level, H_2O and CO_2 splitting utilizing non-stoichiometric ceria, and the production of industrial grade lime. These projects represent significant efforts which bridged the gaps between science, technology, engineering, and demonstration for solar-driven high-temperature receivers and reactors. Additional relevant solar reactor development projects from around the world are summarized and compared. Given the simultaneous demand for carbon-neutral energy vectors and liquid hydrocarbon fuels, combined with the significant technological progress achieved with solar reactors, industrial-scale implementation of solar-driven fuel production and high temperature materials processing is likely to expand significantly within the next decade.

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Nomenclature

d_{sp} spot diameter on quartz window [cm]
D_o diffusion coefficient [cm^2/s]
E_a activation energy [kJ/mol]
ΔH enthalpy change of reaction [kJ/mol]
k_o pre-exponential factor in Arrhenius rate law (units vary) [kg/m^2 s]
$\dot{m}_{diss}$ ZnO dissociation rate [g/min]
p_{CO} partial pressure of carbon monoxide [kPa]
p_{O_2} partial pressure of oxygen [kPa]
p_{Zn} partial pressure of zinc [kPa]
R universal gas constant (8.314) [J/mol K]
t time [s]
T temperature [K]
T_{ox} oxidation temperature [K]
T_{red} reduction temperature [K]
X conversion factor [–]
x elemental H:C ratio [–]
X_{Zn} chemical conversion ZnO to Zn
y elemental O:C ratio [–]

Acronyms
CPC compound parabolic concentrator [–]
CSP concentrating solar power
CST concentrating solar thermal
EAFD electric arc furnace dust [–]
FPR falling particle receiver
HHV higher heating value [kJ/mol]
HFSF high flux solar furnace [–]
HFSS high flux solar simulator [–]
MWSF megaWatt solar furnace
PV photovoltaics
RPC reticulated porous ceramic [–]
TPD tons per day [tons/day]
TGA thermogravimetric analysis [–]
XAS X-ray absorption spectroscopy [–]
XRD X-ray diffraction spectroscopy [–]

Greek symbols
α C:ZnO or CH_4:ZnO molar ratio [–]
δ oxygen non-stoichiometry factor [–]
$\eta_{solar\text{-}to\text{-}fuel}$ solar-to-fuel energy conversion efficiency [%]
$\eta_{solar\text{-}to\text{-}chemical}$ solar-to-chemical energy conversion efficiency [%]
$\eta_{thermal}$ thermal energy conversion efficiency [%]

Research institute acronyms
CIEMAT Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain
CNRS National Center for Scientific Research, France
EIR Federal Institute for Reactor Research, Switzerland
ETHZ Swiss Federal Institute of Technology, Zurich, Switzerland
EPFL École Polytechnique Fédérale de Lausanne
PREC Professorship of Renewable Energy Carriers, ETHZ, Switzerland
PROMES Procédés, Matériaux et Énergie Solaire, Odeillo, France
PSA Plataforma Solar de Almería, Spain
PSI Paul Scherrer Institute, Switzerland
SIN Swiss Institute for Nuclear Research, Switzerland
SNL Sandia National Laboratory, United States
STL Solar Technology Laboratory, PSI, Switzerland
WIS Weizmann Institute of Science, Israel

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