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Development of thermal energy storage material using porous silicon carbide and calcium hydroxide

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Abstract

A thermal chemical energy storage (TCES) material was developed that utilizes surplus heat from nuclear power plants during low demand of electricity. The target temperature of reusing heat is over 450 °C which is utilized for next generation nuclear reactors. Therefore, Calcium hydroxide ($Ca(OH)_2$) was selected as the TCES material because it decomposes at temperatures over 450 ºC under atmospheric pressure. Porous silicon carbide was selected as the support for $Ca(OH)_2$ because of its high porosity, chemical stability, and high thermal conductivity. The reaction performance of newly developed TCES material was studied with thermal gravimetric analysis (TGA).

Keywords: Heat pump; Heat storage; Calcium oxide; Calcium hydroxide; Silicon carbide

1. Introduction

In order to reduce carbon dioxide emission, introducing sustainable energy is being promoted instead of the established thermal power generation. However this may cause a loss in the stability of electrical grids. Even though nuclear power generation has been greatly established in supplying power, it is required to change the power output flexibly. This flexibility in changing the power output conflicts with the aim of reducing life span of nuclear power

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plants, thus, increasing the payback period of initial investment in the plant and its equipment. In order to solve such problem, P. Denholm et. al. proposed to introduce heat storage technology to nuclear power plants [1]. In our research thermal chemical energy storage (TCES) material was proposed for the heat storage technology. The target temperature of reusing heat is over 450 °C which is utilized for next generation nuclear reactors. Fig.1 shows conceptual Sodium-cooled fast reactor (SFR) installed CaO/H_2O TCES system. The SFR system was based on the data of Monju reactor in Japan [2]. Calcium hydroxide ($Ca(OH)_2$) was selected as the TCES material because it decomposes at temperatures over 450 ºC under atmospheric pressure.

Thermo chemical energy storage (TCES) is one of the promising technologies which contribute to realizing sustainable society. Notably, TCES systems can store energy for long periods of time with energy densities that are higher than those of conventional heat storage systems based on sensible and latent heats. For example, the energy density of organic phase change materials (PCMs) is 180–200 kJ kg^{-1} [3], which is lower than that of the TCES system based on $CaO/H_2O/Ca(OH)_2$ (i.e., 1300 kJ kg^{-1}).

TCES that uses a calcium oxide / water / calcium hydroxide ($CaO/H_2O/Ca(OH)_2$) reaction has been researched for the purpose of utilizing unused heat (with temperatures over 450 ºC) because it has high material volumetric energy density; moreover, the reaction exhibits impressive reversibility [4].

$$CaO\ (s) + H_2O\ (g) \rightleftarrows Ca(OH)_2\ (s),\ \Delta H_1 = -104.2\ \text{kJ mol}^{-1} \quad (1)$$

$$H_2O\ (l) \rightleftarrows H_2O\ (g),\ \Delta H_2 = -41.7\ \text{kJ mol}^{-1} \quad (2)$$

The dehydration of $Ca(OH)_2$ and the hydration of CaO shown in Eq. (1) correspond to the heat storage and heat output operating modes, respectively.

TCES systems based on CaO/H_2O have been examined previously. In terms of reaction kinetics the following researches have been discussed. F. Schaube suggested the reaction model considering influence of vapor pressure [5]. Matsuda suggested grain model assuming that the reaction controlling step is reaction on particle surface [6]. Ogura investigated difference in the reversible reaction conversion between open system under atmospheric pressure and closed system under decompression [7]. Some practical applications of the reaction system has been done by the following researchers. Darkwa tried to reduce emission gas from automobile using the reaction system [8]. Pardo made fluidized bed reactor for solar thermal energy storage [4]. The Fluidized bed was selected to overcome reducing vapor diffusivity and low thermal conductivity in TCES materials. They also use alumina or silicon carbide powder to enhance thermal conductivity between reaction material and reactor wall. However this method has problem that fluidizing system consumes energy and expand reactor scale. Ogura proposed to insert cupper fin into packed bed reactor and succeeded to enhance thermal conductivity keeping high energy density [9]. However cupper fin is low durability, because cupper reacts with vapor and calcium hydroxide.

In this research a silicon carbide - diesel particle filter (SiC-DPF) was selected as a support for $Ca(OH)_2$. SiC-DPF containing redox catalyst is widely used as a filter for removing particulate matters in emission gas generated from diesel vehicles. The merits of SiC-DPF include chemical stability, low cost, large pore volume and high thermal conductivity (Reference value, SiC-DPF: 90 W $(mk)^{-1}$[10], Cupper: 400 W$(mk)^{-1}$[11]at r.t..). Therefore, composing SiC-DPF with calcium hydroxide can get over the low thermal conductivity and vapor diffusivity through TCES materials at larger scale.

The main reason to select SiC-DPF for a support of $Ca(OH)_2$ is chemical stability, because the operating conditions represent a harsh environment for supports. Supports are exposed to vapor under high temperature (over 400 ºC) and to $Ca(OH)_2$ particles, which constitute a strong base. SiC-DPF is superior to the other supports such as graphite and metal foams under such harsh conditions. Consequently SiC-DPF is suitable for CaO/H_2O reaction system.

In this work composite materials, which consisted of SiC-DPF and $Ca(OH)_2$, were developed. The effect of SiC-DPF on the hydration of the CaO/H_2O was evaluated using thermal gravimetric analysis (TGA). Finally the effect on reaction kinetics was analyzed using a grain model.