



ELSEVIER

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

ScienceDirect

journal homepage: [www.elsevier.com/locate/hydro](http://www.elsevier.com/locate/hydro)

# Solar hydrogen production via thermochemical iron oxide–iron sulfate water splitting cycle

Rahul R. Bhosale<sup>\*</sup>, Anand Kumar, Leo J.P. van den Broeke, Shahd Gharbia, Dareen Dardor, Mehak Jilani, Jamila Folady, Mashail Shaif Al-Fakih, Mahsa Ali Tarsad

Department of Chemical Engineering, College of Engineering, Qatar University, Doha, Qatar

## ARTICLE INFO

### Article history:

Received 18 September 2014

Received in revised form

19 November 2014

Accepted 25 November 2014

Available online 20 December 2014

### Keywords:

Solar fuel

Iron oxide–iron sulfate water splitting cycle

Thermodynamics

Hydrogen production

## ABSTRACT

This paper reports the thermodynamic analysis of solar H<sub>2</sub> production via two-step thermochemical iron oxide–iron sulfate (IO–IS) water splitting cycle. The first step belongs to the exothermic oxidation of FeO via SO<sub>2</sub> and H<sub>2</sub>O producing FeSO<sub>4</sub> and H<sub>2</sub> and second step corresponds to the endothermic reduction of FeSO<sub>4</sub> into FeO, SO<sub>2</sub>, and O<sub>2</sub>. The products, FeO and SO<sub>2</sub> can be recycled to step 1 and hence, reutilized for the production of H<sub>2</sub> via water splitting reaction. Thermodynamic equilibrium compositions and variations in enthalpy, entropy and Gibbs free energy of the thermal reduction and water splitting reactions were computed as a function of reaction temperatures. Furthermore, the effect of molar flow rate of inert Ar ( $\dot{n}_{Ar}$ ) on thermal reduction temperature ( $T_R$ ) and equilibrium compositions during the thermal reduction of FeSO<sub>4</sub> was also examined. Second law thermodynamic analysis was performed to determine the cycle efficiency ( $\eta_{cycle}$ ) and solar to fuel energy conversion efficiency ( $\eta_{solar-to-fuel}$ ) attainable with and without heat recuperation for varying  $\dot{n}_{Ar}$  (0–30 mol/s) and  $T_R$  (1280–1510 K). Results obtained indicate  $\eta_{cycle} = 39.56\%$  and  $\eta_{solar-to-fuel} = 47.74\%$  (without heat recuperation) and  $\eta_{cycle} = 51.77\%$  and  $\eta_{solar-to-fuel} = 62.43\%$  (by applying 50% heat recuperation) at  $T_R = 1510$  K.

Copyright © 2014, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.

## Introduction

H<sub>2</sub> is considered as one of the potential energy carriers due to its capacity of producing 143 MJ/kg of energy (higher in comparison with the oil, gas, and coal individually) and its environmentally friendly nature (burning of H<sub>2</sub> produces water with no other polluting gases). Water splitting reaction is considered as one of the most promising ways for the production of H<sub>2</sub>. However, direct water thermolysis is not

avored thermodynamically as it requires process heat at temperatures above 2723 K for obtaining a significant degree of dissociation of water [1]. Furthermore, to avoid the formation of an explosive mixture comprised of H<sub>2</sub> and O<sub>2</sub>, a gas separator unit (for the separation of H<sub>2</sub> and O<sub>2</sub> at high temperatures) needs to be equipped near to the water dissociation reactor which further enhances the overall cost of the H<sub>2</sub> production process.

As the direct dissociation of water is not practical due to the high operating temperature and gas separation problem,

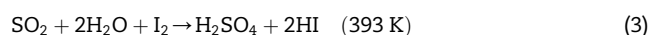
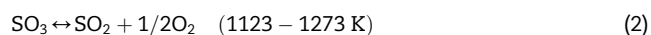
<sup>\*</sup> Corresponding author. Tel.: +974 4403 4168; fax: +974 4403 4131.

E-mail addresses: [rbbhosle@yahoo.com](mailto:rbbhosle@yahoo.com), [rahul.bhosale@qu.edu.qa](mailto:rahul.bhosale@qu.edu.qa) (R.R. Bhosale).  
<http://dx.doi.org/10.1016/j.ijhydene.2014.11.118>

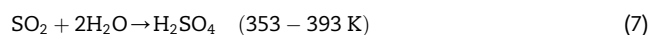
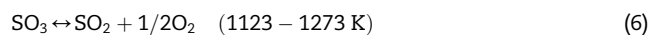
0360-3199/Copyright © 2014, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.

attempts are currently underway to achieve  $H_2$  production via water-splitting reaction at lower operating temperatures and via bypassing the formation of  $H_2$  and  $O_2$  explosive mixture. Several thermochemical cycles such as iron oxide cycle [2–6], zinc/zinc oxide cycle [7–10], tin/tin oxide cycle [8,11–13], mixed ferrite cycle [14–21], ceria cycle [22–24], sulfur–iodine cycle [25–27], and hybrid sulfur cycle [28,29] were investigated towards  $H_2$  production via water-splitting reaction. Among these, the sulfur–iodine cycle (reaction set I) and its variation the hybrid sulfur cycle (reaction set II) are more appealing as the required operating temperatures are lower as compared to other thermochemical cycles.

Reaction set I: sulfur–iodine cycle



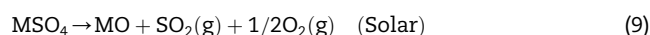
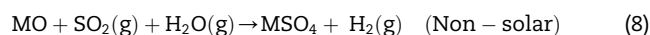
Reaction set II: hybrid sulfur cycle



For both sulfur–iodine cycle and hybrid sulfur cycle, the most energy consuming step is the dissociation of  $SO_3$  into  $SO_2$  and  $O_2$ . The reduction of  $SO_3$  into  $SO_2$  and  $O_2$  is possible only under catalytic conditions and takes place at high temperature due to its endothermic nature. Several metal based catalytic systems have been investigated previously towards the decomposition of the gaseous  $SO_3$  [30]. As sulfation poisoning is a major concern related to such reactions, the

investigated metal catalysts were loaded either on non-sulfating substrates or substrates forming very stable sulfates. At high reaction temperatures, most of the transition metal catalysts (such as nickel, manganese based) undergo formation of stable sulfates and resulted as inefficient in terms of their catalytic activity towards the reduction of  $SO_3$  into  $SO_2$  and  $O_2$  [31]. In contrast, the noble metal catalysts (e.g., platinum based) supported on  $BaSO_4$ – $TiO_2$ ,  $ZrO_2$ , or  $SiO_2$  were observed to be active towards the endothermic dissociation of  $SO_3$ . Although, the noble metal catalysts are attractive for such reactions, they are less preferable due to the limited availability and high cost.

Utilization of metal oxides as the catalytic materials (instead of noble metal catalysts) and converting the sulfur–iodine and hybrid sulfur cycle into a ‘metal oxide–metal sulfate’ cycle operated using concentrated solar energy is one of the alternative to achieve  $H_2$  production at moderate temperatures. Solar ‘metal oxide–metal sulfate’ thermochemical cycle utilizes solar energy, metal oxide (MO),  $SO_2$  and  $H_2O$  for the production of  $H_2$  and  $O_2$ . It is a two-step process in which the first non-solar step belongs to the exothermic oxidation of MO by  $SO_2$  and  $H_2O$  producing metal sulfate ( $MSO_4$ ) and  $H_2$  (reaction 8). The endothermic step two corresponds to the solar thermal reduction of  $MSO_4$  into MO,  $SO_2$ , and  $O_2$ . The MO and  $SO_2$  produced in step 2 are recycled back to step 1 and hence can be used in multiple cycles.



According to the previous investigations [2–24], among the several MO systems examined for the solar thermochemical water splitting application, iron oxide based redox materials are considered as one of the most favorable materials. In this viewpoint, this paper proposes the utilization of the ‘iron oxide–iron sulfate’ (IO–IS) cycle for the production of solar  $H_2$

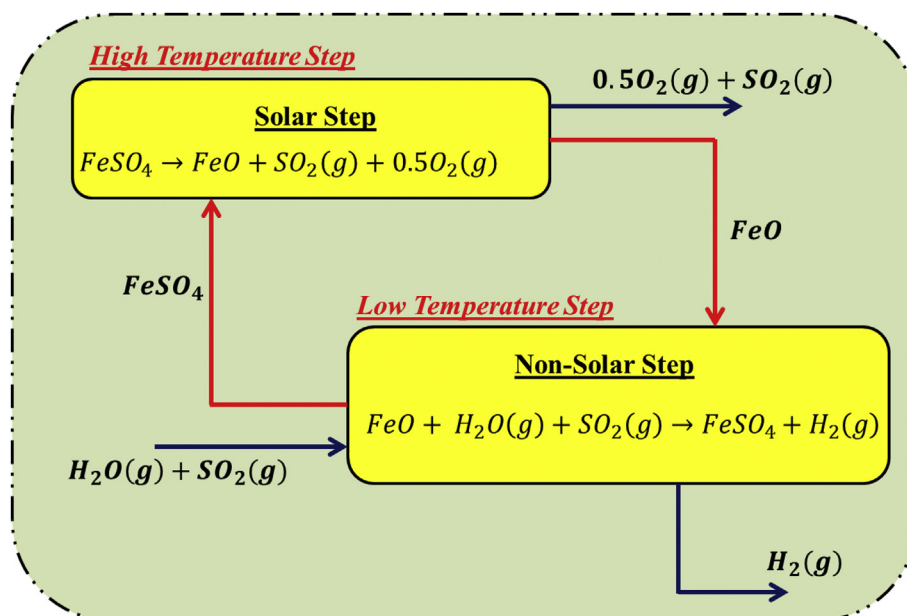


Fig. 1 – Typical two-step solar thermochemical IO–IS water splitting cycle.

Download English Version:

<https://daneshyari.com/en/article/7716477>

Download Persian Version:

<https://daneshyari.com/article/7716477>

[Daneshyari.com](https://daneshyari.com)