A 300 kW solar chemical plant for the carbothermic production of zinc

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The EU research project SOLZINC accomplished a pioneer technology demonstration of a large-scale solar chemical plant. The key component is PSI's 300-kW solar chemical reactor for the production of zinc by carbothermic reduction of ZnO. Its testing at a large-scale solar concentrating facility in the 1300–1500 K range yielded up to 50 kg/h of 95%-purity Zn with energy conversion efficiency (ratio of the reaction enthalpy change to the solar power input) of about 30%. The SOLZINC process provides an efficient thermochemical route for the storage and transportation of solar energy.

Solar-made zinc finds application as a renewable fuel for Zn-air batteries and fuel cells, and can also be reacted with water to form high-purity hydrogen. In either case, the chemical product from these power generation processes is ZnO, which in turn is solar-reduced to Zn (Figure 1). The carbothermic reduction of ZnO, represented by $ZnO+C \rightarrow Zn_{(g)}+CO$, proceeds endothermically ($\Delta H^{o}_{1500K} = 350$ kJ/mol) at above 1200 K. The use of concentrated solar energy as the source of high-temperature process heat offers a CO_2 emission reduction by a factor of 5 vis-à-vis the conventional fossil-fuel-driven electrolytic or imperial smelting processes. Obviously, if biomass is used as a reducing agent, it becomes a zero-net CO_2 process. The cyclic process from solar energy to electricity via solar-processed Zn/air fuel cells is being investigated within the EU's R&D project SOLZINC [1]. We describe the engineering design and present recent experimental results of the 300-kW solar chemical pilot plant installed at the solar tower concentrating facility of the Weizmann Institute (WIS), in Israel (see photo on page 10).

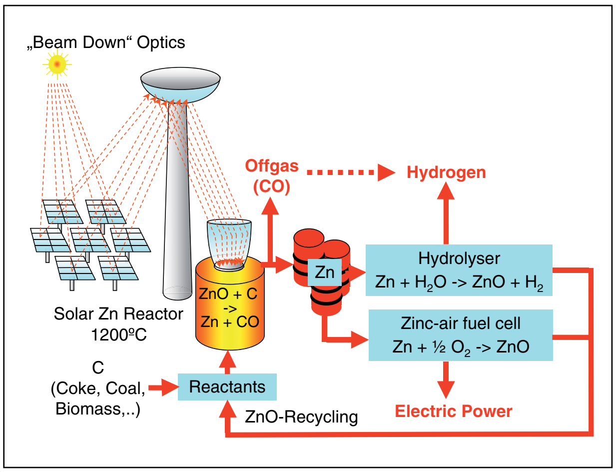

Figure 1: **Closed zinc cycle: producing zinc with solar energy forms a zinc oxide-zinc cycle and allows generation of electricity or hydrogen on demand.**

The pilot solar reactor technology

The design, modelling, fabrication, and experimental investigation of a 5-kW solar chemical reactor prototype for performing the carbothermic reduction of ZnO has been described previously [2, 3]. The 300-kW pilot solar reactor, shown schematically in Figure 2, features two cavities in series, with the upper one functioning as the solar absorber, and the lower one as the reaction chamber. With this arrangement, the upper cavity protects the window against particles and condensable gases, and further serves as a thermal shock absorber. The upper cavity contains the 48-cm diameter aperture with a 12-mm thick quartz window mounted on a water-cooled Cu ring, the 0.8-cm thick SiC partition plates, and inlet/outlet ports for the inert carrier gas for window flushing. The lower, 140-cm diameter and 0.8-m high cylindrical cavity contains the packed bed of ZnO-C mixture. The maximal initial height of the batch is 0.5 m, corresponding to about 500 kg for a full day's operation, so that cooling and recharging of a new batch can be accomplished overnight.

The main components of the SOLZINC pilot plant are depicted in Figure 3. The SiC off-gas pipe is electrically heated to prevent

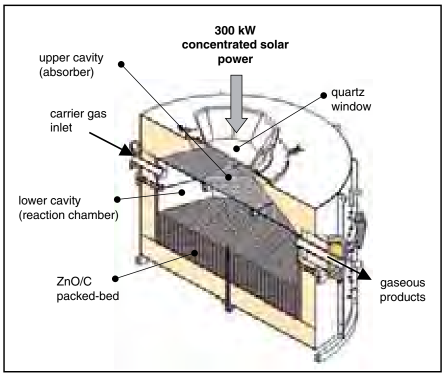

Figure 2: **Schematic of the 300 kW solar chemical reactor: solar absorber (upper cavity) and reaction chamber containing a ZnO-C packed bed (lower cavity) [1].**

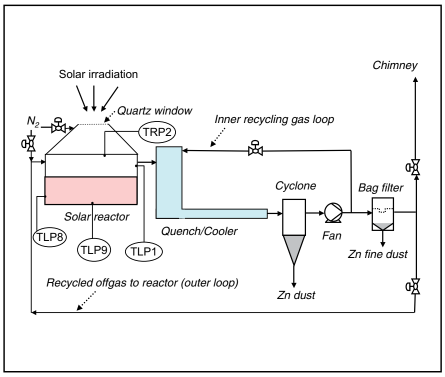

Figure 3: **Flow diagram of SOLZINC solar chemical pilot plant: solar concentrating system, solar reactor, off-gas system, and diagnostic instrumentation.**

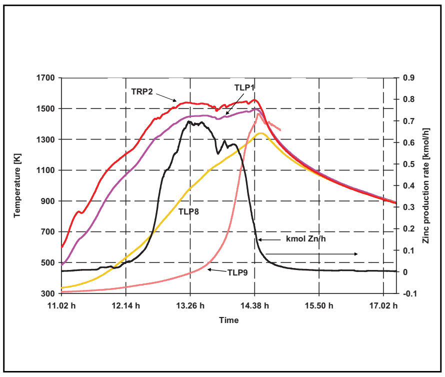

Figure 4: **Temperatures and production rate during a typical test (experiment C in table). TRP2: partition plates; TLP1: reaction chamber; TLP8: SiC lateral wall; TLP9: SiC bottom plate.**

Zn condensation, and extends into the quenching section, where the gas is mixed with recycled off-gas. More than 150 sensors for temperatures, pressures, flow rates, radiative power, gas analysis etc. monitor and control the process.

Experimental results

A 116 kg batch of industrial ZnO powder (Grillo 2011) and industrial beech charcoal powder (Chemviron) with a typical molar stoichiometry α=C/ZnO of 0.9 was distributed uniformly in the lower cavity, resulting in a 12-13-cm thick packed bed. Typically, the solar reactor was heated at a rate of about 10 K/min by successively introducing heliostats until the desired temperature level was reached. The table lists the major operational conditions of selected pilot experimental runs.
Figure 4 shows the time variation of the reactor temperatures during experiment C. Highest temperature of 1535 K is obtained on the partition wall (TRP2), while the temperature in the upper part of the reaction chamber is about 50–100 K lower, as predicted by radiation heat transfer modelling [3, 4]. The temperature at the SiC floor (TLP9) of the reactor indicates a high temperature gradient through the packed bed, which is typical of ablation processes where heat transfer through the bed becomes the rate controlling mechanism. Figure 4 also includes the Zn production rate – with peak at 0.7 kmol/h – determined from the oxygen balance: $\dot{n}_{Zn} = \dot{n}_{CO} + 2\dot{n}_{CO_2}$, where $\dot{n}_i$ is the molar flow rate of species *i*, measured by GC. X-ray-diffraction analysis of samples collected in the cyclone and the bag filter indicated a Zn purity of 95%.
The thermal efficiency of the solar reactor, defined as the ratio of the reaction enthalpy change to the solar power input into the reactor, amounts to about 30%. Losses are mainly due to re-radiation through the aperture and heat conduction through the walls. Higher efficiencies are expected for larger industrial plants because of the improved reaction surface area to wall area ratio. The conceptual design and economic analysis of a 5 MW chemical plant is in progress.

Experiment	**A**	**B**	**C**	**D**	**E**
Stoichiometry α= C/ZnO	0.9	0.9	0.9	1	0.8
N_2 flow rate in upper chamber [Nm^3/h]	6	6	6	6	6
N_2 flow rate in lower chamber [Nm^3/h]	3	3	3–9	3–9	3–9
Outer recycled gas flow rate [Nm^3/h]	0–6	16	0–10	0–10	0–10
Inner recycled gas flow rate [Nm^3/h]	500	500	350	350	350
At maximum power input (plateau):					
$T_{lower\ cavity}$ = TLP1 [K]	1440	1390	1450	1460	1470
Zn molar flow rate (maximal) [kmol/h]	0.64	0.44	0.67	0.7	0.61
Batch height after test [cm]	4	<1	<1	<1	<1

Acknowledgements

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References

[1] E. Guillot et al., Proc. ASME-ISEC, Orlando, (2005)
[2] T. Osinga et al., J. Solar Energy Eng. 126, 633 (2004)
[3] T. Osinga et al., Ind. & Eng. Chemistry Research 43, 7981 (2004)
[4] C. Wieckert, J. Solar Energy Eng. 127, 425 (2005)