

Application of a molten metal catalyst in solar hybrid sulphur cycle for hydrogen production

¹Mehdi Jafarian, ²Christian Sattler, ¹Graham J. Nathan

¹Centre for Energy Technology, Schools of Mechanical
The University of Adelaide, SA 5005, Australia

²Institute of Solar Research, DLR-German Aerospace Center, 51147 Cologne, Germany

E-mail: mehdi.jafarian@adelaide.edu.au

We present a novel technology with potential to lower significantly the cost of CO₂-neutral hydrogen relative to electrolysis and steam methane reforming (SMR). SMR is currently the most cost-effective commercial process for H₂ production at a cost of ~ \$1.5 (kg H₂)⁻¹, but it also produces some 8 tonnes of CO₂ per tonne of H₂ (Shaner et al., 2016). Integrating carbon capture and storage (CCS) into this process is estimated to increase the cost of SMR-derived H₂ to ~\$2.5 (kg H₂)⁻¹ for a CO₂ avoidance of ~90% (Shaner et al., 2016). In contrast, the levelised cost of H₂ production with near zero CO₂ emissions by photoelectrochemical and photovoltaic-electrolytic methods is estimated to be \$11.4 (kg H₂)⁻¹ and \$12.1(kg H₂)⁻¹, respectively (Shaner et al., 2016). While these costs are reducing rapidly with commercial implementation, the best case scenario predicts a future production cost of ~\$2/kg by 2025, i.e. ~\$18/GJ which is still nearly double the current cost of natural gas (~\$10/GJ) on an energy basis (Bruce et al., 2018). Hence, there is a need for new technologies with potential to reduce the price for CO₂ free hydrogen if hydrogen is to make a substantial contribution to CO₂ mitigation.

The Solar Hybrid Sulphur (Sol-HyS) cycle is a hybrid between a concentrated solar thermal energy, and electrolysis for hydrogen production. It has been identified previously as a cycle of highest priority for research and development, due to its potential for future realisation at industrial scale (Thomey et al., 2012). As shown in Figure 1, the HyS cycle comprises two chemical reactions. In the first stage, sulphuric acid is decomposed catalytically in a highly endothermic reaction at 600-1200 °C, suitable for integration of concentrated solar thermal energy. Then, the sulphur dioxide product is electrolysed together with water in the second reaction at temperatures below 100 °C requiring a theoretical voltage of 0.17 V, which is only about a tenth of the value of 1.23 V for conventional water electrolysis. Hence compared to solar powered water electrolysis the HyS requires only one sixth of the electricity (Bayer Botero et al., 2016).

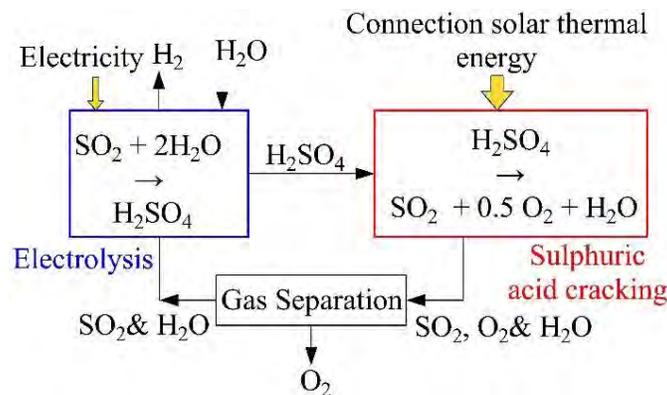


Figure 1. Schematic diagram of the solar hybrid sulphur cycle for hydrogen production (Thomey et al., 2012).

The Sol-HyS cycle has been demonstrated by the German Aerospace Centre (DLR) at TRL-5 (Thomey et al., 2012). This previous work developed a directly irradiated solar receiver/reactor, in which a catalytic coating (Fe_2O_3 or CuFe_2O_3) was applied to a SiSiC honeycomb structure to decompose sulphuric acid (H_2SO_4) at temperatures of above 800 °C. However, the use of solid-state catalysts under conditions of relevance to Sol-HyS cycle is technically challenging due to the heat transfer constraints in the gas-solid systems, corrosiveness of the gaseous reactant/products, deactivation of the catalysts under the harsh conditions and inevitable thermal shocks associated with the intermittent nature of solar thermal energy (Jafarian et al., 2019).

The patent-pending Solar Bubble Receiver/Reactor (SBR²), offers tremendous potential to achieve a break-through in solar receiver/reactor technology, through taking advantages of exceptional heat transfer properties of molten metal/metal oxides in gas-liquid bubbling regimes (Jafarian et al., 2019). On the other hand, a new class of molten metal catalysts i.e. alkaline-metal-vanadate (A-V-O) is emerging that offers potential to address/mitigate the technical challenges associated with the solid-state catalysts for thermal decomposition of SO_3 (Kawada et al., 2014), while also lowering the reactor temperature. On this basis, this paper aims to assess the potential to employ SBR² with a molten metal catalyst in Sol-HyS cycle for efficient thermal decomposition of SO_3 . In particular, the paper aims to evaluate the feasibility of the use of A-V-O in SBR² and to assess the techno-economy of the system.

References

- Bayer Botero, N., Thomey, D., Guerra Niehoff, A., Roeb, M., Sattler, C., Pitz-Paal, R., 2016. Modelling and scaling analysis of a solar reactor for sulphuric acid cracking in a hybrid sulphur cycle process for thermochemical hydrogen production. *International Journal of Hydrogen Energy* 41(19), 8008-8019.
- Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P., 2018. National hydrogen roadmap, CSIRO, Australia,.
- Jafarian, M., Abdollahi, M.R., Nathan, G.J., 2019. Preliminary evaluation of a novel solar bubble receiver for heating a gas. *Solar Energy* 182, 264-277.
- Kawada, T., Tajiri, T., Yamashita, H., Machida, M., 2014. Molten copper hexaoxodivanadate: an efficient catalyst for SO_3 decomposition in solar thermochemical water splitting cycles. *Catalysis Science & Technology* 4(3), 780-785.
- Shaner, M.R., Atwater, H.A., Lewis, N.S., McFarland, E.W., 2016. A comparative technoeconomic analysis of renewable hydrogen production using solar energy. *Energy & Environmental Science* 9(7), 2354-2371.
- Thomey, D., de Oliveira, L., Säck, J.-P., Roeb, M., Sattler, C., 2012. Development and test of a solar reactor for decomposition of sulphuric acid in thermochemical hydrogen production. *International Journal of Hydrogen Energy* 37(21), 16615-16622.