

RECYCLING OF HAZARDOUS SOLID WASTE MATERIAL USING HIGH-TEMPERATURE SOLAR PROCESS HEAT

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A novel high-temperature solar chemical reactor is proposed for the thermal recycling of hazardous solid waste material using concentrated solar power. A 10 kW solar reactor prototype was designed and tested for the carbothermic reduction of electric arc furnace dusts (EAFD). The reactor was subjected to mean solar flux intensities of 2000 kW/m^2 and operated in both batch and continuous mode within the temperature range 1120-1400 K. Extraction of up to 99% and 90% of the Zn originally contained in the EAFD was achieved in the residue for the batch and continuous solar experiments, respectively. The condensed off-gas products consisted mainly of Zn, Pb, and Cl. No ZnO was detected when the O_2 concentration remained below 2 vol.-%. The use of concentrated solar energy as the source of process heat offers the possibility of converting hazardous solid waste material into valuable commodities for processes in closed and sustainable material cycles.

1 INTRODUCTION

In previous papers [1,2] we proposed a novel thermochemical process for recycling hazardous solid waste material using concentrated solar power. The motivation for the development of such a solar-driven process emerged from the fact that current recycling techniques by blast, induction, arc, and plasma furnaces are characterized by their high energy consumption and their concomitant environmental pollution, derived mainly from the combustion of fossil fuels for heat and electricity generation. For example, the theoretical thermal energy requirement for the carbothermic reduction of electric arc furnace dust (EAFD) at 1500 K is 3000 kJ kg^{-1} , discharging at least 0.7 kg CO_2 per kg of EAFD, when coke serves as both the reducing agent and the primary energy source. In practice, emissions are much higher because of inefficiencies associated with heat transfer. Alternatively, the use of concentrated solar energy as the source of process heat avoids greenhouse gas emissions and other pollutants, and further offers the possibility of converting hazardous solid waste material into valuable commodities for processes in closed and sustainable material cycles.

The typical elemental composition of EAFD is shown in Table 1. Thermodynamic equilibrium computations for the carbothermic reduction of EAFD, when C(gr) is

Element	EAFD [wt.-%]
Zn	37.8
Fe	13.5
Pb	10.1
Cu	0.23
Cd	0.09
Cr	0.12
Cl	4.8
S	0.6
Si	1.7
Alkaline earth elements	0 - 5
C	<2

Table 1: Main Elemental Composition of EAFD (O_2 is complementary to 100%).

used as the reducing agent and SiO_2 is employed as the main vitrification agent, indicate that the chemical equilibrium composition of the system at 1500 K consists principally of Zn(g) and CO in the gas phase and Fe, Pb, and SiO_2 in the condensed phase.

This technical note describes briefly the design, fabrication, and testing of a novel solar chemical reactor for recycling EAFD. The main objective of the proposed process is the extraction of metals, especially Zn and Pb, by carbothermic reduction of their metal oxides using solar process heat.

2 SOLAR REACTOR DESIGN AND FABRICATION

The patented solar reactor concept proposed for the solar thermal recycling process is depicted in Figure 1 [3].

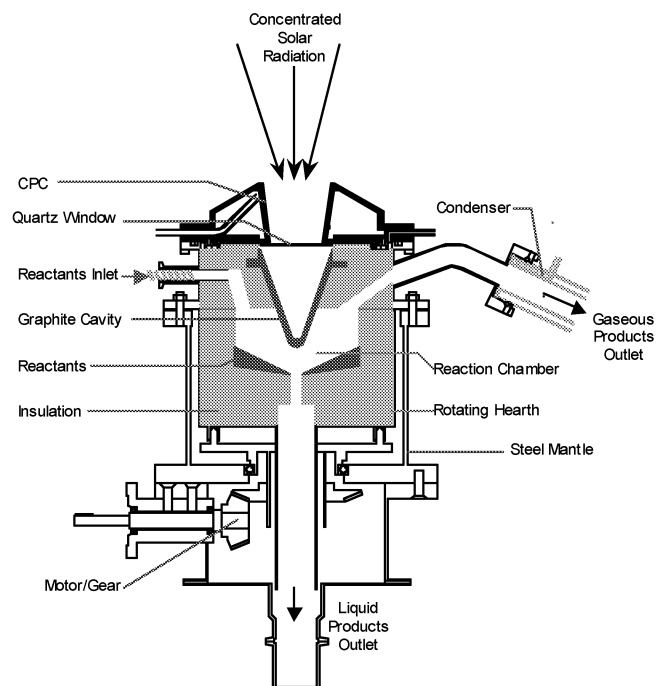


Fig. 1: Scheme of solar reactor configuration.

The inner cavity is a graphite enclosure, with a small windowed opening, to let in concentrated solar power. It serves as the solar receiver, radiant absorber, and radiant emitter. The outer cavity is a well-insulated enclosure containing the inner cavity. It serves as the reaction chamber that is subjected to thermal radiation from the inner cavity. Such a two-cavity reactor concept has the following advantages: 1) The reactants are exposed to uniform irradiation emitted by the inner cavity, even for non-uniform incident solar fluxes; 2) The inner cavity serves as a thermal shock absorber, reducing the sudden thermal loads on the ceramic materials of construction of the outer cavity; 3) The inner cavity further protects the window against particles or condensable gases coming from the reaction chamber; 4) The outer cavity can handle thermochemical processes at elevated temperatures involving multi-phases and controlled atmospheres; 5) The outer cavity allows for batch or continuous mode of operation and for easy adjustment of the residence

time of the reactants to match the kinetics of the reaction. Details of the fabrication of a 10 kW prototype solar reactor are given in [2].

3 SOLAR EXPERIMENTATION

Solar experiments were conducted at PSI's solar furnace, described in [4]. The reactants consisted of a mixture of 87% EAFD (mean particle size $5\ \mu\text{m}$; 70% smaller than $8\ \mu\text{m}$) and 13% activated charcoal (Fluka Chemicals Artikel 03866, water content 6%, ash content 5%). The reactants were continuously screw-fed into the reaction chamber at a mass flow rate varying between 2 and 24 g/min. The gaseous products were continuously removed and directed through a water-cooled Pyrex tube, where part of the Zn and Pb condensed. A battery of particle filters collected the remaining solid products downstream. The gaseous products were analyzed on-line by GC; solid product samples were analyzed by X-ray diffraction and X-ray fluorescence.

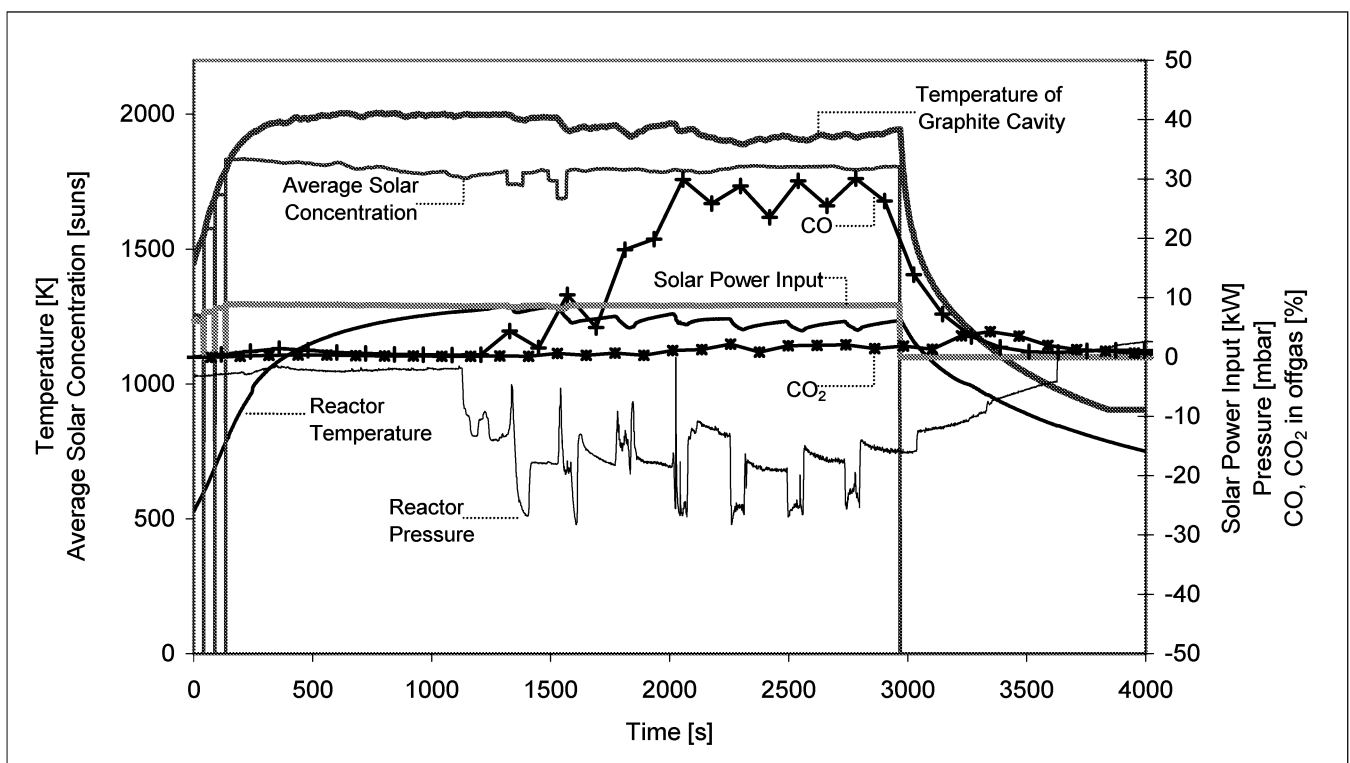


Fig. 2: Variation of the solar power input, the average solar concentration over the entrance of the CPC ($1\ \text{sun} = 1\ \text{kW/m}^2$), the temperature of the graphite inner cavity, the mean temperature of the reaction chamber, the reactor pressure, and the CO and CO₂ concentrations in the off-gas during a representative solar experiment.

4 RESULTS AND DISCUSSION

Figure 2 shows results from a representative solar experiment in continuous mode: The mean solar power flux over the entrance of the CPC was in the range of $1800\text{--}2000\ \text{kW/m}^2$, and at the aperture plane (exit of the CPC) was $2800\ \text{kW/m}^2$. The feed rate was set at $6.4\ \text{g/min}$ during a 1-min. interval every 4 min.,

and a continuous N₂ flow of $10\ \text{l}_n/\text{min}$ was employed. We observed a decrease in the reactor temperature, an increase in the total pressure, and an increase in the CO concentration in the off-gas, all matching the 1-minute time interval during feeding of the reactants and indicating the proceeding of the endothermic reaction.

Results of a set of seven solar experiments in continuous mode of operation are presented in Table 2. The condensed reaction products from the off-gas contained mainly Zn, Pb, and Cl, and some traces of S, K, and Cd. X-ray diffraction showed high-purity Zn (no ZnO) for those experiments without O₂ in the off-gas. Main elements in the residue were Zn, Pb, Fe, Cl, C, Si, alkaline, and alkaline earth elements, with ZnO, Pb, Fe, iron oxides, SiO₂, and KCl being the main phases, as revealed by X-ray diffraction. Such a quality of secondary material can directly be used in blast furnaces for iron production. Extraction of more than 90% of the Zn originally contained in the EAFD

was obtained in two solar experiments: at 1210 K with a feeding rate of 2.2 g/min and at 1250 K with a feeding rate of 6.7 g/min. The latter experiment also resulted in the extraction of up to 80% of the Pb originally contained in the EAFD. More than 99% of the Zn and Pb were extracted from the EAFD in a batch mode experiment at 1400K. In runs with varying O₂ concentration in the carrier gas, high purity Zn (> 95 mol %) was produced when the off-gas contained less than 2 vol.-% O₂, and nearly 100% ZnO was obtained when the off-gas contained more than 5 vol.-% O₂.

T _{reactor} [K]	Q _{solar} [kW]	Feed rate [g/min]	Main condensed elements from the off-gas [wt.-%]			Purity of Zn condensed [mol %]	Main volatile elements in residue [wt.-%]	
			Zn	Pb	Cl		Zn	Pb
1150	8.51	6.4	69.2	3.6	10.1	90.1	28.2	6.1
1210	9.62	2.2	64.2	3.2	17.3	99	9.2	6.7
1210	9.49	12.7	71.5	3.0	8.0	5.0	13.6	5.0
1230	9.42	4.7	69.4	1.8	7.6	100	17.0	7.2
1240	8.53	24	72.2	5.1	11.7	6.4	27.0	4.6
1250	8.99	6.7	69.8	5.9	19.2	91.6	9.95	3.66
1270	8.76	6.6	70.7	3.4	8.2	100	13.7	6.2

Table 2: Nominal reactor temperature, mean solar power input through the entrance of the CPC, reactants feeding rate, composition of condensed elements from the off-gas, purity of condensed Zn, and concentration of Zn and Pb in the residue, for the solar experiments under continuous mode of operation and approximate steady-state conditions.

5 CONCLUSION

There is a pressing need to develop clean technologies that recycle waste materials in a sustainable manner. High-temperature solar thermochemical processes are well suited for the treatment and recycling of hazardous solid wastes contaminated with heavy metals. The use of solar process heat avoids emissions of greenhouse gases and other pollutants. A recent economic assessment for a large-scale solar recycling plant [5] indicates competitiveness vis-à-vis conventional fossil-fuel-based techniques provided the cost of energy will account for the environmental externalities from fossil fuel burning such as the costs for CO₂ mitigation and other pollution abatement measures.

6 ACKNOWLEDGEMENT

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7 REFERENCES

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