Combination of Thermochemical Energy Storage and Small Pressurized Water Reactor for Cogeneration System

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Abstract

In recent decades, small nuclear reactors for cogeneration systems have been studied. Generally, nuclear plants are operated at steady state, but the heat demand load is not steady. Load leveling using thermochemical energy storage (TcES) is a potential method for overcoming this problem. In this work, the heat load of a town was assumed, and the required amount of TcES material for load leveling was estimated. The amount of material required, relative to the volume of the nuclear reactor vessel, was acceptable for installing a TcES system at the nuclear plant.

Keywords: Load leveling; Cogeneration system; Thermochemical energy storage; Magnesium hydroxide; Lithium chloride

1. Introduction

In recent decades, water-cooled reactors [1–3] and a gas-cooled reactor [4] with small capacities (5–330 MWt) have been studied for heating districts in cold areas. Generally, nuclear plants are operated at steady state, but the heat load is not steady. Therefore, research on the conversion and storage of waste heat, which is unused energy, is required. Thermochemical energy storage (TcES) is one of the technologies used for the conversion and storage of unused thermal energy. Load leveling using TcES is a potential method for overcoming this problem [5,6]. Several working pairs have been proposed for TcES in recent decades; for example, metal oxide/H\textsubscript{2}O systems [7–13] and metal oxide/CO\textsubscript{2} systems [14–17].

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TcES based on the MgO/H₂O system has been examined [10,11].

\[
\text{MgO(s) + H₂O(g) } \rightleftharpoons \text{Mg(OH)₂(s) } \Delta H_r^0 = -81.0 \text{ kJ mol}^{-1} \\
\text{H₂O(g) } \rightleftharpoons \text{H₂O(l) } \Delta H_{\text{vap}}^0 = -40.7 \text{ kJ mol}^{-1}
\]

The dehydration reaction in Eq. (1) corresponds to the heat storage operation, while the hydration reaction corresponds in Eq. (1) to the heat output operation.

However, most materials store heat at temperatures higher than 350 °C, which is greater than the temperature of surplus heat from light water reactors. The dehydration rates of Mg(OH)₂ and Ca(OH)₂ are enhanced by surface modification of the metal hydroxides by LiCl [18,19]; for example, the heat storage temperature is 350–400 °C for Mg(OH)₂, whereas it is 250–300 °C for LiCl-modified Mg(OH)₂. Therefore, a LiCl-modified MgO/H₂O system could be used as the TcES material in load leveling. In this paper, LiCl-modified Mg(OH)₂ is denoted as LiCl/Mg(OH)₂. LiCl, Mg(OH)₂, MgO, and H₂O have low toxicities; Thus, LiCl/Mg(OH)₂ is an eco-friendly material for fabricating TcES systems. LiCl/Mg(OH)₂ showed a high heat output density (1.40 × 10³ kJ kg⁻¹ at a dehydration temperature of 300 °C, hydration temperature of 110 °C, water vapor pressure of 57.8 kPa, and vapor supply for 80 min) [20,21]. Though it is necessary to investigate the required amount of TcES material to evaluate its potential for load leveling, it has not been sufficiently studied.

In this work, a cogeneration system using a small nuclear reactor was considered. The load leveling was performed using LiCl/Mg(OH)₂. The heat load of a town was first estimated by sine curve modeling, and then the required amount of LiCl/Mg(OH)₂ for load leveling was estimated. The potential of LiCl/Mg(OH)₂ for load leveling was investigated.

2. Estimation

2.1. Small nuclear reactor

Small nuclear reactors for district heating or cogeneration have been studied in recent decades. Usually, the designed temperature range of the district-heating network is 80–150 °C [1–4]. The heat load is approximately 600–1200 MWt for large cities and 10–50 MWt for towns [22]. Usually, the required temperature for space heating is 80 °C, and that for hot water production is 60 °C [1]. In this work, a small pressurized water reactor (PWR) for combined heat and power generation was considered. The nuclear reactor at Bilibino, Russian Federation, was designed for cogeneration [23], and a heat output of 25 MWt and an electricity output of 11 MWe were obtained from the reactor. In this work, a small reactor with heat and electricity outputs of 10 MWt and 4.4 MWe, respectively (reactor power: 23.3 MWt) was considered. The temperatures of the primary and secondary systems are shown in Table 1. The core output temperature was estimated to be 350 °C and the supply temperature for district heating was estimated to be 95 °C. The generating efficiency of the nuclear power plant was assumed to be 0.33. It was assumed that the electricity load was constant.

<table>
<thead>
<tr>
<th>Heat output [MWt]</th>
<th>Primary system</th>
<th>Secondary system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core inlet temperature [°C]</td>
<td>Core outlet temperature [°C]</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
<td>350</td>
</tr>
</tbody>
</table>
2.2. Material for thermochemical energy storage

LiCl/Mg(OH)$_2$ (LiCl:Mg(OH)$_2$ molar ratio 0.10) was used as the TcES material in the district-heating system. It was assumed that LiCl/Mg(OH)$_2$ was dehydrated at ~300 °C in the reactor, and LiCl/MgO was hydrated at ~140 °C, with a water vapor pressure of 57.8 kPa. The preparation procedure of LiCl/Mg(OH)$_2$ in bench-scale was shown in our previous paper [20].

In previous studies [20,21], dehydration was performed at 300 °C for 30 min and hydration was performed at 110–150 °C for 80 min, for LiCl/Mg(OH)$_2$. The heat output density of LiCl/Mg(OH)$_2$ at a dehydration temperature of 300 °C, hydration temperature of 140 °C, and water vapor pressure of 57.8 kPa was 872 kJ kg$^{-1}$. The operating periods for dehydration (30 min) and hydration (80 min) were sufficiently short compared to the period for changing the heat load. These kinetics of heat storage and heat output were enough fast compared to the kinetics for daily change of the heat load. The chemical reactors were consists of parallel system in this work. Thus, the heat storage and heat output can be performed by switching valves of parallel chemical reactors at different times.

2.3. District heating

In this work, a district heating at winter season is considered. Typical heat load/output were studied in this work. Pressurized water was used as the heating medium. A schematic diagram of the district-heating system with TcES (operated for heat storage) is shown in Figure 1. First, 13.3 MWt of heat were used for power generation. The base load for district heating (10 MWt) was supplied, and surplus heat was stored by the dehydration of LiCl/Mg(OH)$_2$ during the low-heat-demand period. The rest of the heat was used for space heating, supply of hot water, and snow melting. The temperatures at the inlet and outlet of the heat exchangers and the flow rate of water at the peak of heat storage were calculated using Eq. (3). It was assumed that all pipes were insulated.

$$W_{ex} = F \cdot C_p \cdot \Delta T$$

Figure 1  Schematic diagram of district-heating system with thermochemical energy storage (at peak of heat storage operation) during low-heat-demand period.
where $W_{ex}$ [kW] is the rate of heat exchange, $F$ [kg s$^{-1}$] is the water flow rate, $C_p$ [kJ kg$^{-1}$ K$^{-1}$] is the isobaric specific heat capacity of water, and $\Delta T$ [°C] is the temperature drop at the heat exchanger. A schematic diagram of the district-heating system with TcES (operated for heat output) is shown in Figure 2. The base load for district heating (10 MWt) was supplied, and the additional heat was supplied from the hydration of LiCl-modified MgO during a period of high heat demand. The temperature settings for the power generation loop of the small nuclear reactor are shown in Figure 3.

The heat load for district heating was studied by Dotzauer [24]. The heat load was approximately 300 ± 60 MWt for the first 240 h. The heat load for district heating changed by ±20% relative to the base load. In this work, the heat load for a town was modeled using a sine curve. It was assumed that the base load was 10 MWt, and the heat load changed by ±20% relative to the base load during a day. Based on the work of Gadd and Werner [25], peak top was assumed to be at noon, and peak bottom was supposed to be at midnight. The relationship between the heat load ($W_{heat}$ [MWt]) and time ($t$ [s]) was calculated from

$$W_{heat} = 10 + 2\sin\left[\frac{2\pi}{t_0}\left(t - 2.16 \times 10^4\right)\right]$$

(4)
where \( t_0 \) indicates the period of one heat load cycle (= 24 h = 8.64 × 10^4 s); The first term of Eq. (4), 10 MW, is heat output from the small nuclear reactor (base load). A plot of heat load against time in the town is shown in Figure 4.

3. Results and Discussion

3.1. Amount of material

The heat output from the TcES material and heat storage by the TcES material are expressed as shown below.

\[
W_{\text{TcES}} = 2\sin \left( \frac{2\pi}{t_0} (t - 2.16 \times 10^4 \text{s}) \right) 
\]

(5)

The amount of surplus heat for recovery and storage was obtained by the integration of Eq. (5) from the start of heat output \( t = t_1 = 6 \text{ h} = 2.16 \times 10^4 \text{s} \) to the end of heat output \( t = t_2 = 18 \text{ h} = 6.48 \times 10^4 \text{s} \).

\[
Q = 2\int_{t_1}^{t_2} \sin \left( \frac{2\pi}{t_0} (t - 2.16 \times 10^4 \text{s}) \right) \, dt 
\]

(6)

\[
= 55.0 \text{[GJ]} 
\]

The heat output needed for the district-heating system for load leveling was 55.0 GJ (Figure 5); the same amount of heat was required to be stored from the start of heat storage \( t = t_2 = 18 \text{ h} \) to the end of heat storage \( t = t_1 = 6 \text{ h} \) of the next day.

The required amount of LiCl/Mg(OH)\(_2\) was then estimated. The heat output density of LiCl/Mg(OH)\(_2\) was 872 kJ kg\(^{-1}\) under these operating conditions (Section 2.2). Here, 55.0 GJ of heat were needed for storage and output, and 63.1 ton of LiCl/Mg(OH)\(_2\) were required for thermal energy storage. It was assumed that the bulk density of LiCl/Mg(OH)\(_2\) is 0.716 ton m\(^{-3}\). The volume of LiCl/Mg(OH)\(_2\) was estimated to be 88.1 m\(^3\) (Figure 5). Adamov et al. studied a nuclear reactor with a capacity of 10 MWt [1].

![Figure 4](image-url)

Figure 4  Plot of heat load against time in town, and calculated profile of water flow rate in secondary system.
The lower part of their nuclear reactor vessel had a diameter of 3 m and a height of 7 m, and the upper part had a diameter of 7 m and a height of 10 m. The volume of the nuclear reactor vessel (20 MWt capacity) was estimated to be 434 m$^3$. The total volume of the TcES system will be larger than 88.1 m$^3$ because a heat exchanger, water reservoir, and other components are needed. However, compared to the volume of the nuclear reactor vessel, the amount of LiCl/Mg(OH)$_2$ is acceptable for installing a TcES system at the nuclear plant site.

3.2. Water flow rate

The water flow rate in the secondary system ($F_s$ [kg s$^{-1}$]) is expressed as

$$F_s = \frac{W_{\text{heat}}}{C_p \Delta T}$$

(7)

where $W_{\text{heat}}$ [kW] is given by Eq. (4). The calculated profile of $F_s$ is shown in Figure 4. The flow rate at one hour before switching from heat storage operation of the TcES system to heat output operation of the TcES system was calculated to be 75.3 kg s$^{-1}$. The flow rate at one hour after switching was calculated to be 84.5 kg s$^{-1}$. The flow rate increased in 12% in two hours during the switching period. The change in flow rate is thought to be small enough to carry out the switching without causing an unstable situation.

4. Conclusion

A cogeneration system using a small nuclear reactor was considered. The potential use of LiCl/Mg(OH)$_2$ for load leveling was investigated. The heat load of a town was estimated by sine curve modeling. The required amount of LiCl/Mg(OH)$_2$ for load leveling of a 23.3 MWt reactor was 63.1 t (88.1 m$^3$). The amount of LiCl/Mg(OH)$_2$ was acceptable for installing a TcES system combined with a nuclear plant. Therefore, LiCl/Mg(OH)$_2$ is a promising candidate for load leveling for nuclear cogeneration systems.

Figure 5  Heat output and required volume of TcES material in daily operation of district-heating system.
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References


