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Overview of porous media/metal foam application in fuel cells and solar power systems

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A R T I C L E I N F O

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A B S T R A C T

Fuel cells and solar energy are promising candidates for electricity generation. It is forecast that fuel cells and solar power systems will play an important role in reducing the greenhouse gas footprint and replacing fossil fuels. Therefore, the limitations of fuel cells and solar power systems, such as low efficiency, high cost, and low reliability, must be addressed appropriately to enable their full potentials. Metal foam is a new class of material that has gained immense attention due to its excellent properties suitable for a wide range of applications. Its unique characteristics distinguish it from typical solid metals. The properties of metal foam can be modified during the fabrication stage by manipulating its physical structure. The goal of this paper is to review the application of metal foam in fuel cells and solar power systems. Besides, the performance of metal foam in fuel cells and solar systems is also discussed. Metal foam has been applied to the electrodes, gas diffusion layer and flow field of fuel cells to enhance performance, especially in regard to current density and flow distribution. Furthermore, metal foam is a heat exchanger for the solar energy harvesting system to improve its efficiency. Superior performances in experimental testing allows the possibility of commercialization of metal foam products in the renewable energy field.

1. Introduction

Renewable energy, such as solar, waves, geothermal and wind energy, is an energy source that will not be depleted. Using renewable energy can reduce the greenhouse gas footprint by minimizing the consumption of fossil fuels used for electricity generation. This is important to ensure a cleaner and greener environment. In addition, the European Union aims to cover full energy demands, using the renewable and sustainable energy system. This has motivated researchers to explore the application of the renewable energy field to help the European Union achieve the 100% renewable energy target [1]. However, renewable energy also faces challenges due to its low efficiency and high production cost with a low return on investment. Therefore, it is essential to reduce production costs and improve efficiency to promote renewable energy globally [2,3].

Fuel cell is an electrochemical device to convert chemical energy into electrical energy. Unlike a battery, which stores the chemical energy within it, the fuel cell generates electrical energy from the chemical energy supplied at the anode and cathode. Depending on the types of fuel cells, the power density may vary with different types of reactants. Various types of fuel cells are available in the laboratory and market, such as Proton Exchange Membrane Fuel Cell (PEMFC), Microbial Fuel Cell (MFC), Phosphoric Acid Fuel Cell (PAFC), Solid Acid Fuel Cell (SAFC), Solid Oxide Fuel Cell (SOFC), Alkaline Fuel Cell (AFC), Direct Methanol Fuel Cell (DMFC), etc. The by-product of a fuel cell is environmentally friendly, which makes the fuel cell a preferable choice for the renewable energy system. The fuel cell market is growing worldwide, and by 2020, the stationary fuel cell market is expected to reach 50 GW [4]. To advance the commercialization of the fuel cell, different approaches have been taken to improve the existing fuel cell with the aim to reduce the cost and to improve performance through modification of the fuel cell components [5–7].

Solar energy is a permanent heat and light source that is emitted from the sun to the Earth. The Earth receives ~ 170 trillion kW of incoming solar radiation (insolation) at the upper atmosphere. Approximately, 47% of the energy reaches the Earth's surface. The rest is reflected back into space by clouds (~ 17%), absorbed by ozone, water vapor and dust (~ 19%), scattered by air molecules (~ 8%), absorbed by clouds (~ 4%), and reflected into space by the surface (~ 6%) [8,9]. Solar energy is important because it is renewable energy that

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exists abundantly, is non-polluting and is free. The solar energy received by the Earth in one and a half hours (480 EJ) is more than the energy consumption in the year 2011 retrieved from all sources (430 EJ) [10]. Therefore, development of a solar energy harvesting system is an essential approach to promote globally renewable energy production and use to solve the issues of depletion of fossil fuels for electricity generation. Besides, solar energy can help combat global warming by reducing the dependency on fossil fuels, which emit harmful gases into the atmosphere.

There are numerous solar energy harvesting systems available in the market, such as solar chimney, solar thermal energy storage, solar heater, concentrate photovoltaic, solar receiver/collector, solar pond, photovoltaic panel, etc. Low efficiency and high cost are key factors preventing the usage of solar energy harvesting systems abundantly in generating electricity. Hence, improvement of solar energy harvesting systems, such as improving the heat transfer or cooling performance, is crucial in promoting the application of solar energy harvesting systems in the worldwide market.

Metal foam is a new class of material with excellent properties that can be applied in various applications [11]. Metal foam provides excellent mechanical properties and is lightweight, while maintaining high strength and rigidity. It also has excellent acoustic properties for sound absorption application. The complex geometry within the metal foam increases the surface area per unit volume. This is an ideal characteristic for heat transfer application or thermal management applications, such as heat exchangers. By varying the characteristics of metal foam, such as permeability, pore size, pores per inch (PPI), etc., the metal foam can provide a unique interaction with the fluid that flows through it and results in different observations.

There are two classes of metal foam. The first type is open cell, while the second type is a closed cell. Open cell metal foam allows the fluid to flow freely through one cell to another, and the cells are not closed. The typical open cell metal foam structure is shown in Fig. 1. The closed-cell metal foam consists of continuous cell walls, which separate one cell from another with the formation of a discrete section. The geometry of the cell is usually spherical in shape [13]. Depending on the application, different characteristics of metal foam should be chosen to meet the design requirements.

In view of the above, metal foam can bring a new dimension in renewable energy application. For example, it has been used as a gas diffusion layer, electrode or flow field in fuel cells as well as heat transfer media in solar energy harvesting systems to improve efficiency and electrical performance. Metal foam, with its excellent thermal conductivity and high solid to fluid interfacial area that enhances fluid mixing, is an ideal heat transfer candidate for solar energy harvesting systems.

Although there are many solar energy harvesting systems, not every system is suitable for metal foam. Solar chimneys, solar collectors/receivers, solar heat exchangers/heaters and thermal energy storage are solar energy harvesting systems that are appropriate for metal foam [14]. In addition, the cost of metal foam has been significantly reduced due to the advancement of manufacturing methods. For example, Alcoa (USA) introduced a new process to manufacture metal foam which could lead to the price of aluminum foam being as low as USD 5 per kg [11]. This new manufacturing process can greatly help to reduce the production cost, so the metal foam can be commercialized. Selection of metal foam for a certain application is further simplified by standardization by the agency. This will further promote the application of metal foam in the renewable energy field.

In this study, a critical review of applications of metal foam in fuel cells and solar energy harvesting systems is conducted, encompassing various types of metal foam application in fuel cells. This includes proton exchange membrane fuel cells, microbial fuel cells, direct methanol fuel cells, alkaline fuel cells and solid oxide fuel cells. Applications of metal foam in solar collectors and thermal energy storage systems are also discussed. This review not only aims to provide an overview of the performance of the metal foam in fuel cells and solar power systems, but also to provide useful insight into the future development of fuel cells and solar power systems using metal foam. In addition, the challenges associated with metal foam use in fuel cells and solar power systems are also covered in the discussion.

2. Methodology

Despite metal foam having been used in fuel cells and solar power systems for a number of years, the understanding of the flow field and electrical and heat transfer characteristics in such systems is very limited. This is partly due to the complicated internal geometrical structure of (the strut) metal foam. As metal foam generally exhibits a random structure, it is very difficult to obtain a general correlation to describe the characteristics of this material. Numerous studies have suggested that metal foam is suitable for various applications in automotive, aerospace and electronics industries [11]. However, there are few comprehensive reviews of the application of metal foam in the renewable energy field, especially in fuel cells and solar cells.

Hence, a review of the applications of metal foam in different components of the fuel cell system such as anode, cathode and gas diffusion layer is presented. This review not only explores the technological advantages and challenges of these applications, but also proposes approaches to overcome the limitations of these applications. In addition, key factors affecting the performance of these applications are identified with critical discussions of future perspectives of metal foam in the individual components of fuel cells. In addition to the fuel cell system, the applications of metal foam as a heat sink in solar power

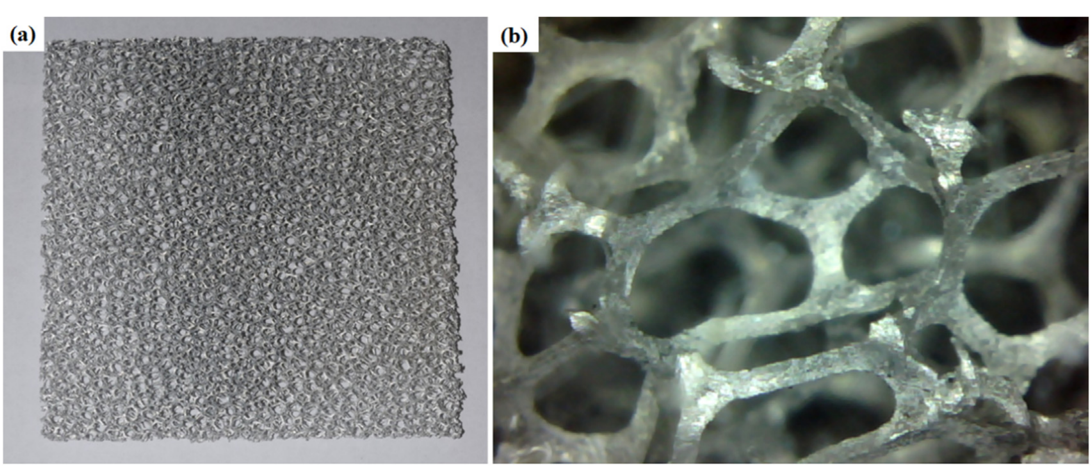

Fig. 1. a) Aluminum foam sample and b) close view of the aluminum foam structure [12].