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# Hydrogen generation by means of the combustion of aluminum powder/sodium borohydride in steam

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ABSTRACT

Hydrogen generation by means of the combustion of aluminum powder with sodium borohydride ($NaBH_4$) addition in steam was studied by a pipe furnace at different temperatures. The ignition temperature and the maximum combustion temperature were obtained by an S-type thermocouple. Ignition delay times and combustion efficiencies were measured. The results show that aluminum powder is not ignited at 450 °C, but aluminum powder with $NaBH_4$ addition is ignited under the same condition. The addition of $NaBH_4$ significantly decreases the ignition delay time of aluminum powder. Moreover, the ignition delay times of aluminum powder without or with $NaBH_4$ addition can decrease with increasing the temperature. Combustion products were analyzed by scanning electron microscopy, X-ray diffraction and a portable hydrogen analyzer. The results indicate that $NaBH_4$ displays a key influence on hydrogen generation. Especially, for aluminum powder with 7 wt% $NaBH_4$ addition, the obtained maximum volume concentration of hydrogen is about 21,000 ppm at 650 °C.



## Introduction

Hydrogen with a high calorific value and zero pollutant emissions is of interest as a regenerative and environmentally friendly fuel [1,2]. At present, the application of portable electronic devices for space and underwater vehicle is becoming widespread and acclaimed. In this context, hydrogen fuel cells have been suggested as power sources for portable applications, and have gained extensive attention [3]. Hydrogen storage, however, is one of the critical challenges in developing the hydrogen fuel cell [4]. Indeed, water contains the abundant hydrogen resource, about 11 wt% [5]. In order to solve this problem, aluminum has been identified as a suitable choice for hydrolyzing metal due to its considerable energy capacity [6]. Therefore, the reaction between aluminum and water is a potential hydrogen generation method, and the hydrogen can be released by the reaction (1) at the high temperature [7].

$$Al + \frac{3}{2} H_2O \rightarrow Al_2O_3 + \frac{3}{2} H_2 \quad (1)$$

During the reaction process of aluminum and water, solid phase products easily cover on the surfaces of aluminum particles and prevent water from contacting the fresh aluminum, which hinder the continued hydrogen generation [6]. Thus, removing the oxide film on the surface of aluminum powder is a key factor to overcome this issue. Many studies have focused on developing the hydrolysis properties of aluminum–water reaction by using mechanical treatments [8], elevating temperature [9], and adding alkaline solution or metal additives [10,11].

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Temperature is recognized as a key factor to influence on hydrogen generation [9,12]. Mahmoodi et al. [13] found that hydrogen generation rate depended crucially on the initial temperature of water. When aluminum powder was immersed in water at initial temperature rising from 50 to 70 °C, the average hydrogen generation rate was significantly increased from 101 to 210 mL $min^{-1}$ $g^{-1}$. Fan et al. [14] studied the effect of hydrolytic temperature on the hydrogen production performance of Al–Li–In–Zn alloy. The result indicated that increasing the temperature from 20 °C to 30, 40 and 50 °C, the hydrogen production efficiencies are 44%, 53%, 75%, and 100%, respectively. Yang et al. [15] investigated the hydrogen generation process of the Al–Li alloy in steam heated to 700 °C. For the Al-20% Li, the obtained maximum hydrogen rate reached about 310 mL $min^{-1}$ $g^{-1}$.

The hydrolysis of borohydrides of light metals (Li, Na, Mg, Al) is a well-known hydrogen generation method. It has attracted common attention and been extensively studied for last decades [16,17]. Compared with pure aluminum powder, the addition of sodium borohydride provided more advantageous to enhance the reactivity of aluminum and water [18]. Fan et al. [19] found that milled Al–Li alloy and solid–state $NaBH_4$ with the addition of $CoCl_2$ had a hydrogen storage capacity as high as 6.4 wt%. Soler et al. [20] proposed a new method to produce the high pure hydrogen by the reaction of aluminum and aqueous alkaline solution. Moreover, they found AlCo/$NaBH_4$ had a more synergistic influence on hydrolysis performance compared to Al/$NaBH_4$. Liu et al. [21] fabricated the solid-state $NaBH_4$/Ru-based catalyst composites by a high-energy ball-milling method. The results showed that the gravimetric hydrogen storage capacity of $NaBH_4/H_2O$ would be affected by the main hydrolyzed product $NaBO_2 \cdot xH_2O$.

It can be found from the discussion above that many efforts are made to investigate the hydrogen generation by aluminum alloy and aqueous solution at a low temperature. However, there is lack about hydrogen generation by aluminum and water at a high temperature. Shafirovich et al. [22–24] focused on the hydrogen yield and combustion efficiency of $NaBH_4/Al/H_2O$ based fuels rather than the effect of $NaBH_4$ on aluminum–water reaction. Therefore, this work focused on the reaction of aluminum powder with different contents of $NaBH_4$ addition and steam that is heated at different temperatures. The combustion products were collected and analyzed by different approaches, so as to reveal the reaction mechanism of aluminum powder with $NaBH_4$ addition in steam. The results of our work will provide a theoretical basic for application of distributed energy supply.

## Experimental section

### *Materials and sample preparation*

The compositions of samples are shown in Table 1. Nano-aluminum (nAl) powder which has an average particle size of 50 nm, was supplied from Jiaozuo Nano Material Inc in China. Fig. 1 shows the scanning electron microscopy (SEM) image of nAl powder. The active aluminum content is approximately 80.8%, which is measured by the principle of permanganatometric method [25]. The solid-state $NaBH_4$ (purity 99.0%, analytical grade chemicals) was purchased from Aladdin of China. nAl powder was adequately mixed with $NaBH_4$ addition in mass ration of 3 wt% and 7 wt%, respectively.

**Table 1 – Compositions of samples.**

| Samples | Al/wt% | $NaBH_4$/wt% |
|---|---|---|
| Al-1 | 100 | – |
| Al-2 | 97 | 3 |
| Al-3 | 93 | 7 |

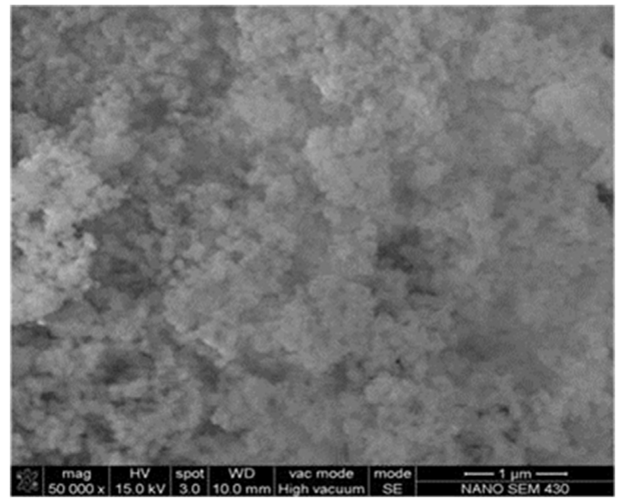


**Fig. 1 – SEM image of aluminum powder with an average particle size of 50 nm.**

### *Apparatus and measurement methods*

A self-built experimental facility is shown schematically in Fig. 2. The high temperature pipe furnace was used to heat steam. The temperature of steam was controlled by a thermoregulator. In order to improve the accuracy of experiment, the quartz tube was kept seal and the steam was flowed into the quartz tube to expel air. The steam was produced through a steam generator. The steam flow was controlled at 15 mL $min^{-1}$. It should be noted that the steam was continuously fed into the quartz tube at different temperatures when the sample was heated. 100 mg of sample was placed in the alumina crucible in each experiment. Once the temperature of steam was stable, the alumina crucible with sample was put into the quartz tube. The practicality picture of feeding device is shown in Fig. 3. Then, the sample immediately reacted with the steam to product hydrogen. An S-type thermocouple was inserted in the middle of sample to monitor the temperature. The temperature data was recorded via a data-acquisition instrument of Agilent (34972A, USA). The gas mixture was cooled and dried by a condensing apparatus and a dryer. Finally, the volume concentration of hydrogen in gas mixture was measured by a portable hydrogen analyzer (GA-21plus, Madur, Austria).