INTRODUCTION

Fuel cell is a promising clean energy technology, which can directly convert the chemical energy into electric energy without the restriction of Carnot cycle. Therefore, fuel cell has the advantages of high efficiency, pollution-free and without charging.\(^1\) During the past decades, fuel cell technology has made great progress, and the manufacturing costs have been greatly reduced.\(^2\) However, its wide application and commercialization are restricted by hydrogen source technology.\(^3\),\(^4\) Hydrogen is an ideal fuel for fuel cells. Portable fuel cells require a reliable hydrogen source, which should have high hydrogen storage capacity and no toxic substances (such as CO), and be as simple and compact as possible. At present, the mature hydrogen storage methods are high pressure compression and low-temperature liquefaction.\(^5\) High pressure compression hydrogen storage usually uses bulky cylinders as containers, which require more than 70 MPa pressure to store 7-8 wt% hydrogen.\(^6\) Low-temperature liquefaction hydrogen storage needs a special adiabatic container and low temperature of \(-252^\circ\)C. For commercial applications, these two traditional hydrogen storage technologies cannot meet the needs of portable fuel cells.
For seeking the suitable hydrogen source for portable fuel cells, many researchers put attentions on in situ hydrogen generation materials, which can produce hydrogen in real time and on site. In addition, in situ hydrogen generation materials are much easier to store and transport than hydrogen. Metal Al is very reactive, which can easily hydrolyze with water to release hydrogen. Al-water reaction by-products are various aluminum hydroxides, including Al(OH)3 and AlOOH, all of which are environmentally friendly and can easily be either reduced to Al for further recycling by a Hall-Heroult process or reused for refractory and calcium aluminate cement production. Meanwhile, metal Al is very abundant and relatively inexpensive. Al-water system has a high gravimetric hydrogen capacity, and the hydrolysis reaction of 1 kg Al can produce as much as 0.11 kg H2. Therefore, metal Al is an excellent candidate for in situ hydrogen production. However, a dense passivating oxide film formed on Al particle surface when fresh Al is exposed to air, resulting in a long induction time before hydrogen release from Al-water reaction.

To overcome the inhibition effect of the passivating oxide film and shorten the induction time, diverse methods were developed to activate Al: using alkalis as promoters,11-14 alloying Al with Li, Ga, Sn, Mg, In, Fe, or Cu by either ball milling or melting,15-23 high-energy ball milling Al with metal oxide, graphite, metal hydride, soluble inorganic salt, BiOCl, polytetrafluoroethylene, etc,24-33 Al surface modification,34,35 as well as implementing different catalysts.36-42 Soler et al11 and Ma et al13 used low corrosive Na2SnO3 to replace NaOH and demonstrated that Na2SnO3 promoted Al-water reaction. During the hydrolysis process of Al, some Na2SnO3 is reduced to Sn, which forms Al-Sn galvanic microcell with Al, promoting Al corrosion and inhibiting the repassivation of Al. Qiao et al23 demonstrated that Ga-based Al alloys prepared using the high-frequency induction melting method have excellent hydrogen generation performance. The proposed mechanism was based on the reaction of Al dissolved in Ga-based eutectic liquid with water and the transport of Al from grains to liquid Ga-based alloys. Zhao et al42 synthesized Al-BiOCl composite by ball milling method and studied the hydrogen production performance of Al-BiOCl system. They revealed that the fresh surface of Al, Bi, Bi2O3, and AlCl3 were produced during milling, which promoted the Al-water reaction. Zhang et al55 fabricated the reduced graphene oxide-wrapped Al composite using an ultrasonic atomization method and found that this composite reacted with water and produced hydrogen upon exposure to the infrared light. Alarcón et al43 developed a new way to generate hydrogen by laser irradiation of Al in water. They thought that laser ablation combined with ultrasound could remove the passive film from Al surface and accelerate the Al-water reaction.

Among various activation methods, Al-water reaction promoted by special catalysts is a potential hydrogen production technology, because it does not require alkaline condition and activation of Al. So far, researchers have found that Co-B, Ni-B, Fe-B, Co-Fe-B, TiO2, α-Al2O3, γ-Al2O3, and Al(OH)3 could catalyze Al-water reaction,36-42,44 and the hydrogen generation performance is closely related to the activity of catalysts. However, the activity of these catalysts is poor, and how to improve the activity of catalysts is the current research hot spot. In the present work, we used wet chemical reduction method to synthesize Fe/AlOOH composite with excellent catalytic activity. The effect of Fe/AlOOH composite on Al-water reaction dynamics was investigated systematically for the first time, and a possible catalytic mechanism was given.

2 | EXPERIMENTAL PROCEDURE

Al powder (1.75 μm, 99.9% purity, Henan Yuanyang Powder Technology Co., Ltd., Xinxiang, China), AlOOH powder (5 μm, 99.9% purity, Hangzhou Wan Jing New Material Co., Ltd., Hangzhou, China) and NaBH4 (97% purity, Tianjin Kemiou Chemical Reagent Co., Tianjin, China) were used in the present work. In addition, absolute ethanol and analytical reagent grade FeCl3·6H2O purchased from Sinopharm Chemical Reagent Co., Ltd. were used in the experiment.

Fe/AlOOH catalyst was synthesized using a wet chemical reduction method described elsewhere.45 3-12 mmol AlOOH powders and 200 mL of deionized (DI) water were added into a beaker and then ultrasonically treated using KQ3200E ultrasonic cleaner at 40 kHz and 150 W for 1 hour. After that, 6 mmol FeCl3·6H2O was added and ultrasonication was resumed for another 0.5 hour. The resulting suspension was combined with 18 mmol NaBH4 powders in another beaker within 30 seconds and stirred by hand. In this case, FeCl3·6H2O reacted intensely with NaBH4 and a black precipitate formed according to the following equation.

$$FeCl_3 + 3NaBH_4 + 9H_2O \rightarrow Fe \downarrow + 3NaCl + 10.5H_2 + 3B(OH)_3.$$  \hspace{1cm} (1)

Finally, the Fe/AlOOH catalyst was obtained by filtering the mixture suspension using a filter paper, washing with DI water and absolute ethanol, and then drying for 20 hours at room temperature. Some freshly formed Fe would be oxidized by oxygen during the filtration and drying process.

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3.$$  \hspace{1cm} (2)

Therefore, the Fe/AlOOH composite is a mixture of AlOOH, Fe, and small quantities of Fe2O3. For comparison, Fe catalyst was synthesized using the same procedure as that to prepare Fe/AlOOH catalyst but without AlOOH addition.

The Al-water reaction experiments catalyzed by Fe/AlOOH composite were carried out in a double-necked flask with better airtightness. During each experiment, 1.0 g of Al
powder was put into 250 mL of Fe/AlOOH suspension and then mixed evenly. The concentration of Fe/AlOOH in suspension is 5-30 wt%, and the AlOOH:Fe molar ratio of Fe/AlOOH catalyst varies from 0.5:1 to 2:1. A thermostat water bath was used to control the reaction temperature, which had an accuracy of ±1°C. During all the H2 evolution tests, suspension mixtures were not agitated. The hydrogen generated by Al-water reaction was measured by water trap method using an inverted burette filled with tap water. The hydrogen yield \( \alpha \) was calculated using the following formula:

\[
\alpha = \frac{V_{H2}}{V_0} \times 100\% ,
\]

where \( V_{H2} \) and \( V_0 \) are the actual and theoretical (calculated based on the assumption that all the Al powder was consumed during Al-water reaction) hydrogen volumes, respectively. In order to ensure the repeatability of each hydrogen generation test, at least two same tests were carried out.

X-ray diffraction (No. D8 Advance, Bruker Co., Germany) was used to analyze the phase composition of Fe/AlOOH catalyst and reaction by-products. Additionally, the morphologies of these materials were analyzed by scanning electron microscopy (No. Sigma 500/VP, Carl Zeiss Co., Germany), and the distribution of different elements in Fe/AlOOH catalyst was checked by EDX mapping. Surface area analyzer (Micromeritics ASAP 2020, USA) was used to analyze the specific surface area and pore size distribution of different catalysts. Brunauer-Emmett-Teller (BET), Barrett-Joyner-Halenda (BJH), and empirical \( t \)-plot methods were used to determine the specific surface area, pore size distribution and the external surface area, respectively.

# RESULTS AND DISCUSSION

## Characterization of Fe/AlOOH catalyst

Figure 1a and b shows the morphologies of as-received pure Al powder and AlOOH composite. Clearly, the surfaces of Al particles are dense and smooth (Figure 1a). For AlOOH, its shape is irregular, and the particle size of AlOOH ranges from submicro-sized to microsized (Figure 1b). Figure 1c shows the X-ray diffraction patterns of as-received pure Al powder and Fe/AlOOH catalyst. It is clear that only metal Al phase is present in as-received Al powder, which confirms its high purity. Fe/AlOOH catalyst is amorphous, and the diffraction peak at 2θ of 45º suggests the presence of metal Fe. But the peaks of AlOOH are not obvious; the possible reason is that the AlOOH particle surfaces are covered by many Fe grains or agglomerates.

Figure 2A and B shows the morphologies of Fe and Fe/AlOOH catalysts. It is found that both Fe and Fe/AlOOH catalysts demonstrate porosity, but the pore size of Fe catalyst is obvious larger than that of Fe/AlOOH catalyst. There are many agglomerates in Fe and Fe/AlOOH catalysts, and the grain size of Fe catalyst is dozens of nanometers (Figure 2A). For Fe/AlOOH catalyst, we can only see the Fe grains or agglomerates, indicating that the AlOOH particle is completely covered by Fe grains or agglomerates. The grain size of Fe in Fe/AlOOH catalyst is about 10-15 nm, which is much smaller than that of Fe catalyst (Figure 2B). This is because AlOOH acts as crystallization nuclei during the preparation process of Fe/AlOOH, Fe is produced on AlOOH surface, which inhibits the growth of Fe grains and increases the surface area of Fe/AlOOH.

Figure 2C-F shows the EDX mapping of Al, O, Fe, and B in Fe/AlOOH catalyst. It is found that the Fe/AlOOH catalyst contains Al, O, and Fe, but almost no B is detected. Thus, it can be speculated that the Fe in Fe/AlOOH catalyst is in the form of element Fe rather than Fe-B or Fe2B, which is consistent with the result of XRD in Figure 2. In addition, it seems that the Fe particles are distributed equally on AlOOH surface.

Figure 3A shows the N2 adsorption-desorption isotherms of Fe and Fe/AlOOH catalysts. The isotherms showed the characteristics of type IV isotherms based on the IUPAC classification, which indicates the presence of mesopores. Figure 3B shows the pore size distribution of Fe and Fe/AlOOH catalysts. It is noticed that the pores in Fe/AlOOH catalyst are in the 2.2-70 nm range and mostly mesoporous. But Fe catalyst has a wider pore size distribution, and they contain both macropores and mesopores. Table 1 lists the BET and external surface area as well as pore volume and average pore size of Fe and Fe/AlOOH catalysts. The BET surface areas of Fe and Fe/AlOOH catalysts are 70.0 and 80.6 m²/g, respectively. External surface areas of both catalysts are very close to the BET surface areas because of the absence of micropores. The average pore size of Fe catalyst is much larger than that of Fe/AlOOH catalyst, which agrees with the SEM observations shown in Figure 2A and B. The activity of catalyst is closely related to the contact between catalyst and Al particles.\(^{46}\) For Fe and Fe/AlOOH catalysts, the average pore sizes are 35.7 and 18.1 nm, respectively, which is much smaller than the particle size of Al powder (1.75 \( \mu \)m). Therefore, the surface attributed from the pores in catalysts cannot be contact with Al particles, and the pore size distribution of catalyst has no contribution to its catalytic activity.

## Al-water reaction catalyzed by Fe/AlOOH catalyst

Induction time is an important parameter to evaluate the hydrogen production performance of Al-water reaction. In this work, the induction time refers to the time when hydrogen is released and the hydrogen generation rate exceeds 0.67 ml/
min/g-Al. Figure 4A shows the H₂ evolution from DI water using pure Al powder without and with the addition of 10 wt% different catalysts at 40°C. It can be seen that pure Al powder could hydrolyze to release hydrogen at 40°C, but it needs a long induction time (3.0 hours) before hydrogen release from Al-water reaction. Obviously, the addition of catalysts significantly shortens the induction time, and the Al-water reaction dynamics are closely related to the kinds of catalysts. Both Fe and AlOOH catalysts greatly decrease the induction time and accelerate the hydrolysis reaction of Al. However, the H₂ yield of Al-water reaction catalyzed by Fe catalyst is much higher than that catalyzed by AlOOH catalyst. When Fe/AlOOH catalyst was used, the induction time was further decreased. Table 2 gives the hydrogen production data of Al powder in DI water without and with the addition of 10 wt% different catalysts at 40°C. It is found that AlOOH, Fe, and Fe/AlOOH catalysts decrease the induction time from 3 hours to 0.58 hours, 0.33 hours, and 0.17 hours, respectively. Thus, it concludes that the catalytic activity of different catalysts is in the following order: Fe/AlOOH > Fe > AlOOH. For Al-water reaction catalyzed by Fe/AlOOH catalyst, the induction time is the shortest and
the H$_2$ yield can reach 94.3% within 3.7 hours, indicating that Fe/AlOOH is an efficient catalyst for Al-water reaction. Therefore, Al-Fe/AlOOH-H$_2$O system can be used to provide hydrogen source for portable fuel cells.

Figure 4B shows the H$_2$ evolution at 40°C from Al-water reaction catalyzed by Fe/AlOOH composite with different molar ratios of AlOOH to Fe. It is found that the hydrogen generation performance of Al-water reaction catalyzed by Fe/AlOOH correlated with the molar ratio of AlOOH to Fe, indicating that the molar ratio of AlOOH to Fe has important impact on the catalytic activity of Fe/AlOOH composite. When the molar ratio of AlOOH to Fe increased from 0.5:1 to 1:1, the induction time decreased from 0.28 hours to 0.17 hours. However, further increasing the molar ratio of AlOOH to Fe, the induction time increased, implying that the induction time did not linearly correlate with the molar ratio of AlOOH to Fe. When the molar ratio of AlOOH to Fe is 1:1, Fe/AlOOH has the best catalytic activity. Previous work showed that the activity of catalyst strongly correlated with its active area, which refers to the surface area of catalyst that is capable of contact with Al particle. During the preparation of Fe/AlOOH catalyst, AlOOH acts as crystallization nuclei. FeCl$_3$·6H$_2$O reacts vigorously with NaBH$_4$ and produces Fe on AlOOH surface, which prevents the aggregation and inhibits the growth of Fe grains. Figure 4C shows the schematic representation of the structure of Fe/AlOOH catalysts with different molar ratios of AlOOH to Fe. When the molar ratio of AlOOH to Fe is 0.5:1, there are few AlOOH nuclei in suspension. In this case, the Fe grain formed is larger, and there are some Fe aggregates, as shown in Figure 4C. Increasing the molar ratio of AlOOH to Fe to 1:1, the number of AlOOH nuclei increases, and there are enough nuclei for Fe crystallization. Therefore, the Fe grain is small, and the surface area of Fe/AlOOH with the AlOOH:Fe molar ratio of 1:1 is larger than that with the AlOOH:Fe molar ratio of 0.5:1. When further increasing the molar ratio to 2:1, the AlOOH nuclei are excess, so some surface of AlOOH is not covered by Fe grains or aggregates (Figure 4C). As the catalytic activity of Fe is better than that of AlOOH (Figure 4A), the catalytic activity of Fe/AlOOH with the AlOOH:Fe molar ratio of 1:1 is better than that with the AlOOH:Fe molar ratio of 2:1. This explains why the Al-water reaction catalyzed by Fe/AlOOH catalyst with the AlOOH:Fe molar ratio of 1:1 has the best hydrogen production performance.

Figure 5A shows the H$_2$ evolution from Al-water reaction catalyzed by different weight contents of Fe/AlOOH catalyst at 40°C. It is found that the content of Fe/AlOOH has great effect on Al-water reaction dynamics, and increasing the content of Fe/AlOOH improves the hydrogen generation performance of Al-water reaction. When the content of Fe/AlOOH increases from 5 wt% to 30 wt%, the induction time decreases from 0.27 to 0.12 hours, and the H$_2$ yield increases from 90.8% to 93.6%. When the Fe/AlOOH content increases in the suspension, the active surface of Fe/AlOOH catalyst increases so that the probability of contact between Al and Fe/AlOOH increases, which shortens the induction time and promotes the Al-water reaction.

In practical application, the weight ratio of Al to water is often very high (higher than 1:30) in order to improve the hydrogen storage capacity of Al-water system. If the

![Figure 3](image)

**Figure 3** (A) N$_2$ adsorption-desorption isotherms and (B) pore size distribution of Fe and Fe/AlOOH catalysts

| Catalysts   | Average pore size (nm) | Pore volume (cm$^3$/g) | BET surface area (m$^2$/g) | External surface area (m$^2$/g) |
|-------------|------------------------|------------------------|-----------------------------|---------------------------------|
| Fe          | 35.7                   | 0.537                  | 70.0                        | 70.0                            |
| Fe/AlOOH$^a$| 18.1                   | 0.368                  | 80.6                        | 78.9                            |

$^a$The molar ratio of AlOOH to Fe in Fe/AlOOH catalysts is 1:1.
Al:water ratio is different, the hydrogen production performance of Al-water reaction may be different. In order to clarify this problem, we investigated the effect of Al:water ratio on Al-water reaction dynamics, as shown in Figure 5B. It can be seen that the Al:water ratio has little effect on Al-water reaction. The reaction dynamics difference is mainly reflected in the induction time, increasing the Al:water ratio decreases the induction time. When the Al:water ratio increases to 1:30, there is almost no induction time, indicating that the hydrogen generation performance of Al-Fe/AlOOH-water system can meet the requirement of portable fuel cells. In fact, the effect of the Al:water ratio on the Al-water reaction can be ascribed to the following two reasons: (1) Increasing the Al:water ratio can increase the concentration of Fe/AlOOH catalyst, which enhances the contact chance of Al with Fe/AlOOH, promoting the Al-water reaction. (2) Al-water reaction is an exothermic process, and the reaction heat is as high as 426.5 kJ/mol. Although the reaction was conducted in a thermostat water bath, the heat release from Al-water reaction can increase the local temperature. When increasing the Al:water ratio, the increment of local reaction temperature in Al-water reaction process becomes more obvious, accelerating the Al-water reaction.

Figure 5C shows the H₂ evolution from Al-water catalyzed by 10 wt% Fe/AlOOH catalyst at different temperatures. It is clear that the reaction temperature has greatly impact on Al-water reaction dynamics. Increasing the reaction temperature can greatly shorten the induction time and increase the hydrogen generation rate. Increasing the reaction temperature from 35°C to 60°C, the induction time decreases from 0.95 to 0 hours, and the maximum hydrogen generation rate (MHGR) increases from 7.0 to 69.5 mL/min/g-Al. At 60°C, the H₂ yield can reach 95% within 2 hours, which can meet the requirement of portable fuel cells.

To quantitatively describe the temperature effect, we used Arrhenius equation,

$$k = A \exp \left( -\frac{E_a}{RT} \right)$$

(4)

where $A$ is pre-exponential factor, $E_a$ is the activation energy, $R$ and $T$ are the gas constant and reaction temperature,
respectively, and $k$ is the rate constant, which is related to the surface chemical reaction. $k$ was calculated from the experimental data shown in Figure 5C using the equation shown below:\textsuperscript{10}

$$1 - (1 - \alpha)^{1/3} = kt. \quad (5)$$

The activation energy of Al-water reaction was determined from the $k$ vs $1/T$ plot using Equation 4, as shown in Figure 5D. The activation energy of Al-water reaction catalyzed by Fe/AlOOH composite was equal to 51.2 kJ/mol, which is much lower than the activation energy of Al-water reaction without using catalyst (about 68.1 kJ/mol for 2.25 μm pure Al powder).\textsuperscript{10} Thus, it can be inferred that the presence of Fe/AlOOH composite significantly decreases the activation energy of Al-water reaction, which further validates that Fe/AlOOH can be used as an efficient catalyst to promote Al-water reaction.

In order to investigate the stability of Fe/AlOOH, the fresh Fe/AlOOH catalyst was stored for a period of time in air, and then, it was used to catalyze Al-water reaction and hydrogen generation was measured, as shown in Figure 6. It is found that after the Fe/AlOOH catalyst was stored for a period of time, its catalytic activity slightly degraded. When the Fe/AlOOH catalyst was stored for 101 days, the induction time increased from 0.17 to 0.22 hours, and the $H_2$ yield decreased from 94.3% to 88.2%, implying that Fe/AlOOH catalyst has good stability.

Figure 7A and B shows the X-ray patterns for by-products of Al-water reaction without and with the addition of 10 wt% Fe/AlOOH catalyst. For the reaction of pure Al with water, the diffraction peaks of metal Al were still detected, which indicates that pure Al powder cannot completely react with water when no catalyst was used. However, the diffraction peaks of metal Al disappeared when Fe/AlOOH catalyst was used, which further validated the high catalytic effect of Fe/AlOOH on Al-water reaction. Figure 7A and B also shows that the Al-water reaction by-products are the mixture of bayerite and boehmite. Therefore, the equation of Al-water reaction can be written as.

$$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2 \uparrow. \quad (6)$$
3.3 Catalytic mechanisms

Typically, the surfaces of Al particles are covered by a passivating oxide film, which inhibits the reaction of Al with water. When Al powder is put into water, its surface passivating oxide film will undergo a hydration process,47,48 which results in the induction time of Al-water reaction. After the hydration process, the oxide film will eventually break from Al surface, exposing the inner Al to water. In this case, the inner Al can continuously react with water and generate hydrogen.

When no catalyst is added, the hydration process takes a long time. However, the induction time greatly shortened when Fe/AlOOH catalyst is added. As schematically shown in Figure 8, the catalytic effect of Fe/AlOOH composite on the hydration process of passivating oxide film can be ascribed to the following two phenomena: (a) AlOOH has a defect spinel structure, and some cation sites are vacant, so AlOOH has high surface chemical activity.49 When AlOOH particles come into contact with H2O molecules, they can break and dissociate H2O molecules into H+ and OH− ions.50 As a result, when Fe/AlOOH was added into water, some AlOOH particles are contact with Al particles. In this case, the H+ and OH− ions dissociated from H2O molecules on AlOOH surfaces are easy to hydrate with the passivating oxide film on Al particle surfaces, accelerating the hydration process. (b) The electrochemical potential of Fe is about −0.44 V, which is much higher than the potential of Al (−1.66 V). Thus, Fe and Al can form a galvanic microcell when Al is contact with Fe. For Al-Fe galvanic microcell, metal Al and Fe act as anode and cathode, respectively. The cell reaction equations are as following:

Fe cathode: \[2 \text{H}_2\text{O} + 2e^- = 2\text{OH}^- + \text{H}_2,\]  
(8)

Al anode: \[\text{Al} = \text{Al}^{3+} + 3e^-.\]  
(9)

The OH− formed on the Fe cathode could hydrate with the surface passivating oxide film of Al particle, accelerating the hydration process. When AlOOH is used as catalyst, only the first phenomenon occurs during the Al-water reaction. When Fe is used as catalyst, only the second phenomenon occurs. However, both phenomena occur when Fe/AlOOH catalyst is used. In addition, the appearance of AlOOH inhibits the aggregation of Fe and increases the active area of catalyst (Figure 2A and B and Table 1). This explains why Fe/AlOOH has the best catalytic activity and why the induction time of Al-water reaction promoted by Fe/AlOOH catalyst is much shorter than that promoted by Fe or AlOOH catalysts (Figure 4A).
CONCLUSIONS

In this work, a high-activity Fe/AIOOH composite with better stability is synthesized using wet chemical reduction method, and it is used as catalyst to promote Al-water reaction. It is found that both Fe and AIOOH catalysts greatly promote the Al-water reaction and shorten the induction time, and Fe/AIOOH further promotes the Al-water reaction. The catalytic activity of Fe/AIOOH composite is directly correlated with its active area, which is closely related to the molar ratio of AIOOH to Fe. In addition, increasing the weight content of Fe/AIOOH, reaction temperature, and the weight ratio of Al to water can improve the hydrogen generation performance of Al-water reaction. When the Al:water ratio is higher than 1:30, there is almost no induction for Al-water reaction catalyzed by Fe/AIOOH, and the maximum hydrogen generation rate is as high as 19.4 mL/min/g-Al. The mechanism analyses show that the dissociation of water molecules on AIOOH surface and the galvanic microinteraction between Fe and Al could accelerate the hydration process of surface passivating oxide film of Al particle, improving the Al-water reaction dynamics. This work demonstrates a novel and effective way to produce hydrogen from Al-water reaction for portable fuel cells.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Grant nos. 51872181 and 51801093), the Key scientific research projects of Henan Province Colleges and Universities (No. 18A150039), and the Henan Provincial Key Science and Technology Research Project (No. 182102311047).

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