A new high efficiency solar fuels reactor concept based on a liquid metal heat transfer fluid: modeling and efficiency estimation

Cansheng Yuan[ab], Yoshiaki Kawajiri[a], Asegun Henry[b,c]

a. School of Chemical & Biomolecular Engineering, Georgia Institute of Technology

b. George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology

c. School of Materials Science and Engineering, Georgia Institute of Technology

The idea of using solar energy as high temperature process heat to make fuel has been around for more than three decades.[1–4] This idea has gained increased attention over the last few years as interest has shifted to two-step partial redox cycles,[5–12] based on oxygen storage material (OSM) such as ceria, which have been demonstrated for repeatable performance of hundreds of cycles[10]. Two-step partial redox cycles undergo the reduction reaction and oxidation reaction to make a fuel, such as hydrogen from water. Current reactor designs for these cycles have efficiencies on the order of 1%, but improvements in processing of ceria porous medium, which increase mass loading and volumetric absorption of concentrated solar radiation, have led to efficiency improvements of up to 4%.[8] The efficiency is constrained by the power density mismatch of fuel output and solar energy input. To overcome this issue of a power density mismatch between the photo-thermal conversion and the thermal-chemical conversion, one can attempt to decouple the two processes.[5]

In this study, we propose a decoupled design using novel reactor system with two separate devices (i.e. a solar-thermal conversion device and a separately thermal-chemical reactor) connected through a liquid metal heat transfer fluid (LMHTF). The LMHTF first absorb concentrated sunlight at high temperatures through a solar receiver, and then it is pumped to a thermochemical reactor which uses the LMHTF to deliver the heat to the OSM and produce fuel. This approach, however, hinges on the usage of a high temperature heat transfer fluid that is chemically stable at sufficiently high temperatures. Molten salts[13,14], glasses[15] and metals[16,17] are among the only classes of fluids that are liquid at temperatures of 1,000 °C or above. Among these choices, liquid metals have a number of advantages that could prove useful for the application of thermochemical reactors. [16,17] Therefore, we have designed a new type of solar fuels reactor that uses liquid metal as a heat transfer fluid and to overcome not only the issues associated with the power density mismatch, but can also facilitate highly efficient solid phase heat exchange, which has been cited as another major source of inefficiency in the literature.[2,7,18] To recuperate the solid phase heat, we utilize an array of sealed reactor chambers which are operated at different temperatures. This reactor array allows the LMHTF to circulate and to recuperate the heat between chambers. Another benefit comes from this array of reactor chambers is that we can operate the reduction reaction step and oxidation reaction step simultaneously in different chambers. Since each chamber is sealed separately, the pressure of the reactor chambers and the flow rate of the purge gas can be controlled independently in order to obtain an optimal combination of pumping work and purging gas to achieve the maximum efficiency. The reactor system is modeled in

gPROMS and the results suggests that our new reactor design can exhibit thermal-to-chemical efficiencies well beyond 20% that is needed for economic viability.[6,19]

1. Funk, J. E. & Reinstrom, R. M. Energy requirements in production of hydrogen from water. *Ind. Eng. Chem. Process Des. Dev.* **5,** (1966).

2. Nakamura, T. Hydrogen production from water utilizing solar heat at high temperatures. *Sol. Energy* **19,** 467–475 (1977).

3. Steinfeld, A and Frei, A and Kuhn, P and Wuillemin, D. Solar thermal production of zinc and syngas via combined ZnO-reduction and CH< sub> 4</sub>-reforming processes. *Int. J. Hydrogen Energy* **20,** 793–804 (1995).

4. Steinfeld, A. Solar thermochemical production of hydrogen—a review. *Sol. Energy* **78,** 603–615 (2005).

5. Ermanoski, I., Siegel, N. P. & Stechel, E. B. A New Reactor Concept for Efficient Solar-Thermochemical Fuel Production. *J. Sol. Energy Eng.* **135,** 031002 (2013).

6. Siegel, N. P., Miller, J. E., Ermanoski, I., Diver, R. B. & Stechel, E. B. Factors affecting the efficiency of solar driven metal oxide thermochemical cycles. *Ind. Eng. Chem. Res.* **52,** 3276–3286 (2013).

7. Lapp, J., Davidson, J. H. & Lipiński, W. Efficiency of two-step solar thermochemical non-stoichiometric redox cycles with heat recovery. *Energy* **37,** 591–600 (2012).

8. Furler, P. *et al.* Solar Thermochemical CO 2 Splitting Utilizing a Reticulated Porous Ceria Redox System. (2012).

9. Diver, R. B., Miller, J. E., Allendorf, M. D., Siegel, N. P. & Hogan, R. E. Solar Thermochemical Water-Splitting Ferrite-Cycle Heat Engines. *J. Sol. Energy Eng.* **130,** 041001 (2008).

10. Chueh, W. C. *et al.* High-flux solar-driven thermochemical dissociation of CO2 and H2O using nonstoichiometric ceria. *Science* **330,** 1797–801 (2010).

11. Bader, R., Venstrom, L. J., Davidson, J. H. & Lipin, W. Thermodynamic Analysis of Isothermal Redox Cycling of Ceria for Solar Fuel Production. (2013).

12. Xu, R. & Wiesner, T. F. Dynamic model of a solar thermochemical water-splitting reactor with integrated energy collection and storage. *Int. J. Hydrogen Energy* **37,** 2210–2223 (2012).

13. Hasuike, H., Yoshizawa, Y., Suzuki, A. & Tamaura, Y. Study on design of molten salt solar receivers for beam-down solar concentrator. *Sol. Energy* **80,** 1255–1262 (2006).

14. Lata, J. M., Rodríguez, M. & de Lara, M. A. High Flux Central Receivers of Molten Salts for the New Generation of Commercial Stand-Alone Solar Power Plants. *J. Sol. Energy Eng.* **130,** 021002 (2008).

15. Deubener, J., Helsch, G., Moiseev, a. & Bornhöft, H. Glasses for solar energy conversion systems. *J. Eur. Ceram. Soc.* **29,** 1203–1210 (2009).

16. Sharafat, S. & Ghoniem, N. Summary of Thermo-Physical Properties of Sn , Comparison of Properties of Sn , Sn-Li , Li , and Pb-Li. 1–51

17. Subasic, N. Thermodynamic evaluation of Sn-Zr phase diagram. *Calphad* **22,** 157–165 (1998).

18. Steinfeld, A., Sanders, S. & Palumbo, R. DESIGN ASPECTS OF SOLAR THERMOCHEMICAL ENGINEERING — A CASE STUDY : TWO-STEP WATER-SPLITTING CYCLE USING THE Fe 3 O 4 / FeO REDOX SYSTEM. **65,** 43–53 (1999).

19. Kim, J., Johnson, T. a., Miller, J. E., Stechel, E. B. & Maravelias, C. T. Fuel production from CO2 using solar-thermal energy: system level analysis. *Energy Environ. Sci.* **5,** 8417 (2012).