



## Sol-Gel Synthesis of $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ Nanoparticles: Effect of Addition of Proton Scavenger and Gel Aging Time

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### ABSTRACT

*In this paper, the sol-gel synthesis of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  nanoparticles via sol-gel method for the production of solar fuels via thermochemical  $\text{H}_2\text{O}/\text{CO}_2$  splitting cycles is reported. Sol-gel synthesis of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  nanoparticles includes dissolution of metal precursors in ethanol, addition of propylene oxide as a proton scavenger to achieve gel formation, aging of the gel, gel drying, and subsequent calcination in presence of air. The effect of addition of propylene oxide as a proton scavenger and gel aging time on physico-chemical properties of sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was investigated in detail. Various characterization techniques such as powder X-ray diffraction (XRD), BET surface area analyzer (BET), and scanning electron microscope (SEM) were utilized in this study. The end results indicate significant increase in specific surface area (SSA) and pore volume ( $P_v$ ) of the sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  because of the increase in the amount of proton scavenger used during synthesis. In contrast, the phase composition and crystallite size ( $C_s$ ) of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was observed to be unaffected due to the change in the amount of proton scavenger used and gel aging time.*

**Keywords:** Sol-gel, propylene oxide, solar fuels,  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  nanoparticles.

### INTRODUCTION

Production of solar fuels such as solar  $\text{H}_2$  or solar syngas (a mixture of  $\text{H}_2$  and  $\text{CO}$ ) via a two-step metal oxide based thermochemical  $\text{H}_2\text{O}$  and  $\text{CO}_2$  splitting cycle is one of the most promising new technologies for the storage of solar energy in terms of chemical fuels [1-6]. Among the various materials investigated in past solar thermochemical  $\text{H}_2\text{O}$  and  $\text{CO}_2$  splitting cycles, in recent years, research has been focused towards mixed ferrite materials. Different ferrite materials have been investigated which includes: Ni-ferrite, Zn-ferrite, Co-ferrite, Mn-ferrite, Sn-ferrite, Ni-Zn-ferrite, Ni-Mn-ferrite, Ni-Sn-ferrite, and others [7-33]. Although these materials showed promising results in terms of solar fuel production, material stability (grain growth due to sintering) due to thermal cycling is an issue which poses limitation for the ferrite based thermochemical cycles to be a commercial process.

In past, several researchers have used various grain growth inhibitors such as  $ZrO_2$ ,  $Y_2O_3$ , YSZ, MgO as additives to the ferrite materials to reduce the sintering effect during multiple thermochemical cycles. In most of the cases, these grain growth inhibitors were mechanically added to the ferrite materials (mechanical mixing). Due to this mechanical addition, a non-homogenous mixture of these grain growth inhibitors and the ferrite particles were observed. Therefore, in this study, we have attempted to synthesize ferrite/grain growth inhibitor mixture via chemical approach. As an example, the mixture of  $CoFe_2O_4/ZrO_2$  nanoparticles was synthesized via sol-gel method. The effect of two synthesis parameters i.e. amounts of proton scavenger added and gel aging time on physico-chemical properties of the sol-gel derived  $CoFe_2O_4/ZrO_2$  nanoparticles was investigated in detail.

## MATERIALS AND METHODS

**Materials:** The precursors and chemicals required for the synthesis of  $CoFe_2O_4/ZrO_2$  nanoparticles i.e. cobalt (II) nitrate hexahydrate (ACS reagent,  $\geq 98\%$ ), iron (III) nitrate nonahydrate (ACS reagent,  $\geq 98\%$ ), ethanol, and propylene oxide (gelation agent) were purchased from Alfa Aesar and Sigma Aldrich and used without any pre-treatment.

**Synthesis of  $CoFe_2O_4/ZrO_2$  nanoparticles:** The  $CoFe_2O_4/ZrO_2$  nanoparticles were derived via sol-gel method. At first, cobalt (II) nitrate hexahydrate and iron (III) nitrate nonahydrate were dissolved in ethanol (in respective weight ratio) by using a sonic bath. After the dissolution, different amounts of propylene oxide (as a proton scavenger) were added drop-wise and the gel formation was achieved. The  $CoFe_2O_4/ZrO_2$  gel was aged for multiple hours at atmospheric conditions. After aging, the gel was dried at  $100^\circ C$  for 2 h using a temperature-controlled hot plate. The dried powder obtained was further calcined at  $1000^\circ C$ . The obtained calcined powder was stored in a dry atmosphere and then further characterized to determine the phase composition, crystallite size ( $C_s$ ), specific surface area (SSA), pore volume ( $P_v$ ), and particle morphology.

**Characterization of sol-gel derived  $CoFe_2O_4/ZrO_2$  nanoparticles:** The physico-chemical characterization of the sol-gel derived  $CoFe_2O_4/ZrO_2$  was carried out by using different characterization techniques. The phase composition and  $C_s$  of  $CoFe_2O_4/ZrO_2$  was determined by using powder X-ray diffractometer.  $C_s$  was calculated by using the Scherrer's equation. The SSA and  $P_v$  of the sol-gel derived  $CoFe_2O_4/ZrO_2$  was estimated using the BET surface area analyzer via the adsorption/desorption isotherms obtained after degassing the calcined powder at  $200^\circ C$  for 12 h. The particle morphology was determined using scanning electron microscope (SEM).

## RESULTS AND DISCUSSION

The effect of addition of propylene oxide as a proton scavenger on the gel time, phase composition,  $C_s$ , SSA and  $P_v$  of the sol-gel derived  $CoFe_2O_4/ZrO_2$  was studied in detail. At first, the variation in the gel time with respect to the amounts of propylene oxide added was examined and the obtained results are presented in fig. 1 (10 g of metal precursors + 20 ml of ethanol). As shown in fig. 1, as the amounts of propylene oxide added increases the time required for gel formation decreases. By adding 5 ml of propylene oxide, the  $CoFe_2O_4/ZrO_2$  gel formation can be achieved in 450 sec. As the amount increase upto 10 mL, the gel time decreases to 380 sec. Furthermore increase in the amount of propylene oxide added induces a quick  $CoFe_2O_4/ZrO_2$  gel formation. For instance, when 15 and 20 mL of propylene oxide was added the gel was formed in 300 and 200 sec, respectively. Addition of propylene oxide as a proton scavenger helps in freezing the molecular chains and reducing the time required for gel formation.

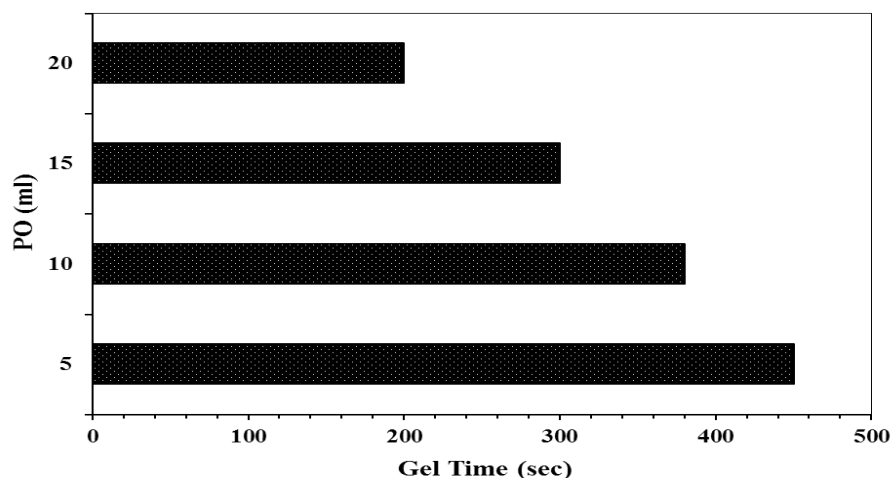


Fig. 1: Effect of amount of propylene oxide added as a proton scavenger on time required for  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  gel formation.

In addition to the gel time, the phase composition and the  $C_s$  of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  gel prepared by adding different amount of propylene oxide and aged for 24 h was also determined. The aged gel was dried at  $100^\circ\text{C}$  and further calcined at  $1000^\circ\text{C}$  in presence of air. The calcined powder was further characterized using a powder X-ray diffractometer. The XRD patterns obtained are reported in fig. 2. These XRD patterns indicate that due to the addition of different amounts of proton scavenger the phase composition of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  does not altered.

Furthermore, by utilizing results obtained via X-ray diffraction, the  $C_s$  of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was calculated by using Scherrer's equation. The variation in the  $C_s$  of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  as a function of propylene oxide added as a proton scavenger is shown in fig. 3. The reported results indicate that the  $C_s$  of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  also remains unaffected due to the increase in the amount of propylene oxide added during sol-gel synthesis. The  $C_s$  of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  calcined at  $1000^\circ\text{C}$  was observed to be in the range of 53.56 to 53.95 nm. These results further indicate that the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  nanoparticles are formed.

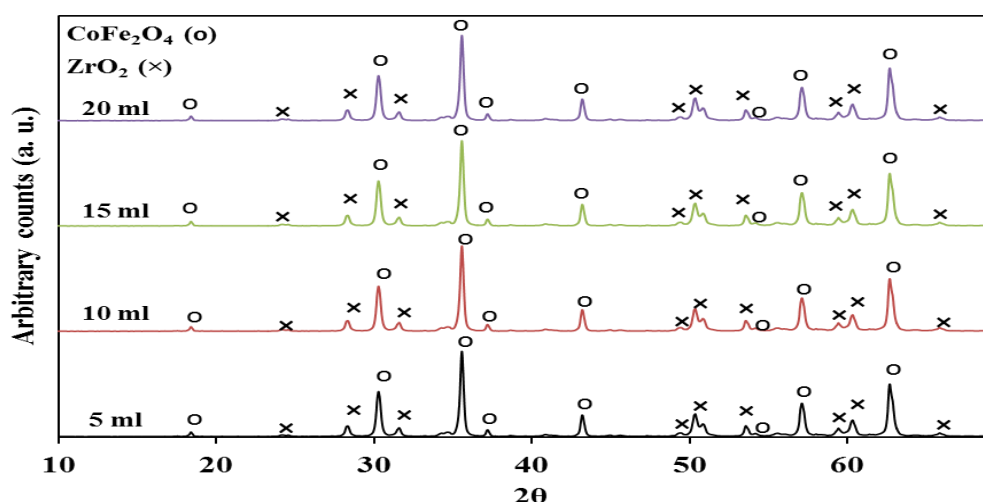


Fig. 2: Effect of amount of propylene oxide added as a proton scavenger on phase composition of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ .

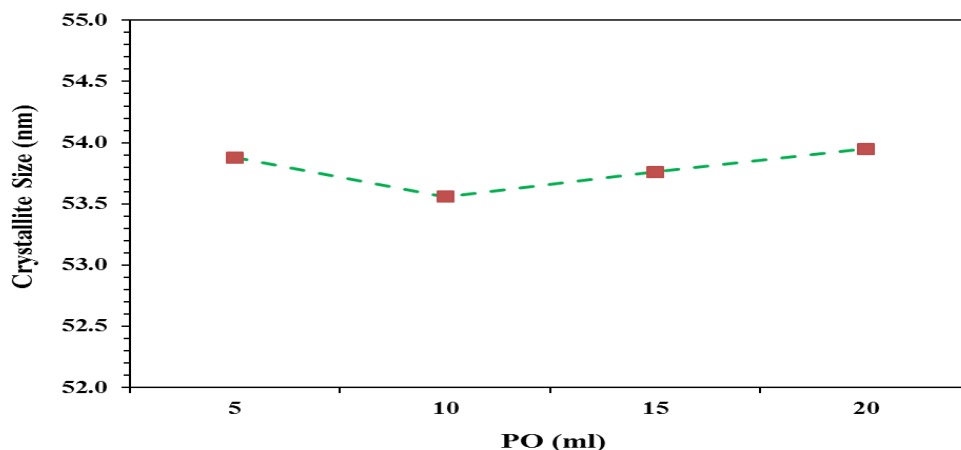


Fig. 3: Effect of amount of propylene oxide added as a proton scavenger on  $C_s$  of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ .

After analysing the effect of amount of propylene oxide added as a proton scavenger on gel time, phase composition and  $C_s$ , the variation in the SSA and  $P_v$  was also explored. As shown in fig. 4, the SSA of the sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was observed to be increased with the increase in the amount of propylene oxide used. Initially, when 5 mL of propylene oxide was added, the SSA of the derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was observed to be equal to  $2.45 \text{ m}^2 \text{ g}^{-1}$ . As the amount of propylene oxide added increases to 10, 15, and 20 mL, the SSA was also increased by a factor of 2.27, 3.55, and 4.18, respectively.

Similar to the SSA, the  $P_v$  was also observed to be boosted as the amount of propylene oxide used was increased (Fig. 5). At propylene oxide amount equal to 5 mL, the  $P_v$  of the sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was observed to be  $4.6 \times 10^{-4} \text{ cm}^3 \text{ g}^{-1}$ . As the amount of propylene oxide increases to 10 mL, the  $P_v$  was also increased to  $8.5 \times 10^{-4} \text{ cm}^3 \text{ g}^{-1}$ . With further increase in the amount of propylene oxide used (15 and 20 mL), the  $P_v$  of the sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was observed to be enhanced to  $13.8 \times 10^{-4}$  and  $15.0 \times 10^{-4} \text{ cm}^3 \text{ g}^{-1}$ , respectively.

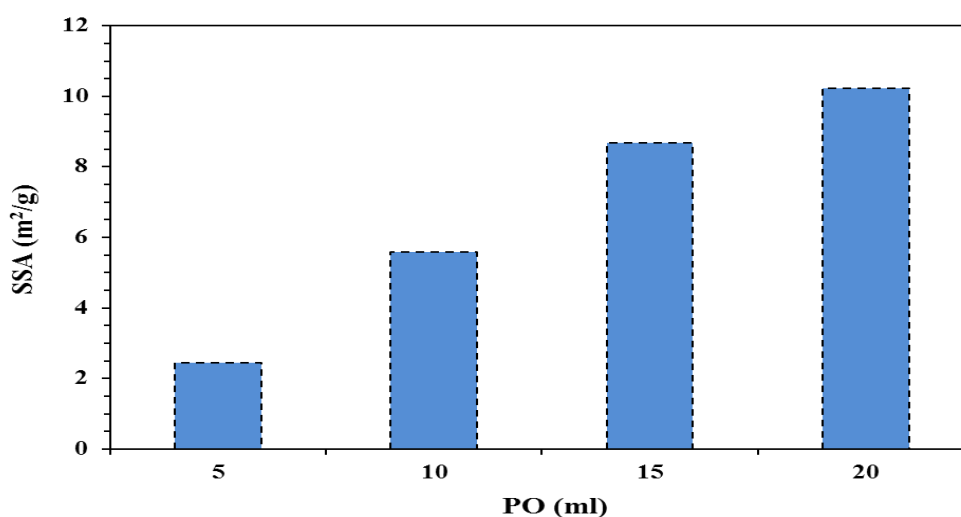


Fig. 4: Effect of amount of propylene oxide added as a proton scavenger on SSA of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ .

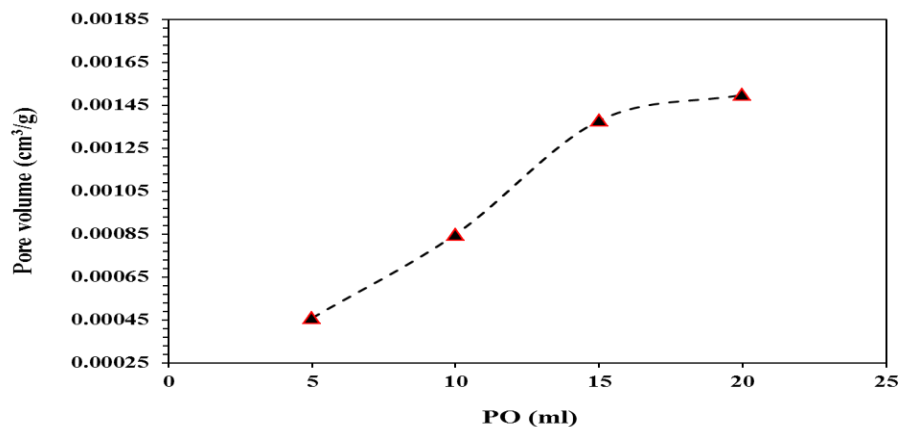


Fig. 5: Effect of amount of propylene oxide added as a proton scavenger on  $P_V$  of the  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ .

The particle morphology of the sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was also analyzed via SEM analysis. The SEM picture is reported in fig. 6 and it indicates formation of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  nanoparticles in the range of 50 to 100 nm.

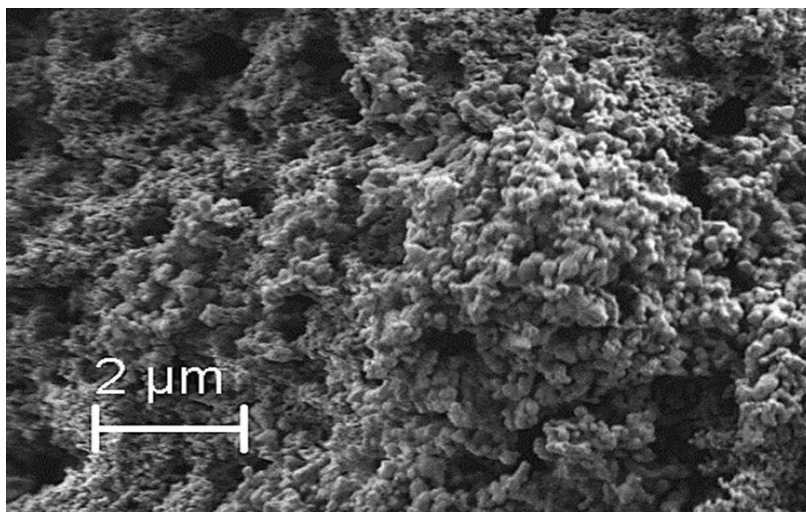


Fig. 6: SEM image of sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ .

After investigating the effect of addition of proton scavenger on physico-chemical properties of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ , the effect of aging time was also examined. Aging of the gels provides them the required mechanical strength and improves the molecular network connectivity which results into significant homogeneity of the synthesized material. To study the effect of aging on physico-chemical properties of sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ , the gels prepared with 20 mL of propylene oxide were used. These gels were aged for different time intervals (24 to 120 h) at atmospheric conditions. After aging, the gels were dried and further calcined at  $1000^\circ\text{C}$  in air. The calcined powder was further characterized using powder X-ray diffraction and BET surface area analyzer. The characterization results indicate no change in the phase composition,  $C_s$ , SSA, and  $P_V$  of the sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ . This observation indicates that although aging helps to achieve the desired chemical homogeneity, other physico-chemical properties such as phase composition, SSA, porosity, and crystallite size stays intact.

## APPLICATIONS

The sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  will be examined towards their redox reactivity and thermal stability by performing multiple solar thermochemical  $\text{H}_2\text{O}$  and  $\text{CO}_2$  splitting cycles by using a Thermogravimetric analyzer (TGA). The  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  synthesized in this paper shows promising physico-chemical properties such as phase pure composition, no impurities, high SSA and porosity, and also nanoparticle morphology. Therefore, it is expected that this material will perform better during thermochemical cycles as compared to previously investigated ferrite/grain growth inhibitor mixtures.

## CONCLUSIONS

The synthesis of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  nanoparticles was successfully achieved via propylene oxide assisted sol-gel method. Effect of propylene oxide as a proton scavenger and aging time on physico-chemical properties of sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was investigated in detail. It was observed that with the increase in the amount of propylene oxide used during the sol-gel synthesis of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$ , the time required for gel formation decreases. For instance, as the amount of propylene oxide used increase from 5 to 20 ml, the gel time decreases by 250 sec. The phase composition and crystallite size of the sol-gel derived  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  was observed to be unaffected due to the increase in the amount of propylene oxide used using synthesis. However, the SSA and pore volume was observed to be increased significantly. For instance, as the usage of propylene oxide increase from 5 to 20 mL, the SSA was increased by a factor of 4.18 and the pore volume was enhanced by a factor of 3.26, respectively. The study of effect of gel aging shows that, although the chemical homogeneity can be increased via aging, the physico-chemical properties of  $\text{CoFe}_2\text{O}_4/\text{ZrO}_2$  remained unaltered.

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## REFERENCES

- [1] R. R. Bhosale, A. Kumar, F. AlMomani, I. Alxneit, [Sol-gel derived  $\text{CeO}_2\text{-Fe}_2\text{O}_3$  nanoparticles: Synthesis, characterization and solar thermochemical application], *Ceram. Int.*, **2016**, in press. doi:10.1016/j.ceramint.2016.01.042.
- [2] J. Scheffe, A. Steinfeld, [Oxygen exchange materials for solar thermochemical splitting of  $\text{H}_2\text{O}$  and  $\text{CO}_2$  : a review], *Mater. Today*, 2014, 17, 341 – 348.
- [3] D. Dardor, R. R. Bhosale, S. Gharbia, A. AlNouss, A. Kumar, F. AlMomani, [Solar carbon production via thermochemical  $\text{ZnO}/\text{Zn}$  carbon dioxide splitting cycle], *J. Emerg. Trends Eng. Appl. Sci.*, **2015**, 6, 129 – 135.
- [4] D. Dardor, R. R. Bhosale, S. Gharbia, A. Kumar, F. AlMomani, [Solar thermochemical conversion of  $\text{CO}_2$  into C via  $\text{SnO}_2/\text{SnO}$  redox cycle: Thermodynamic study], *Int. J. Eng. Res. Appl.*, **2015**, 5, 134 – 140.
- [5] R. R. Bhosale, A. Kumar, F. AlMomani, U. Ghosh, D. Dardor, Z. Bouabidi, M. Ali, S. Yousefi, A. AlNouss, M. S. Anis, M. H. Usmani, M. H. Ali, R. S. Azzam, A. Banu, [Solar co-production of samarium and syngas via methanothermal reduction of samarium sesquioxide], *Energy Convers. Manage.*, **2016**, 112, 413 – 422.



- [6] R. R. Bhosale, A. Kumar, F. AlMomani, S. Al-Muhtaseb, R. Gupta, I. Alxneit, [Assessment of  $Ce_xZr_yHf_zO_2$  based oxides as potential solar thermochemical  $CO_2$  splitting materials], *Ceram. Int.*, **2016**, in press. doi:10.1016/j.ceramint.2016.02.100
- [7] A. M. Turkey, [Catalytic oxidation of CO over pure and doped Cu-Ni-O System], *J.Applicable.Chem*, 2016, 5 (1), 219 – 230.
- [8] V. K. Mahajan, G. H. Sonawane, [Improved photocatalytic activity of  $CeO_2$  coupling ultrasound for Eosin-Y degradation], *J.Applicable.Chem*, 2015, 4 (5), 1500 – 1506.
- [9] B. Suryanarayana, V. Raghavendra, K. ChandraMouli, [Structural, electrical and magnetic properties of  $Ni_{0.5}Zn_{0.5}Fe_2O_4$  nanoscale particles by co-precipitation method], *J.Applicable.Chem*, 2015, 4 (4), 1237 – 1242.
- [10] C. S. Thatte, M. V. Rathnam, M. S. Kumar, [Synthesis, characterization and application of Chitosan based Schiff base-transition metal complexes (Mn,Cu,Co,Ni)], *J.Applicable.Chem*, 2013, 2 (5), 1192 – 1206.
- [11] B. R. Gaikwad, P. P. Khirade, D. V. Kurmude, A. B. Shinde, A. A. Pandit, K. M. Jadhav, [Comparative study of the structural and magnetic properties of magnesium ferrite prepared by ceramic and sol-gel auto combustion technique], *J.Applicable.Chem*, 2013, 2 (5), 1275 – 1280.
- [12] M. R. Devi, C. Kannan, [Synthesis of unusual large pore Mg substituted alumino phosphate ( $MgAlPO_4$ ) mesoporous molecular sieve and its catalytic activity], *J.Applicable.Chem*, 2013, 2 (3), 398 – 404.
- [13] C. Agrafiotis, C. Pagkoura, A. Zygogianni, G. Karagiannakis, M. Kostoglou, A. G. Konstandopoulos, [Hydrogen production via solar-aided water splitting thermochemical cycles: Combustion synthesis and preliminary evaluation of spinel redox-pair materials], *Int. J. Hydrogen Energy*, **2012**, 37, 8964 – 8980.
- [14] N. Gokon, T. Kodama, N. Imaizumi, J. Umeda, T. Seo, [Ferrite/zirconia-coated foam device prepared by spin coating for solar demonstration of thermochemical water-splitting], *Int. J. Hydrogen Energy*, **2011**, 36, 2014 – 2028.
- [15] R. R. Bhosale, R. V. Shende, J. A. Puszynski, [ $H_2$  generation from thermochemical water splitting using sol-gel derived Ni-ferrite], *J. Energy Power Eng*, **2010**, 4, 27 – 38.
- [16] R. R. Bhosale, R. V. Shende, J. A. Puszynski, [ $H_2$  generation from thermochemical water-splitting using sol-gel synthesized Zn/Sn/Mn-doped Ni-ferrite], *Int. Rev. Chem. Eng*, **2010**, 2, 852 – 862.
- [17] F. Fresno, T. Yoshida, N. Gokon, R. Fernandez-Saavedra, T. Kodama, [Comparative study of the activity of nickel ferrites for solar hydrogen production by two-step thermochemical cycles], *Int. J. Hydrogen Energy*, **2010**, 35, 8503 – 8510.
- [18] M. Roeb, N. Gathmann, M. Neises, C. Sattler, R. Pitz-Paal, [Thermodynamic analysis of two-step solar water splitting with mixed iron oxides], *Int. J. Energy Res*, **2009**, 33, 893 – 902.
- [19] R. R. Bhosale, R. P. Khadka, J. A. Puszynski, R. V. Shende, [ $H_2$  generation from two-step thermochemical water-splitting reaction using sol-gel derived  $Sn_xFe_yO_z$ ], *J. Renewable Sustainable Energy*, 2011, 3, 063104-1 – 063104-12.
- [20] R. R. Bhosale, R. V. Shende, J. A. Puszynski, [Thermochemical water-splitting for  $H_2$  generation using sol-gel derived Mn-ferrite in a packed bed reactor], *Int. J. Hydrogen Energy*, **2012**, 37, 2924 – 2934.
- [21] F. Fresno, R. Fernandez-Saavedra, M. Gomez-Mancebo, A. Vidal, M. Sanchez, M. Rucandio, A. Quejido, M. Romero, [Solar hydrogen production by two-step thermochemical cycles: Evaluation of the activity of commercial ferrites], *Int. J. Hydrogen Energy*, **2009**, 34, 2918 – 2924.

- [22] M. Allendorf, R. Diver, N. Siegel, J. Miller, [Two-step water splitting using mixed-metal ferrites: thermodynamic analysis and characterization of synthesized materials], *Energy Fuels*, **2008**, 22, 4115 – 4124.
- [23] R. R. Bhosale, A. Kumar, L.J.P. van den Broeke, S. Gharbia, D. Dardor, M. Jilani, J. Folady, M. Al-Fakih, M. Tarsad, [Solar hydrogen production via thermochemical iron oxide–iron sulfate water splitting cycle], *Int. J. Hydrogen Energy*, **2015**, 40, 1639 – 1650.
- [24] T. Kodama, N. Gokon, R. Yamamoto, [Thermochemical two-step water splitting by ZrO<sub>2</sub>-supported Ni<sub>x</sub>Fe<sub>3-x</sub>O<sub>4</sub> for solar hydrogen production], *Sol. Energy*, **2008**, 82, 73 – 79.
- [25] J. R. Scheffe, J. Li, A. W. Weimer, [A spinel ferrite/hercynite water-splitting redox cycle], *Int. J. Hydrogen Energy*, **2010**, 35, 3333 – 3340.
- [26] J. E. Miller, M. Allendorf, R. Diver, L. Evans, N. Siegel, J. Stuecker, [Metal oxide composites and structures for ultra-high temperature solar thermochemical cycles], *J. Mater. Sci*, **2008**, 43, 4714 – 4728.
- [27] T. Kodama, Y. Kondoh, R. Yamamoto, H. Andou, N. Satou, [Thermochemical two-step water splitting by ZrO<sub>2</sub>-supported Ni<sub>x</sub>Fe<sub>3-x</sub>O<sub>4</sub> for solar hydrogen production], *Sol. Energy*, **2008**, 78, 623 – 631.
- [28] R. R. Bhosale, A. Kumar, F. AlMomani, I. Alxneit, [Propylene oxide assisted sol–gel synthesis of zinc ferrite nanoparticles for solar fuel production], *Ceram. Int*, **2016**, 42, 2431 – 2438.
- [29] M. Neises, M. Roeb, M. Schmucker, C. Sattler, R. Pitz-Paal, [Kinetic investigations of the hydrogen production step of a thermochemical cycle using mixed iron oxides coated on ceramic substrates], *Int. J. Energy Res*, **2010**, 34, 651 – 661.
- [30] S. Lorentzou, A. Zygogianni, K. Tousimi, C. Agrafiotis, A. G. Konstandopoulos, [Advanced synthesis of nanostructured materials for environmental applications], *J. Alloys Compd*, **2009**, 483, 302 – 305.
- [31] R. R. Bhosale, A. Kumar, F. AlMomani, [Solar thermochemical hydrogen production via terbium oxide based redox reactions], *Int. J. Photoenergy*, **2016**, vol. 2016, Article ID 9727895, 9 pages, 2016. doi:10.1155/2016/9727895.
- [32] S. Lorentzou, A. C. Agrafiotis, A. G. Konstandopoulos, [Aerosol spray pyrolysis synthesis of water-splitting ferrites for solar hydrogen production], *Granular Matter*, **2008**, 10, 113 – 122.
- [33] H. Kaneko, T. Miura, A. Fuse, H. Ishihara, S. Taku, H. Fukuzumi, Y. Naganuma, Y. Tamaura, [Rotary-type solar reactor for solar hydrogen production with two-step water splitting process], *Energy Fuels*, **2007**, 21, 2287 – 2293.

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