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Review Article

The kinetics of lightweight solid-state hydrogen storage materials: A review

Nurul Zafirah Abd.Khalim Khafidz [a], Zahira Yaakob [a,b,*], Kean Long Lim [a], Sharifah Najiha Timmiati [a]

[a] Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[b] Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

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ABSTRACT

Hydrogen is conventionally stored as either a compressed gas or a cryogenic liquid. However, the lack of efficient storage materials has thus far critically limited the widespread adoption of hydrogen, and to overcome this limitation, a promising solid-state storage method is needed. Attractive lightweight metal-based materials for solid-state storage are characterized by the capability to reversibly store a large quantity of hydrogen and should meet or exceed the United States Department of Energy (DOE) on-board storage targets. However, the undesirable kinetic performances of metal hydrides as solid-state storage materials have hindered their practical use as hydrogen storage systems. The kinetic performances, which include the rate of hydrogen uptake or release, are among the most critical requirements of a storage system, and these performances can be determined using the hydrogen absorption and desorption rates. Thus, determining the relevant kinetics is required to supply sufficient amounts of hydrogen and to achieve fast refueling in the system. This review summarizes the kinetic performances and the efforts toward enhancing the hydrogen absorption/desorption kinetics of light metal-based materials.

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* *Corresponding author*. Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia. Tel.: +60 3 89216420; fax: +60 3 89216148.
E-mail address: zahira@ukm.edu.my (Z. Yaakob).

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Introduction

A solid-state metal hydride hydrogen storage canister with interesting features of low-pressure operation, safety and scalability and is potentially useful for transportable applications, such as compact portable or mobile systems [1]. In a light metal hydride tank system, the hydrogen uptake and release are governed by kinetic reactions that can be characterized by poor absorption/desorption kinetics [2]. The storage and release of hydrogen for mobile applications preferably occur over the temperature and pressure ranges of 0 °C–100 °C and 1 bar–10 bar, respectively. According to the United States Department of Energy (DOE), the goal for the on-board automotive performance of a hydrogen charging and discharging system is the capability of receiving a 5 kg fill of H_2 in 3.3 min (corresponding to 1.5 kg H_2/min) for the temperature range from 25 °C to 120 °C by 2017 [3]. Accordingly, new insights and strategies for the development of hydrogen storage materials are essential for meeting these critical kinetic goals by 2017.

Solid-state storage via chemical means within the storage materials has potential advantages over conventional storage by providing improved energy efficiency, safety and high volumetric and gravimetric storage capacities, as well as presenting the capability to absorb/desorb at a medium temperature of 300 °C and a pressure between 1 bar and 10 bar [4,5]. Chemisorption involves strong chemical bonding between the solid material and hydrogen atoms, leading to the formation of hydrides [6]. Materials that function via chemisorption can uptake large amounts of hydrogen; however, a high desorption temperature is required for some hydrides because of their sluggish kinetics. Accordingly, different types of solid-state storage materials have been developed, including metal hydrides, complex hydrides [7] and chemical hydrides. Solid-state storage offers the best opportunity for meeting the requirements of a storage system in which hydrogen can be stored reversibly and irreversibly and can provide another approach for addressing the challenges associated with hydrogen storage [8].

Currently, researchers are optimistic regarding the investigations of numerous types of alternative energy storage methods for addressing energy issues using efficient, relatively inexpensive and eco-friendly nanomaterial [9]. One of the potential types of materials for solid-state storage systems is metal hydrides, which exhibit high energy efficiency. The hydrogen kinetics of these compounds can attain a faster rate under suitable temperature and hydrogen pressure conditions during the absorption/desorption process [10,11]. Because the release of hydrogen from a hydride bed is limited by an endothermic desorption process, Song et al. [12] stated that the metal hydrides are considerably safer for storing hydrogen in portable fuel cells for mobile applications. However, the applications of conventional metal hydrides have been hindered by the use of heavy tanks, contributing to a poor gravimetric density (<2 wt% H_2), which is not suitable for mobile and automotive applications [13]. Hence, research on new storage materials has shifted toward light metals, such as Ti, Li, B, Na, Mg and Al in hydride forms, for use as solid-state storage materials [14]. These light metal-based materials are considered to be a particularly important category because they can store a high density of hydrogen, but this capability is prevented by their poor kinetics, high thermodynamic stability and high desorption temperature [2,15]. The highest volumetric and gravimetric densities of hydrogen observed in some metal hydrides (i.e., Li, Mg, B and Al) ranged from 80 kg/m^3 to 150 kg/m^3 and up to 7.6 wt% H_2, respectively [14]. A comparison between lightweight and heavyweight solid-state materials is presented in Table 1.

It is important to determine the hydrogen absorption/desorption kinetic properties with respect to the rate at which the material can charge/discharge stored hydrogen and maintain a desired power [16]. A resistance analysis was performed by comparing the transport phenomena and intrinsic kinetics using a kinetic model from Lozano et al. [17,18]. Ley et al. [1] predicted that the driving force for hydrogen transportation, intrinsic kinetics and heat transfer can be the drawbacks during hydrogen sorption. The results indicated that hydrogen transportation has an insignificant effect (independent of the size of the reactor), that the intrinsic kinetics play a critical role in a small cell of 2 mm and that heat transfer is the main problem during absorption in a scale-up tank. In general, the kinetic characteristics are easily affected by intrinsic (material behavior) and extrinsic parameters. The intrinsic factors include the physical-chemical behavior of the materials, cycling stability and equilibrium hydrogen sorption properties [19] as well as surface [20] and bulk properties [13,21]. In contrast, the extrinsic factors include the powder morphology and heat transfer or mass transport and focus on the kinetic properties [21].

The hydrogen absorption or desorption in a hydrogen storage material is controlled by the thermal management (heat transfer) [22,23] either into or out of the hydride fine particles. This issue is particularly important in hydrogen storage systems when high volumes and a rapid transfer of

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