An Overview of the Methods of Enhancement of the Reaction Kinetics of Al-Water Reaction in an Aqueous Medium and the Prospect of the Economic Viability

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1 Introduction

The environmental pollution caused by the burning of fossil fuel is a major challenge in the present scenario. The fossil fuel is getting reduced due to its wide applications mainly for power generation. Hydrogen gas is assumed to be a source for future power production. Among the various method of production of hydrogen gas, the chemical method has dominated the market. The production of hydrogen gas from Al-water reaction in the presence of aqueous NaOH solution is considered as a low-cost production method. The raw material used in the reaction is Al scrap. Moreover, Al has several advantages, e.g. high-energy density, lightweight, etc. However, ball milling of aluminum and mechanical alloying with other elements can enhance the yield of hydrogen. The production of hydrogen gas also depends on the size of the Al particles, initial reaction temperature, and concentration of NaOH solution.

2 Activated Al Metal

The Al-water reaction is a surface reaction process. Al alloyed with other metals like In, Ga, Sn, Bi, etc., have a fair production rate as reported [1]. Ball milled Al with salt particles can accelerate the reaction and increase the yield of hydrogen gas. Maximum hydrogen production of 75 ml/min per gram of Al has been reported for Al particles milled with salt particles [2]. Fan *et. al.*[3] have reported the hydrolysis effectiveness of Al metal alloyed with other metals. It is stated that the ball milling

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P. Mahanta et al. (eds.), *Advances in Thermofluids and Renewable Energy*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-16-3497-0_47

of Al with Zn, Ca, Ga, Bi, Mg, In, and Sn is much more productive than making alloys of these metals by the process of melting.

3 Size of Al Particles

One of the main parameters that affect the production of hydrogen is the size of the Al particles. Al particles with smaller size are found to be profound in the liberation of hydrogen gas [4]. It was reported that 60–80% of hydrogen gas can be obtained using 6 μm size of Al particles. The research carried out by Elitzur S. *et. al.*[5] shows that the hydrogen production rate depends on the specific surface area (m^2/g) of the Al particles. It also implies that the rate of kinetics is dependent on the shape of the raw Al.

4 The Effect of the Characteristics of Water

The type of water used for the reaction has a prominent role in the production rate. The amount of salt content in the water affects the reaction kinetics. The reaction rate is faster for the water that contains more salt particles [6]. Wang *et.al.*[7] have carried out experiments to investigate the effect of deionized water and tap water in the production of hydrogen gas. The same set of the experiment conducted with tap water has very less yield of hydrogen. Phung *et.al.*[8] have carried out experiments with distilled water, deionized water, tap water, and ultrapure water to observe the effect on the hydrogen production rate.

5 Transition to the Hydrogen Economy

The optimum combination of the aforesaid parameters can contribute to the production of the maximum amount of hydrogen gas at a faster rate. However, the analysis of economic aspects of hydrogen energy is crucial in entering into the market. The critical evaluation of the usage of hydrogen gas for commercial purposes is discussed in the following subsections.

5.1 Hydrogen Transportation and Distribution

Demir *et.al.* [9] have assessed the cost-effectiveness and the performance of the hydrogen delivery system. They have adopted three different methods of hydrogen transportation and distribution. Hydrogen transmission by a pressurized tank, gas pipeline and cryogenic liquid transport are three modes as mentioned. The hydrogen gas transmission through the existing natural gas pipeline is envisaged by another researcher [10]. However, to realize the hydrogen economy and marketing breakthrough some challenges have to be overcome. The problem related to the embrittlement of hydrogen gas does not only depend on the material property but also the pipeline history. A thorough examination is required to stream hydrogen through the natural gas pipe. It is suggested that the transition of traditional energy to hydrogen energy is possible by combining hydrogen with natural gas and delivery through the natural gas pipelines. The delivery infrastructure of hydrogen gas concedes a substantial cash outflow. The storage and transmission cost assessment in the European perspective have been carried out by Tzimas *et.al.* [11]. It is proposed that pipelines of a 1–4 million km length are necessary to enter the hydrogen economy in the European energy system. Out of which 35,000 km of pipelines are required for high-pressure hydrogen transport and 400,000 km for a medium range of transmission by 2050. The production cost for this infrastructure is estimated to be 700–2200 thousand million euros. The successful entry of the commercial use of hydrogen gas is mostly depending upon infrastructure development. This is also one of the issues that restrict the technical modification of automobile engines fuelled by hydrogen gas. The cost of the hydrogen delivery system is directly related to the span of the H_2 transportation and distribution network. However, the market demand for hydrogen is a key point for the wide-spread of the delivery system. The efficient design of a hydrogen delivery network depends on many factors like the geographical location of the place, market demand, and number of refueling stations within the city radius [12]. Optimum design of the hydrogen delivery network considers cost-effectiveness, ease of distribution, environmentally benign character, and easy operation process by the end-users. A substantial amount of exploration has been conducted in this aspect [13, 14]. A various optimization model for the economic benefits of the hydrogen delivery system has been proposed [15, 16]. The commercial feasibility of hydrogen gas has been studied by considering the cost associated with the production of hydrogen gas, transportation, and distribution through various channels to the refueling stations. Weisberg and co-workers [17] have constructed a glass tube fiber channel that operates at 200 K and 700 bar can transport hydrogen gas with a minimum cost 1/kg USD. The optimization of the location of refueling stations for the convenience of the automobiles has been done by applying the statistical tool called, mixed-integer linear model by another researcher [18]. The infrastructure expenditure for hydrogen fuel stations has been surveyed by Weinert and Lipman [16].

5.2 Hydrogen Refueling Station Setting Model

The work carried out by Weinert and Lipman implicates that a small power station of hydrogen contain a capacity 30 kg/day has a setup cost is only 0.5 million USD. However, for a refueling station of capacity 1000 kg/day, the cost rises to five million USD.

The traditional power system can be replaced by a brand new technology that incorporates the mixing of hydrogen gas with natural gas. The power drawn by the integrated gas-energy system is cost-effective and environmentally friendly. However, the operational cost and the CO_2 emission level are under study. The investigation regarding the optimal cost of the hybrid gas-energy system is carried out by many researchers [19]. The economic and environmental issues relating to the integration of hydrogen and natural power system are not addressed yet. The operating cost and the CO_2 emission level are greatly reduced in the case of gas-fuelled power systems than coal-fuelled system [20]. The market demand and the production capacity of hydrogen are very less compared to gasoline. The fostering of the hydrogen economy into the energy market is hindered owing to the high-capital cost of the hydrogen station. Lee *et.al.*[21] have shown a cost comparative study between different fuels. The analysis includes all types of cost starting from the capital to the labor cost and from the distribution cost to maintenance cost. The study also illustrates the social and environmental costs owing to the emission of NO_x, CO_2, etc. However, the result so obtained is varied from geographical locations. For the life cycle assessment of the different fuel, the effect of social cost has been pivotal. The cost of fuel for future reference is also demonstrated. The way to cut down the price of fuel cell vehicles by reducing the production cost is described in this literature.

5.3 Fuel Cell Vehicle and Hydrogen Energy

It is anticipated that by 2030 most of the hydrogen vehicles will be powered by fuel cells [22]. The evolution of fuel cell vehicle makes a pavement to the development of hydrogen supply chain infrastructure. The growing demand in the market encourages the hydrogen economy. It is predicted that within the next few years the hydrogen vehicle will be running on the road due to the sustainable development in the hydrogen delivery system [23]. The fuel efficiency of the fuel cell vehicle is estimated to be 30 km/l by Lee *et.al* [21]. The hydrogen-fuelled vehicles have good fuel efficiency and maintenance cost is low. There are less numbers of moving parts in the vehicle. In spite, the fuel cell vehicle has demerits of being very expensive to penetrate the hydrogen economy. Moreover, due to the limited hydrogen energy infrastructure available the technology has not grown as expected. The price of an average model of a hydrogen car is almost 50% higher than a gasoline car. The various drawbacks of the fuel cell vehicles impede the hydrogen economy and lacking it to qualify with the fossil fuel energy system. A cost comparative assessment has been presented in Table 1 [24].

Table 1 Comparison of the average price of hydrogen vehicle with petrol vehicle [24]

Sr No	Brand	Category of vehicle	Average price ($)	The average price of the counterpart ($)
1	Hyundai ix 35 (fuel cell)	SUV	68,309–70,000	33,000
2	Hyundai Tuscon (FCEV)	SUV	68,309–70,000	33,000
3	Toyota Mirai	D class	58,365–65,00	25,000
4	Honda Clarity	D class	59,385–59,385	25,000

6 Conclusions

The production of hydrogen gas from an Al-water reaction is a promising method. The evolution of hydrogen gas can be enriched by optimizing the factors that affect the reaction kinetics. It is environmentally friendly fuel for power production. However, the hydrogen delivery system is very costly and as a result, is not able to acquire the momentum in the market. Nevertheless, one key point to be addressed is the technological expansion to distribute hydrogen energy to the end-users. The various technical aspects and delivery infrastructure have to be explored for the transition. The injection of hydrogen gas with natural gas and transmit through the existing pipeline is an emerging field of study. Thus, sustainable hydrogen economy can be fostered by adopting technical modification of the delivery channel to penetrate the market and liberalize the dependency on traditional fuel.

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