# **RSC Advances**

## PAPER

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Cite this: RSC Adv., 2016, 6, 35305

# Kinetics study of the Al–water reaction promoted by an ultrasonically prepared Al(OH)<sub>3</sub> suspension<sup>†</sup>

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The kinetics of the Al-water reaction promoted by an ultrasonically prepared Al(OH)<sub>3</sub> suspension is investigated. It is found that the induction time for the beginning of the Al-water reaction decreases and the reaction rate increases with increasing suspension concentration, volume, and temperature, because the Al-water reaction is exothermic. When the weight ratio of Al to water increases to 1 : 15, there is almost no induction time, and more than 80% of Al in the Al(OH)<sub>3</sub> suspension is consumed within 40 min, which is comparable to the behavior of Al in NaOH solution. A collision model based on Brownian motion is proposed to analyze the reaction process, which shows that the contact between Al and Al(OH)<sub>3</sub> particles and the reaction heat are two key factors that control the reaction progress.

Received 19th January 2016 Accepted 3rd April 2016

DOI: 10.1039/c6ra01627h

www.rsc.org/advances

## 1. Introduction

Hydrogen has a high calorific value, and its reaction by-product is environmentally benign, which makes it an ideal fuel for fuel cells. Storage and transportation of hydrogen remain a problem, however, due to its low boiling point (-252 °C) and very poor compressibility. There has been a great deal of research to solve this problem. Hydrogen-generation materials are one of the choices, because they are reactive toward hydrolysis in water and generate hydrogen on site, which makes them suitable for portable applications. Al metal is a promising hydrogen-generation material due to its relatively low price, light atomic weight, and abundance ( $\sim$ 8.1%) in the Earth's crust.<sup>1,2</sup> One kg of Al reacts with water to generate as much as 0.11 kg H<sub>2</sub>, although, usually, there is a dense passive oxide film on the Al particle surface, inhibiting the reaction of Al with water.<sup>3-5</sup>

In the past few years, many methods have been developed to activate Al metal so that Al can directly react with water, *e.g.* using an alkaline solution,<sup>6-14</sup> alloying Al by doping with Ga, In, Bi, Sn, *etc.*,<sup>15-23</sup> mechanically milling Al metal with special oxides and soluble inorganic salts,<sup>24-29</sup> mixing Al with alkaline chemicals,<sup>30-33</sup> ceramic oxide modification, *etc.*<sup>34-39</sup> For the

above methods, however, the pollution concerns about alkaline solutions, the high price of rare metals, and the need for complicated activation procedures have set back the prospects for Al-hydrogen technology in commercial applications.

Recently, a neutral Al(OH)<sub>3</sub> suspension was used to promote the Al-water reaction,<sup>40-46</sup> and no processing procedure was needed to activate the Al metal. Therefore, this is a relatively simple way to realize the Al-water reaction to generate hydrogen, although the Al-water reaction rate is slow if commercial Al(OH)<sub>3</sub> powder is used. Yang et al. prepared a highactivity Al(OH)<sub>3</sub> suspension by the reaction of Al with water using an ultrasonic procedure.<sup>42</sup> This high-activity Al(OH)<sub>3</sub> suspension considerably promotes the Al-water reaction and hydrogen generation. In this work, the Al-water reaction kinetics promoted by the ultrasonically prepared Al(OH)<sub>3</sub> suspension is investigated, with the results indicating that when the weight ratio of Al to water increases to a high value in practical application, the hydrogen-generation rate is fast and comparable to that of Al in NaOH solution, which could meet the practical requirement.

## 2. Experimental procedure

Two kinds of Al powders with the average sizes of 1.32  $\mu$ m (99.9% purity, Henan Yuan Yang Aluminum Industry Co., China) and 7.29  $\mu$ m (99.9% purity; High Purity Chemical Co., Tokyo, Japan) were used in the present study. The procedure to prepare Al(OH)<sub>3</sub> suspension by an ultrasonic method was given in a previous work,<sup>42</sup> where 1.32  $\mu$ m Al powder was put into a beaker with deionized water, and then ultrasonically treated in an ultrasonic vessel (40 kHz, 150 W) at 40 °C for a certain time period (~4.5 h) so that the Al powder could completely react with water.

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<sup>†</sup> Electronic supplementary information (ESI) available. See DOI: 10.1039/c6ra01627h

The Al-water reaction tests in the above ultrasonically prepared Al(OH)<sub>3</sub> suspension were carried out in a closed glass reactor with a volume of ~1300 ml, under which a thermostatically controlled water bath was placed to control the reaction temperature (if not specially mentioned).<sup>47</sup> The real temperature in the Al(OH)<sub>3</sub> suspension was measured by a thermometer inside the reactor. 7.29  $\mu$ m Al powder was used in all the reaction tests, in which the Al powder was suspended in Al(OH)<sub>3</sub> suspension and no agitation was used. As the reaction of Al with water produces only H<sub>2</sub>, the amount of generated H<sub>2</sub> was used to characterize the progress of the reaction of Al with water. The hydrogen evolution is determined by the gas pressure in the reactor using the ideal-gas equation:

$$\alpha_{\rm s} = \frac{(P - P_{\rm initial}) (V_{\rm reactor} - V_{\rm H_2O} - V_{\rm Al})}{n_0 R T}$$
(1)

where  $\alpha_s$  is the hydrogen yield; *P* and *P*<sub>initial</sub> are the total gas pressure and the initial gas pressure in the reactor, respectively (the initial gas pressure is 1 bar); *V*<sub>reactor</sub>, *V*<sub>H<sub>2</sub>O</sub>, and *V*<sub>Al</sub> are the volumes of the reactor, water, and Al powder, respectively; and  $n_0$  is the theoretical number of hydrogen moles obtained by reacting all of the Al metal. At least two identical tests were carried out to test the reproducibility of each hydrogengeneration curve. Scanning electron microscopy (SEM) was used to observe the morphologies of the pure Al powders and the Al(OH)<sub>3</sub> obtained by filtering and drying the Al(OH)<sub>3</sub> suspension.

## 3. Results

Fig. 1 shows the morphologies of the pure Al powders and the  $Al(OH)_3$  particles obtained from the  $Al(OH)_3$  suspension.

Fig. 2 shows  $H_2$  evolution by the addition of 7.29  $\mu$ m Al powder into deionized water (250 ml) or Al(OH)<sub>3</sub> suspensions with different volumes at 25 °C, where 1.0 g of Al powder is added into water or suspension in each test and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is always 9 : 1.



Fig. 2 H<sub>2</sub> evolution by the addition of 7.29  $\mu$ m Al powder into deionized water (250 ml) or Al(OH)<sub>3</sub> suspensions with different volumes at 25 °C, where 1.0 g of Al powder is used in each test and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is always 9 : 1. The inset shows the variation of temperature with time for the Al–water reaction in 30 ml Al(OH)<sub>3</sub> suspension.



Fig. 1 SEM micrographs of pure Al powders with the average particle sizes of  $1.32 \,\mu$ m (a) and  $7.29 \,\mu$ m (b), and Al(OH)<sub>3</sub> powder prepared by the reaction of  $1.32 \,\mu$ m Al powder with water using an ultrasonic procedure (c).

The induction time for the Al-water reaction in deionized water is long (>50 h, details not shown), however, it decreases to ~3 h when an high-activity  $Al(OH)_3$  suspension with the same volume is used. It can be seen that when the weight ratio of Al to water in the suspension increases from 1 : 250 (250 ml water) to 1 : 30 (30 ml water), the induction time decreases from ~3 h to ~1 h, indicating that increasing the  $Al(OH)_3$  concentration in the suspension decreases the induction time, because the amount of  $Al(OH)_3$  in all the suspensions is the same. The inset in Fig. 2 shows that there is a small temperature rise during the reaction in the 30 ml suspension, even though a thermostatically controlled water bath is used, indicating that the reaction heat (426.5 kJ mol  $Al^{-1}$ ) cannot diffuse away within a limited time.

Fig. 3 shows  $H_2$  evolution by the addition of 7.29 µm Al powder into Al(OH)<sub>3</sub> suspensions with a solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension that is always 8 : 2, where the other parameters are the same as those in Fig. 2. Compared with the results in Fig. 2, it is clear that the induction time decreases and the reaction rate increases with increasing Al(OH)<sub>3</sub> concentration in suspensions with the same volume. In Fig. 3, when the weight ratio of Al to water in the suspension increases from 1 : 250 (250 ml water) to 1 : 30 (30 ml water), the induction time decreases from ~2 h to ~0.5 h. Furthermore, the temperature rise during the reaction in the 30 ml suspension in Fig. 3 is higher than that in Fig. 2, indicating that more reaction heat doesn't diffuse away due to the faster reaction rate.

Fig. 4 shows  $H_2$  evolution by the addition of 7.29 µm Al powder into 30 ml of Al(OH)<sub>3</sub> suspension at different temperatures, where the weight ratio of Al to water in the suspension is 1 : 30. It can be seen that the induction time decreases and the reaction rate increases with increasing temperature. The induction time for a solid volume ratio 8 : 2 of Al to Al(OH)<sub>3</sub> in the suspension is shorter and its reaction rate is faster than those for a solid volume ratio 9 : 1. For the suspension with the solid volume ratio 8 : 2 of Al to Al(OH)<sub>3</sub>, when the temperature increases to 35 °C (308 K), there is no reaction induction time,



Fig. 3 H<sub>2</sub> evolution by the addition of 7.29  $\mu$ m Al powder into Al(OH)<sub>3</sub> suspensions with different volumes at 25 °C, where 1.0 g of Al powder is used in each test and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is always 8 : 2. The inset shows the variation of temperature with time for the Al–water reaction in 30 ml Al(OH)<sub>3</sub> suspension.



Fig. 4  $H_2$  evolution by the addition of 7.29  $\mu$ m Al powder into 30 ml of Al(OH)<sub>3</sub> suspension at different temperatures, where 1.0 g of Al powder is used in each test and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is always (a) 9 : 1 and (b) 8 : 2, respectively.

and >90% of the Al metal is consumed within 2.5 h. When the temperature is 55 °C (328 K), >90% of the Al metal is consumed within 1 h for both of the above suspensions. This indicates that temperature is an important factor affecting the induction time and reaction rate.

If no thermostatically controlled water bath is used, the heat generated by the Al-water reaction will diffuse more slowly, because the thermal conductivity of air (0.023 W  $m^{-1}$  $K^{-1}$ ) is much lower than that of water (0.6 W m<sup>-1</sup> K<sup>-1</sup>), which is close to the situation in practical application. In this case, the temperature of the suspension will increase rapidly with the progress of the reaction. Fig. 5 shows the H<sub>2</sub> evolution and variation of water temperature by the addition of 7.29 µm Al powder into the Al(OH)<sub>3</sub> suspension at an initial temperature of 25 °C without thermostatic control of the water bath, where the weight ratio of Al to water is always 1:30 and the solid volume ratio of Al to  $Al(OH)_3$  in the suspensions is 8 : 2. (This means that the amount of Al powder increases linearly with increasing suspension volume.) It can be seen that the reaction rate and water temperature rise increase rapidly with increasing suspension volume. This is because with the increase in suspension volume, more Al metal joins the reaction, and more reaction heat is released as the reaction progresses, so that the water temperature increases more rapidly (Fig. 5(b)), leading to an increase in the Al-water reaction rate (Fig. 5(a)). When the suspension volume is 250 ml, the highest suspension temperature is ~92.5 °C, and >90% of metal Al is consumed within 1 h.

As the weight ratio of Al to water in the ideal reaction equation is  $1:2,^1$  in practical application, this ratio in the suspension should be above 1:15. Fig. 6 shows H<sub>2</sub> evolution and variation of water temperature by the addition of 7.29 µm Al powder into Al(OH)<sub>3</sub> suspensions with different Al to water ratios, where the suspension volume is 50 ml and the solid

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Fig. 5 (a) H<sub>2</sub> evolution and (b) variation of water temperature for the Al-water reaction by the addition of 7.29  $\mu$ m Al powder into Al(OH)<sub>3</sub> suspensions with different volumes, where the initial temperature in the suspensions is 25 °C, the weight ratio of Al to water is always 1 : 30 and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is 8 : 2. No thermostat is used in this experiment.



Fig. 6 (a) H<sub>2</sub> evolution and (b) variation of water temperature for the Al-water reaction by the addition of 7.29  $\mu$ m Al powder into 50 ml of Al(OH)<sub>3</sub> suspension with different Al to water weight ratios, where the initial temperature in the suspensions is 25 °C and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is 8 : 2. No thermostat is used in this experiment.

volume ratio of Al to Al(OH)<sub>3</sub> in suspension is always 8 : 2. It can been seen that when the weight ratio of Al to water in the suspension increases to 1:15, the highest suspension temperature is ~94 °C, and >80% of the Al metal in the Al(OH)<sub>3</sub> suspension is consumed within 40 min. This reaction rate is comparable to that of Al powder in NaOH solution and could meet the practical requirement for portable applications.<sup>9</sup>

## Model analyses

#### 4.1 Induction time

A previous study showed that the induction time required before the beginning of the Al-water reaction originates from the hydration of the passive oxide film on the Al surface.<sup>3</sup> When the hydrated front meets the metal beneath the Al surface, the water molecules react with the Al metal and generate hydrogen.  $H_2$  molecules accumulate to form small  $H_2$  bubbles at the Al : Al<sub>2</sub>O<sub>3</sub> interface. When the reaction gas pressure in the  $H_2$ bubbles exceeds the critical gas pressure that the hydrated oxide film can sustain (Fig. 2 in ref. 3), the film on the Al particle surface breaks. Then, the Al surface on the inside comes in direct contact with the water on the outside, and the beginning of the Al-water reaction is observed. The induction time is the time period that extends from putting the Al particles into water to the breaking of the Al surface oxide film.

It was confirmed that  $Al(OH)_3$  particles can act as a catalyst to assist the reaction of Al with water,<sup>39-42</sup> because  $Al(OH)_3$  can dissociate  $H_2O$  molecules into ions, which can promote the hydration of the passive oxide film on the Al surface when  $Al(OH)_3$  particles come into contact with Al particles in water, leading to a shorter induction time for the Al-water reaction. Therefore, the contact area between the  $Al(OH)_3$  and Al particles is an important factor that affects the catalytic performance towards the Al-water reaction.

When no agitation is used, the movement of small particles (usually  $<10 \ \mu$ m) in liquid observes the rule of Brownian motion, which is caused by collisions with molecules of the surrounding medium.<sup>48,49</sup> The speed of Brownian particles in solution follows the Maxwell–Boltzmann rate distribution:

$$f(\nu) = 4\pi \left(\frac{m^*}{2\pi kT}\right)^{3/2} \exp\left(-\frac{m^*\nu^2}{2kT}\right)\nu^2$$
(2a)

where

$$m^* = m + \frac{1}{2}m_{\rm f}$$
 with  $m_{\rm f} = \frac{4}{3}\pi r^3 \rho_{\rm L}$  (2b)

is the effective mass of the Brownian particle in liquid, which is the sum of the particle mass and half of the mass of the displaced fluid  $(m_{\rm f})$ .<sup>49</sup> Here, a spherical particle with a radius of *r* is assumed, and the liquid density is  $\rho_{\rm L}$ . The average speed of Brownian particles in solution can be calculated as<sup>50</sup>

$$\overline{\nu} = \int_0^\infty \nu f(\nu) \mathrm{d}\nu = \sqrt{\frac{8kT}{\pi m^*}}.$$
(3)

If two kind of particles with different masses  $m_1$  and  $m_2$  move in the same liquid, their relative average speed can be obtained by vector calculation<sup>50</sup>

$$\overline{\nu}_{12} = \sqrt{\frac{8kT}{\pi\mu}} \tag{4a}$$

where

$$\mu = \frac{m_1^* m_2^*}{m_1^* + m_2^*} \tag{4b}$$

is the reduced mass, and  $m_1^*$  and  $m_2^*$  are the effective masses of the two kinds of particles in the liquid. If Al and Al(OH)<sub>3</sub> particles are assumed to be spherical with radii of  $r_1$  and  $r_2$ , respectively, the average collision frequency per unit time between one Al particle and the Al(OH)<sub>3</sub> particles in the water can be written as

$$\overline{Z}_{1} = \frac{N_{2}}{V} \pi (r_{1} + r_{2})^{2} \overline{\nu}_{12} = \frac{N_{2}}{V} (r_{1} + r_{2})^{2} \sqrt{\frac{8\pi kT}{\mu}}$$
(5)

where V is the water volume and  $N_2$  is the total number of Al(OH)<sub>3</sub> particles.  $N_2$  is equal to the Al(OH)<sub>3</sub> mass in suspension divided by one Al(OH)<sub>3</sub> particle mass.

Previous work<sup>3</sup> indicated that the induction time for the Alwater reaction includes three parts

$$t_0 = t_i + t_s + t_e \tag{6}$$

where  $t_i$  is the hydration time of the native oxide film,  $t_s$  is the time from the beginning of H<sub>2</sub> generation at the Al : Al<sub>2</sub>O<sub>3</sub> interface to the H diffusion saturation in bulk Al, and  $t_e$  is the time interval from the H diffusion saturation in bulk Al to the time that the gas pressure in H<sub>2</sub> bubbles at the Al : Al<sub>2</sub>O<sub>3</sub> interface reaches the critical value. As Al(OH)<sub>3</sub> particles promote the hydration of the Al surface oxide film, the hydration rate,  $v_h$ , should be proportional to the contact area between the Al and the Al(OH)<sub>3</sub> particles

$$\nu_{\rm h} = \frac{k_1 \overline{Z}_1}{4\pi r_1^2} S \tag{7a}$$

with

Paper

$$k_1 = k_{10} \exp\left(-\frac{E_1}{RT}\right) \tag{7b}$$

the rate constant for the catalytic hydration reaction by Al(OH)<sub>3</sub>, where  $k_{10}$  is a constant and  $E_1$  is the activation energy for the hydration reaction. The maximum contact area between one Al particle and an Al(OH)<sub>3</sub> particle during an elastic collision is (see the ESI<sup>†</sup>)

$$S = 2r_2 \sqrt[3]{\frac{3\pi kT}{E}} \tag{8}$$

where it is assumed that Al and Al(OH)<sub>3</sub> have the same Young's modulus (*E*). The hydration rate can be obtained by inserting eqn (5) and (8) into eqn (7)

$$\nu_{\rm h} = 2k_{10}\frac{N_2}{V}\left(1 + \frac{r_2}{r_1}\right)^2 r_2 \sqrt[6]{\frac{9k^5T^5}{8\pi\mu^3 E^2}} \exp\left(-\frac{E_1}{RT}\right). \tag{9}$$

If it is assumed that the oxide film thickness of Al particles with different radii is the same (h),<sup>3</sup> the hydration time of the native oxide film can be written as

$$t_{\rm i} = \frac{h}{\nu_{\rm h}} = \frac{c_1}{\frac{N_2}{V} \left(1 + \frac{r_2}{r_1}\right)^2 r_2 \sqrt[6]{\frac{T^5}{\mu^3}}} \exp\left(\frac{E_1}{RT}\right)$$
(10a)

with

$$c_1 = \frac{h}{2k_{10}\sqrt[6]{\frac{9k^5}{8\pi E^2}}}.$$
 (10b)

where  $\nu_{\rm h}$  is the movement velocity of the hydration front of the Al surface oxide film, which represents the transportation speed of water molecules moving to the Al : Al<sub>2</sub>O<sub>3</sub> interface. As both the H diffusion saturation and the critical gas pressure in H<sub>2</sub> bubbles at the Al : Al<sub>2</sub>O<sub>3</sub> interface are related to the Al particle volume,<sup>3,47</sup> if the water molecule transportation is the rate-controlling step, then

$$t_{\rm s} + t_{\rm e} = \frac{k_2 r_1}{\nu_{\rm h}} = \frac{c_2 r_1}{\frac{N_2}{V} \left(1 + \frac{r_2}{r_1}\right)^2 r_2 \sqrt[6]{\frac{T^5}{\mu^3}}} \exp\left(\frac{E_1}{RT}\right)$$
(11a)

with

$$_{2} = \frac{k_{2}}{2k_{10}\sqrt[6]{\frac{9k^{5}}{8\pi E^{2}}}}$$
(11b)

where  $k_2$  is a constant. The total induction time is as follows:

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$$t_0 = t_i + t_s + t_e = \frac{(c_1 + c_2 r_1)}{\frac{N_2}{V} \left(1 + \frac{r_2}{r_1}\right)^2 r_2 \sqrt[6]{\frac{T^5}{\mu^3}} \exp\left(\frac{E_1}{RT}\right).$$
(12)

#### 4.2 Reaction temperature

The reaction equation of Al with water can be written as<sup>1,41</sup>

$$Al + 3H_2O \rightarrow Al(OH)_3 + \frac{3}{2}H_2\uparrow,$$
(13)

$$\Delta H_{298}^0 = -426.5 \text{ kJ mol}^{-1}$$

which is an exothermic reaction. Therefore, the temperature of the suspension will increase as the reaction progresses

$$T = T_0 + \frac{\Delta Q - \Delta Q_s}{m_{\rm w} c_{\rm w}} \tag{14}$$

where  $T_0$  is the initial temperature, and  $m_w$  and  $c_w$  are the water mass and specific heat, respectively. The total released reaction heat is

$$\Delta Q = -\alpha_{\rm s} M_{\rm Al} \Delta H_{298}^0 \tag{15}$$

where  $\alpha_s$  is the reaction ratio for the Al metal and  $M_{Al}$  is the number of Al moles. The heat diffused to the outside during the reaction is

$$\Delta Q_{\rm s} = k_{\rm s} S_{\rm v} t \frac{T - T_0}{2} = k_{\rm s} \left( 36\pi V^2 \right)^{1/3} t \frac{T - T_0}{2} \tag{16}$$

where  $k_s$  is the heat diffusivity per unit time and area, *t* is the reaction time (excluding the induction time), and  $S_v$  is the surface area of the suspension. Here, as an approximation, the shape of the suspension is viewed as a sphere, and a linear

temperature rise is assumed. The suspension temperature can be obtained by inserting eqn (15) and (16) into eqn (14)

$$T = T_0 - \frac{\alpha_{\rm s} M_{\rm Al} \Delta H_{298}^0}{m_{\rm w} c_{\rm w} + \frac{k_{\rm s} (36\pi V^2)^{1/3} t}{2}}$$
(17)

#### 4.3 Hydrogen evolution

The Al-water reaction is a solid-liquid heterogeneous system, and its reaction dynamics can be described by the shrinking core model.<sup>47</sup> It was confirmed that at the initial stage (excluding the induction time), the surface chemical reaction is the rate-controlling step, and its rate equation can be written<sup>47</sup>

$$1 - (1 - \alpha)^{1/3} = k_2 t \tag{18a}$$

with

$$k_2 = k_{20} \exp\left(-\frac{E_2}{RT}\right) \tag{18b}$$

the rate constant for the Al–water reaction, where  $\alpha$  is the hydrogen yield of the considered Al particle,  $k_{20}$  is a constant and  $E_2$  is the activation energy. In fact, the activation energy,  $E_2$ , is a function of the Al particle size<sup>47</sup> and can be described by

$$E_2 = a + br_1 \tag{19}$$

where a and b are the constants, which can be obtained by fitting the experimental results in Fig. 11 of ref. 47. From eqn (18), the hydrogen yield of one Al particle can be obtained

$$\alpha = 1 - (1 - k_2 t)^3 = 1 - \left[ 1 - k_{20} t \exp\left(-\frac{E_2}{RT}\right) \right]^3$$
(20)

In the real Al powder, there is a particle size distribution, which can be described by a log-normal function<sup>51</sup>

$$f(r_1) = \frac{A}{r_1 \sigma \sqrt{2\pi}} \exp\left[-\frac{\left(\ln r_1 - \mu\right)^2}{2\sigma^2}\right]$$
(21)

where *A* is a constant,  $\sigma$  is the standard deviation, and  $\mu = \ln r_v$  with  $r_v$  the average radius. As the induction time is a function of the Al particle size, the dependence of total hydrogen yield on time for Al powder can be written

$$\alpha_{s} = \frac{\int_{0}^{\infty} \theta(t-t_{0})\alpha(t-t_{0})f(r_{1})r_{1}^{3}dr_{1}}{\int_{0}^{\infty} f(r_{1})r_{1}^{3}dr_{1}}$$

$$= \frac{\int_{0}^{\infty} \theta(t-t_{0})\left\{1 - \left[1 - k_{20}(t-t_{0})\exp\left(-\frac{E_{2}}{RT}\right)\right]^{3}\right\}f(r_{1})r_{1}^{3}dr_{1}}{\int_{0}^{\infty} f(r_{1})r_{1}^{3}dr_{1}}$$
(22)

where

$$\theta(t - t_0) = \begin{cases} 1 & t > t_0 \\ 0 & t < t_0 \end{cases}$$
(23)

is a step function. Eqn (22) can be calculated self-consistently by combining it with eqn (12) and (17), using a Fortran program on a workstation.

#### 4.4 Numerical calculation

Before the numerical calculations, the parameters in the above equations need to be determined. The effective masses of the Al and  $Al(OH)_3$  particles can be calculated by eqn (2b), and their masses are

$$m_1 = \frac{4}{3}\pi r_1^{3}\rho_{\rm Al}$$
 and  $m_2 = \frac{4}{3}\pi r_2^{3}\rho_{\rm Al(OH)}$ 

where  $\rho_{Al}$  and  $\rho_{Al(OH)_2}$  are the densities of the Al and Al(OH)<sub>3</sub> particles, respectively. In the numerical calculations, 7.29 µm Al powder is considered, and the parameters A,  $\sigma$ , and  $r_v$  are obtained by fitting the 7.29 µm Al particle size distribution (Fig. 12(a) in ref. 47) with eqn (21). In order to determine the parameters in eqn (12), (1.32) µm Al powder was also used for hydrogen-generation testing, where 1.0 g of Al powder was added into 250 ml Al(OH)3 suspension with a solid volume ratio 9 : 1 of Al to Al(OH)<sub>3</sub> at 25 °C. The induction time for 1.32  $\mu$ m Al powder is 0.91 h, so by combining this result with the induction time (2.5 h) of 7.29 µm Al powder under the same conditions (Fig. 2), we can obtain the ratio of  $c_1$  to  $c_2$ , where the average size is viewed as the size of all the Al particles. The final values of  $c_1$ ,  $c_2$ , and  $E_1$  can be obtained by fitting the induction time at different temperatures in Fig. 4(a) with eqn (12). As the temperature rise for the Al-water reaction in 30 ml Al(OH)<sub>3</sub> suspension in Fig. 5(b) is approximately linear from the beginning of the reaction to the time of the highest temperature point, we used eqn (17) to fit the data in 30 ml  $Al(OH)_3$ suspension for this time interval and obtained the heat diffusivity  $k_s$ . The constant  $k_{20}$  in eqn (18b) can be obtained from the rate constant  $k_2$  for the Al-water reaction using 7.29 µm Al powder in 250 ml deionized water at 40 °C (Fig. 10 in ref. 47). The fitting software used in this work is OriginPro 8.0, the physical and fitting parameters are listed in Tables 1 and 2, respectively.

Fig. 7 shows the theoretical dependence of the induction time for the Al-water reaction on the Al particle size at different temperatures in 250 ml Al(OH)<sub>3</sub> suspension, where 1 g of Al powder was used in each test. It can be seen that the induction time increases with increasing Al particle size and decreases with increasing temperature and Al(OH)<sub>3</sub> content in the suspension, which is consistent with the experimental results in Fig. 2–4. Fig. 8 shows the dependence of induction time on

Table 1 The physical parameters used in the model calculation

Parameter	Value
$\rho_{\rm L}$ $\rho_{\rm Al}$	$1.0 \text{ g cm}^{-3}$ 2.70 g cm $^{-3}$
$ ho_{ m Al(OH)_3}$ $ ho_{ m W}$	2.42 g cm <sup>-3</sup> 4.178 J g <sup>-1</sup> K <sup>-1</sup>
$r_2$	150 nm

 
 Table 2
 The parameters obtained by fitting the related equations with the experimental data

Parameter	Value
Α	0 17656 um
σ	0.63134
r <sub>v</sub>	1.4688 μm
<i>C</i> <sub>1</sub>	$4.004 \times 10^{-3} \ \text{hour} \ \text{K}^{5/6} \ \mu\text{m}^{-2} \ \text{g}^{-1/2}$
$c_2$	$2.472 \times 10^{-3} \text{ hour K}^{5/6} \ \mu m^{-3} \ g^{-1/2}$
$E_1$	55.89 kJ mol $^{-1}$
k <sub>s</sub>	$15.23 \text{ J K}^{-1} \text{ cm}^{-2} \text{ hour}^{-1}$
a	64.98 kJ mol <sup>-1</sup>
b	$0.8635 \text{ kJ mol}^{-1} \mu \text{m}^{-1}$
$k_{20}$	$3.759 \times 10^{10} \text{ hour}^{-1}$



Fig. 7 Dependence of induction time for the Al–water reaction on Al particle size at different temperatures in 250 ml Al(OH)<sub>3</sub> suspension, where 1 g of Al is used in each test and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is (a) 9:1 and (b) 8:2, respectively.

water volume at different temperatures, where 1 g of Al powder was used in each test. It can be seen that when the Al content in the suspension is a constant, the induction time increases with increasing water volume and decreases with increasing temperature and Al(OH)<sub>3</sub> content, which is also in agreement with the experimental results in Fig. 2–4.

Fig. 9 and 10 show the hydrogen evolution and water temperature for the Al-water reaction in  $Al(OH)_3$  suspensions with different volumes, where 1 g of 7.29 µm Al powder with a particle size distribution is used in each test. It can be seen that when the weight of Al powder in the suspension is a constant, the induction time increases and the hydrogengeneration rate decreases with increasing water volume, which is consistent with the experimental results in Fig. 2 and 3. Furthermore, the induction time decreases and the hydrogengeneration rate increases with increasing  $Al(OH)_3$  content in the suspension, which is also in agreement with the experimental results in Fig. 2 and 3. At the same time, the water



Fig. 8 Dependence of induction time for the Al–water reaction on suspension volume at different temperatures, where the Al particle size is 7.29  $\mu$ m, 1 g of Al is used in each test, and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is (a) 9 : 1 and (b) 8 : 2, respectively.



Fig. 9 Variation of (a) hydrogen yield and (b) water temperature with time for the Al-water reaction in Al(OH)<sub>3</sub> suspensions with different volumes, where the initial temperature is 25 °C, 1 g of 7.29  $\mu$ m Al powder with a particle size distribution is used in each test, and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is 9 : 1.

temperature rise decreases with increasing water volume, but the theoretical value in 30 ml  $Al(OH)_3$  suspension in Fig. 9 and 10 is much higher than the experimental temperature rise in Fig. 2 and 3. This is because in the practical experiment, a thermostatically controlled water bath is used to control the temperature, while no thermostat is considered in the theoretical calculation.

Fig. 11 and 12 show the hydrogen evolution and water temperature for the Al-water reaction in 30 ml of  $Al(OH)_3$ suspension for different initial temperatures, where 1 g of 7.29



**Fig. 10** Variation of (a) hydrogen yield and (b) water temperature with time for the Al-water reaction in Al(OH)<sub>3</sub> suspensions with different volumes, where the initial temperature is 25 °C, 1 g of 7.29  $\mu$ m Al powder with a particle size distribution is used in each test, and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is 8 : 2.



Fig. 11 Variation of (a) hydrogen yield and (b) water temperature with time for the Al-water reaction in 30 ml of Al(OH)<sub>3</sub> suspension at different initial temperatures, where 1 g of 7.29  $\mu$ m Al powder with a particle size distribution is used in each test and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is 9 : 1.

 $\mu$ m Al powder is used in each test. It can be seen that the induction time decreases and the hydrogen-generation rate increases with increasing initial temperature and increasing Al(OH)<sub>3</sub> content in the suspension, which is consistent with the experimental results in Fig. 4. Furthermore, the water temperature rise increases with increasing initial temperature and increasing Al(OH)<sub>3</sub> content.

Fig. 13 shows the hydrogen evolution and water temperature for the Al–water reaction in Al(OH)<sub>3</sub> suspensions with different volumes using 7.29  $\mu$ m Al powder, where the weight ratio of Al



**Fig. 12** Variation of (a) hydrogen yield and (b) water temperature with time for the Al-water reaction in 30 ml of Al(OH)<sub>3</sub> suspension at different initial temperatures, where 1 g of 7.29  $\mu$ m Al powder with a particle size distribution is used in each test and the solid volume ratio of Al to Al(OH)<sub>3</sub> in the suspension is 8 : 2.



Fig. 13 Variation of (a) hydrogen yield and (b) water temperature with time for the Al-water reaction in  $Al(OH)_3$  suspensions with different volumes using 7.29  $\mu$ m Al powder with a particle size distribution, where the initial temperature of the suspensions is 25 °C, the weight ratio of Al to water is always 1 : 30 and the solid volume ratio of Al to Al(OH)\_3 in the suspension is 8 : 2.

to water is always 1:30 and the solid volume ratio of Al to  $Al(OH)_3$  is 8:2. It can be seen that the induction time decreases, and the hydrogen-generation rate and the rate at which the water temperature rises increase with increasing suspension volume. These results are consistent with the experimental results in Fig. 5.

It should be noted that the theoretical results in Fig. 7–13 are in qualitative agreement with the experimental results, indicating that the theoretical analyses reveal the basic physical mechanisms in the Al–water reaction promoted by the  $Al(OH)_3$  suspension, although there is a difference in the quantitative comparisons between the theoretical calculations and the experimental results. This is because the rate eqn (18) describing the Al–water reaction is only suitable for the initial stage of the reaction. After the initial stage, the mass transfer in the by-product layer is the rate-controlling step, and in this case, the rate eqn (18) is inapplicable.<sup>47</sup> For Al powder with a particle size distribution, the small Al particles will start to react at an earlier time than the large Al particles due to their different induction times, so it is possible that the small Al particles have reacted away when the large Al particles start to react. Therefore, the model analyses are only suitable for the initial stage of the Al–water reaction.

In fact, eqn (12) indicates that the induction time for the Alwater reaction is proportional to the Al radius and inversely proportional to the Al(OH)<sub>3</sub> concentration  $(N_2/V)$  and temperature, because an Al particle with a larger radius takes a longer time to reach H diffusion saturation in the bulk Al and the critical gas pressure in the H<sub>2</sub> bubbles at the Al : Al<sub>2</sub>O<sub>3</sub> interface (eqn (11a)). Increasing the Al(OH)<sub>3</sub> concentration will increase the collision frequency between the Al and Al(OH)<sub>3</sub> particles (eqn (5)), leading to an increase in their contact area. Moreover, increasing the temperature will increase the hydration reaction rate of the Al surface oxide film (eqn (7b)). This is why the induction time increases with increasing water volume when the  $Al(OH)_3$  content is fixed, as shown in Fig. 3 and 4, and increasing the temperature decreases the induction time (Fig. 4). Eqn (17) indicates that the temperature rise during the Al-water reaction is proportional to the number of Al moles, because more heat is released when more Al joins the reaction. At the same time, the Al-water reaction rate is proportional to the temperature (eqn (18b)). As the Al powder has a particle size distribution, with the smaller particles reacting first, the induction time decreases, and the hydrogen-generation rate increases with increasing Al content, as shown in Fig. 5. Our results imply that it is possible for the Al-water reaction rate to reach the practical requirement for portable application if a higher Al(OH)<sub>3</sub> concentration and a suitable Al content are chosen.

## 5. Conclusions

In this work, the effects of kinetic factors on the Al–water reaction promoted by an ultrasonically prepared  $Al(OH)_3$  suspension were investigated. It was found that the induction time for the Al–water reaction increases and the hydrogengeneration rate decreases with increasing water volume when the solid Al and  $Al(OH)_3$  contents are fixed, because the  $Al(OH)_3$  concentration in the suspension decreases. The induction time decreases, and the hydrogen-generation rate increases with increasing suspension volume when the ratio of Al to water and the  $Al(OH)_3$  concentration are fixed, because more Al joins the reaction and produces more heat, leading to a faster and higher temperature rise. A model analysis has been conducted based on Brownian motion, which shows that the contact area between the Al and  $Al(OH)_3$  particles and the reaction heat are

two important factors that affect the progress of the reaction. The theoretical calculations are in qualitative agreement with the experimental results.

## Acknowledgements

We would like to thank the financial support of Shanghai Key Laboratory of High Temperature Superconductors (No. 14DZ2260700).

## References

- 1 Z. Y. Deng, J. M. F. Ferreira and Y. Sakka, *J. Am. Ceram. Soc.*, 2008, **91**, 3825–3834.
- 2 X. N. Huang, T. Gao, X. L. Pan, D. Wei, C. J. Lv, L. S. Qin and Y. X. Huang, *J. Power Sources*, 2013, **229**, 133–140.
- 3 Z. Y. Deng, J. M. F. Ferreira, Y. Tanaka and J. H. Ye, *J. Am. Ceram. Soc.*, 2007, **90**, 1521–1526.
- 4 W. Z. Gai and Z. Y. Deng, Int. J. Hydrogen Energy, 2014, 39, 13491-13497.
- 5 Y. Yavor, S. Goroshin, J. M. Bergthorson and D. L. Frost, *Int. J. Hydrogen Energy*, 2015, **40**, 1026–1036.
- 6 D. Belitskus, J. Electrochem. Soc., 1970, 117, 1097-1099.
- 7 L. Soler, J. Macanas, M. Munoz and J. Casado, *Int. J. Hydrogen Energy*, 2007, **32**, 4702–4710.
- 8 L. Soler, A. M. Candela, J. Macanas, M. Munoz and J. Casado, *J. Power Sources*, 2009, **192**, 21–26.
- 9 C. R. Jung, A. Kundu, B. Ku, J. H. Gil, H. R. Lee and J. H. Jang, *J. Power Sources*, 2008, **175**, 490–494.
- 10 E. D. Wang, P. F. Shi, C. Y. Du and X. R. Wang, J. Power Sources, 2008, 181, 144–148.
- 11 T. Hiraki and T. Akiyama, *Int. J. Hydrogen Energy*, 2009, 34, 153–161.
- 12 H. B. Dai, G. L. Ma, H. J. Xia and P. Wang, *Energy Environ. Sci.*, 2011, **4**, 2206–2212.
- 13 M. K. Yu, M. J. Kim, B. Y. Yoon, S. K. Oh, D. H. Nam and H. S. Kwon, *Int. J. Hydrogen Energy*, 2014, **39**, 19416–19423.
- 14 G. D. Yao, X. Zeng, Y. J. Jin, H. Zhong, J. Duo and F. M. Jin, *Int. J. Hydrogen Energy*, 2015, **40**, 14284–14289.
- 15 O. V. Kravchenko, K. N. Semenenko, B. M. Bulychev and K. B. Kalmykov, *J. Alloys Compd.*, 2005, **397**, 58–62.
- 16 M. Q. Fan, F. Xu and L. X. Sun, *Int. J. Hydrogen Energy*, 2007, 32, 2809–2815.
- 17 V. Rosenband and A. Gany, *Int. J. Hydrogen Energy*, 2010, 35, 10898–10904.
- 18 W. Wang, D. M. Chen and K. Yang, *Int. J. Hydrogen Energy*, 2010, **35**, 12011–12019.
- 19 J. T. Ziebarth, J. M. Woodall, R. A. Kramer and G. Choi, *Int. J. Hydrogen Energy*, 2011, **36**, 5271–5279.
- 20 X. Y. Chen, Z. W. Zhao, X. H. Liu, M. M. Hao, A. L. Chen and Z. Y. Tang, *J. Power Sources*, 2014, **254**, 345–352.
- 21 S. Elitzur, V. Rosenband and A. Gany, *Int. J. Hydrogen Energy*, 2014, **39**, 6328–6334.
- 22 T. P. Huang, Q. Gao, D. Liu, S. N. Xu, C. B. Guo, J. J. Zou and C. D. Wei, *Int. J. Hydrogen Energy*, 2015, **40**, 2354–2362.
- 23 W. J. Yang, T. Y. Zhang, J. H. Zhou, W. Shi, J. Z. Liu and K. F. Cen, *Energy*, 2015, 88, 537–543.

- 24 B. Alinejad and K. Mahmoodi, *Int. J. Hydrogen Energy*, 2009, **34**, 7934–7938.
- 25 E. Czech and T. Troczynski, *Int. J. Hydrogen Energy*, 2010, **35**, 1029–1037.
- 26 P. Dupiano, D. Stamatis and E. L. Dreizin, *Int. J. Hydrogen Energy*, 2011, **36**, 4781–4791.
- 27 S. Liu, M. Q. Fan, C. Wang, Y. X. Huang, D. Chen, L. Q. Bai, et al., Int. J. Hydrogen Energy, 2012, 37, 1014–1020.
- 28 S. S. Razavi-Tousi and J. A. Szpunar, *Metall. Mater. Trans. E*, 2014, **1**, 247–256.
- 29 S. S. Razavi-Tousi and J. A. Szpunar, *Electrochim. Acta*, 2014, 127, 95–105.
- 30 Y. A. Liu, X. H. Wang, H. Z. Liu, Z. H. Dong, S. Q. Li, H. W. Ge and M. Yan, *Energy*, 2014, **72**, 421–426.
- 31 Y. A. Liu, X. H. Wang, H. Z. Liu, Z. H. Dong, S. Q. Li, H. W. Ge and M. Yan, *Energy*, 2015, **84**, 714–721.
- 32 Y. A. Liu, X. H. Wang, H. Z. Liu, Z. H. Dong, S. Q. Li, H. W. Ge and M. Yan, *RSC Adv.*, 2015, 5, 60460–60466.
- 33 Y. A. Liu, X. H. Wang, H. Z. Liu, Z. H. Dong, S. Q. Li, H. W. Ge and M. Yan, *Energy*, 2015, **89**, 907–913.
- 34 Z. Y. Deng, Y. F. Liu, Y. Tanaka, J. H. Ye and Y. Sakka, *J. Am. Ceram. Soc.*, 2005, **88**, 977–979.
- 35 Z. Y. Deng, Y. B. Tang, L. L. Zhu, Y. Sakka and J. H. Ye, *Int. J. Hydrogen Energy*, 2010, **35**, 9561–9568.
- 36 Z. Y. Deng, W. H. Liu, W. Z. Gai, Y. Sakka, J. H. Ye and Z. W. Ou, J. Am. Ceram. Soc., 2010, 93, 2534–2536.
- 37 W. H. Liu, W. Z. Gai, Z. Y. Deng and J. W. Tang, *J. Am. Ceram. Soc.*, 2012, **95**, 1193–1196.

- 38 C. S. Fang, W. Z. Gai and Z. Y. Deng, J. Am. Ceram. Soc., 2014, 97, 44–47.
- 39 W. Z. Gai, Y. Shi, Z. Y. Deng and J. G. Zhou, *Int. J. Hydrogen Energy*, 2015, **40**, 12057–12062.
- 40 H. T. Teng, T. Y. Lee, Y. K. Chen, H. W. Wang and G. Z. Cao, *J. Power Sources*, 2012, **219**, 16–21.
- 41 W. Z. Gai, C. S. Fang and Z. Y. Deng, *Int. J. Energy Res.*, 2014, **38**, 918–925.
- 42 Y. Yang, W. Z. Gai, Z. Y. Deng and J. G. Zhou, *Int. J. Hydrogen Energy*, 2014, **39**, 18734–18742.
- 43 H. X. Meng, N. Wang, Y. M. Dong, Z. L. Jia, L. J. Gao and Y. J. Chai, *J. Power Sources*, 2014, **268**, 550–556.
- 44 N. Wang, H. X. Meng, Y. M. Dong, Z. L. Jia, L. J. Gao and Y. J. Chai, *Int. J. Hydrogen Energy*, 2014, **39**, 16936–16943.
- 45 Y. H. Lu and H. T. Chen, *Phys. Chem. Chem. Phys.*, 2015, **17**, 6834–6843.
- 46 H. W. Wang and M. S. Chin, *Int. J. Chem. Eng. Appl.*, 2015, 6, 146–151.
- 47 W. Z. Gai, W. H. Liu, Z. Y. Deng and J. G. Zhou, *Int. J. Hydrogen Energy*, 2012, **37**, 13132–13140.
- 48 T. C. Li, S. Kheifets, D. Medellin and M. G. Raizen, *Science*, 2010, **328**, 1673–1675.
- 49 J. Y. Mo, A. Simha, S. Kheifets and M. G. Raizen, *Opt. Express*, 2015, **23**, 1888–1893.
- 50 Y. H. Qin, *Thermodynamics*, Higher Education Press, Beijing, 2008.
- 51 Z. Y. Deng, J. M. F. Ferreira, Y. Tanaka and Y. Isoda, *Acta Mater.*, 2007, 55, 3663–3669.