

Research paper

## A review for Ca(OH)<sub>2</sub>/CaO thermochemical energy storage systems



Kai Wang, Ting Yan <sup>\*</sup>, R.K. Li, W.G. Pan <sup>\*</sup>

College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 200090, PR China

Key Laboratory of Clean Power Generation and Environmental Protection Technology in Mechanical Industry, Shanghai 200090, PR China

### ARTICLE INFO

**Keywords:**

Ca(OH)<sub>2</sub>/CaO  
Thermochemical energy storage  
Material properties  
Modification  
Reactor

### ABSTRACT

Thermochemical energy storage is an essential component of thermal energy storage, which solves the intermittent and long-term energy storage problems of certain renewable energy sources. The appropriate decomposition temperature, high heat storage capacity of the CaO/Ca(OH)<sub>2</sub> system makes it one of the successful thermochemical energy storage materials. To better predict reaction process of the thermochemical heat storage process, and lay a foundation for the application design and control of the thermochemical heat storage, we summarized and analyzed the research on the physical and chemical properties of the materials by scholars in recent years. These studies include the structure changes as the reaction occurs, the specific heat capacity and the energy density under different conditions and chemical reaction directions, reaction enthalpy and the reaction kinetics during dehydration/hydration. However, some inherent problem (e.g. low thermal conductivity, agglomeration and influence of carbon dioxide during the reaction) limit the performance of this material. By adding other materials to calcium hydroxide to prepare composite materials, researchers can solve these problems to a certain extent. Therefore, this paper reviews the research status of such composite materials from the perspective of the types of added materials. Finally, to better apply the CaO/Ca(OH)<sub>2</sub> thermal storage system to actual production, the performance of this material in different types of reaction beds is summarized.

### 1. Introduction

Primary energy sources such as coal, oil and natural gas still occupy for more than half of global energy consumption, although global energy consumption has slowed down compared to previous periods. The utilization of fossil fuels has brought a series of troubles to the living environment of human beings. To deal with these problems, researchers around the world are working on renewable energy sources to replace fossil fuels, such as solar energy, wind energy and geothermal energy. The efficient use of renewable energy, especially solar energy, plays a crucial role in reducing the consumption of fossil fuels and has become a forward-looking approach to combating rising global temperatures [1]. In addition to finding new renewable energy sources, improving the utilization of primary energy is also a way to save energy. For example, in the steel industry, which is rich in thermal energy resources, waste heat recovery systems in plants can withdraw most of the waste heat [2,3]. The solar heat varies with weather, location, time of day and season. Therefore, its characteristics are unstable and discontinuous.

Advanced thermal storage technique is needed to address this issue of inconsistent supply and demand times.

Thermal energy storage (TES) is an essential technology for solving the contradiction between energy supply and demand. TES is generally classified into the following categories: sensible thermal energy storage (STES), latent thermal energy storage (LTES) and thermochemical energy storage (TCES) [4–6]. Although STES and LTES are two of the best studied methods and are more mature, however, the energy storage density of STES is the lowest among all the TES methods and phase change materials for the LTES have some inherent drawbacks (e.g. leakage and corrosion during the reaction) [7]. Furthermore, it has higher requirements for insulation measures. For the long-term heat storage, STES and LTES cannot meet the criteria [8]. Since TCES has low heat loss [9], it minimizes the heat loss to the environment and therefore has the potential to achieve long-term heat storage. In addition, it can store energy at close to ambient temperature [10], and it has a higher energy storage density [11].

Table 1 shows the characteristics and comparison of three different

**Abbreviations:** TES, Thermal energy storage; STES, sensible thermal energy storage; LTES, latent thermal energy storage; TCES, thermochemical energy storage; CMC, carboxymethyl cellulose; CHP, chemical heat pump; HTF, heat transfer fluid; CSP, concentrated solar power.

\* Corresponding authors.

E-mail addresses: [yt81725@126.com](mailto:yt81725@126.com) (T. Yan), [pweiguo@163.com](mailto:pweiguo@163.com) (W.G. Pan).

<https://doi.org/10.1016/j.est.2022.104612>

Received 19 November 2021; Received in revised form 12 February 2022; Accepted 5 April 2022

Available online 27 April 2022

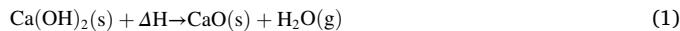
2352-152X/© 2022 Elsevier Ltd. All rights reserved.

**Table 1**  
Comparison of the different thermal energy storage system [16].

	STES	LTES	TCES
Technology Maturity	Simple Industrial scale	Slightly harder Pilot/Industrial scale	Complex Lab scale
Volumetric density	~50 kWh/m <sup>3</sup>	~100 kWh/m <sup>3</sup>	~500 kWh/m <sup>3</sup>
Gravimetric density	~0.02–0.03 kWh/kg	~0.05–0.1 kWh/kg	~0.5–1 kWh/kg
Storage period	Short-term	Short-term	Long-term

heat storage systems. From the table, it can be concluded that TCES has the essential research value and application prospects. However, the investigation of TCES is still in the early development stages. Research on TCES is still mainly inside the laboratory, while the other two have been applied in practical applications. Fig. 1 shows the factors that need to be considered when designing a suitable thermochemical reaction system. In terms of materials, there are many materials compatible with medium-temperature thermochemical energy storage, such as hydroxides, metal hydrides and metal oxides [12]. The commonly used metal hydroxides are  $\text{Ca}(\text{OH})_2/\text{CaO}$ ,  $\text{Mg}(\text{OH})_2/\text{MgO}$ ,  $\text{Ba}(\text{OH})_2/\text{BaO}$ ,  $\text{Ni}(\text{OH})_2/\text{NiO}$  and  $\text{Sr}(\text{OH})_2/\text{SrO}$ , their decomposition temperature and reaction enthalpies of hydroxides are shown in Table 2. As can be seen from the table,  $\text{Ca}(\text{OH})_2/\text{CaO}$  has the highest reaction enthalpy, and its decomposition temperature matches the temperature of the concentrated solar power plants and the waste heat temperature of the coal-fired power plant. Many studies have proven that  $\text{CaO}$  and  $\text{Ca}(\text{OH})_2$  are widely used in industry [13] and are abundant inexpensive [14]. Among the five reaction pairs,  $\text{Mg}(\text{OH})_2/\text{MgO}$  and  $\text{Ca}(\text{OH})_2/\text{CaO}$  are the most studied.  $\text{Ca}(\text{OH})_2/\text{CaO}$  has a higher reaction enthalpy and is cheaper than  $\text{Mg}(\text{OH})_2/\text{MgO}$  [15]. Based on these factors, researchers concluded that  $\text{CaO}/\text{Ca}(\text{OH})_2$  is the most successful material for medium-temperature thermal storage.

The thermochemical reaction of  $\text{Ca}(\text{OH})_2/\text{CaO}$  is reversible, endothermic or exothermic step based on the following reversible solid-gas reaction:

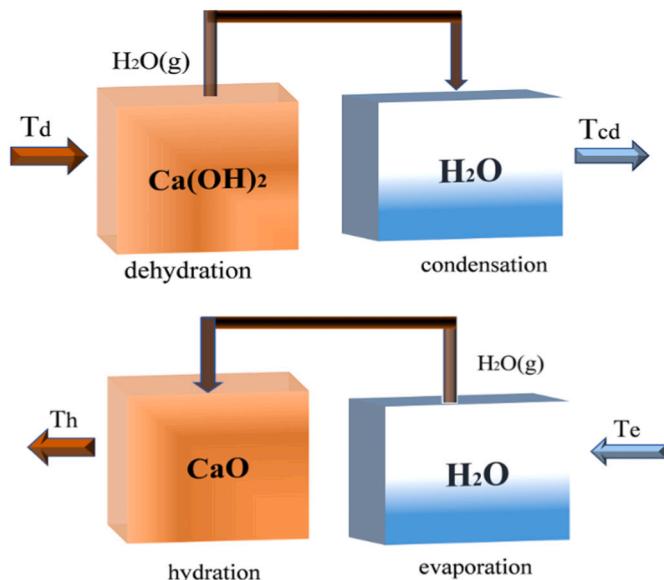


$\Delta H$  is the enthalpy of reaction, and the magnitude of enthalpy and its influencing factors will be described later. The functional flow diagram of calcium hydroxide/calcium oxide heat storage system is shown in Fig. 2. During the dehydration process, the calcium hydroxide is heated and decomposed into calcium oxide and water vapor. When exothermic, water is heated to form steam, and the water vapor reacts with calcium oxide to produce calcium hydroxide and release heat.

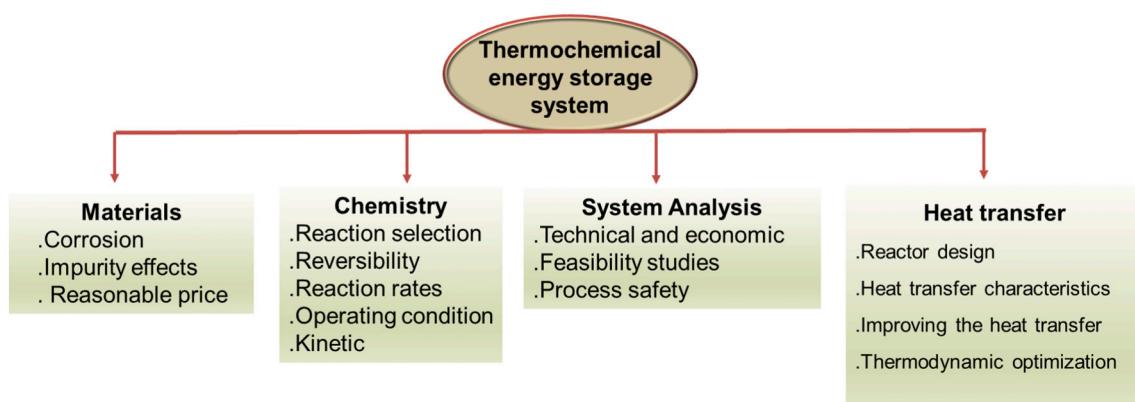
In this article, to better understand and control the occurrence of the reaction, physical and chemical properties of the material have been introduced. At the same time, the latest literatures on how to improve heat transfer performance during the reaction and how to solve the phenomenon of material sintering during the reaction are also introduced. Also, the performance of the reaction in different reactors is summarized.

**Table 2**  
Decomposition temperature and reaction enthalpy of hydroxide [15].

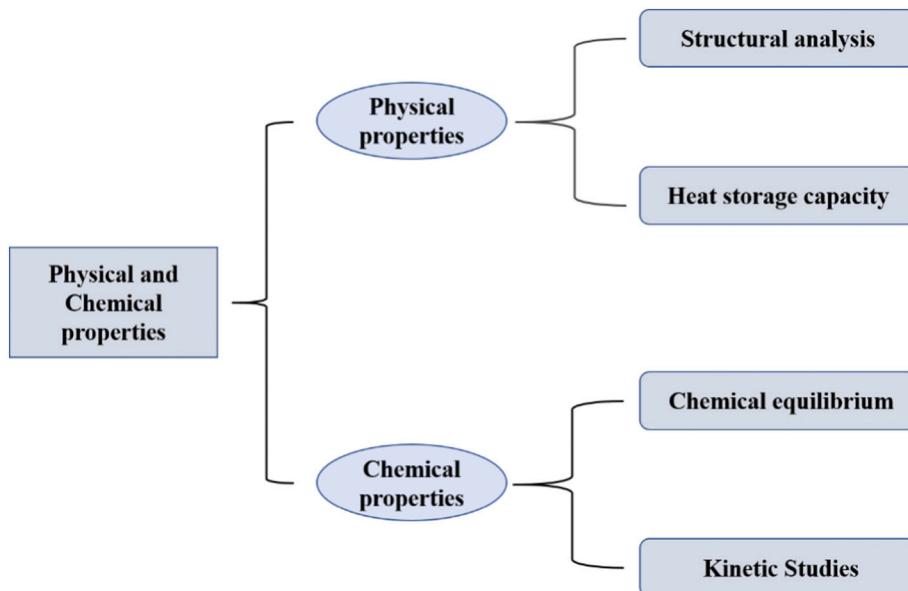
Content	Material				
	Ca(OH) <sub>2</sub> /CaO	Mg(OH) <sub>2</sub> /MgO	Ba(OH) <sub>2</sub> /BaO	Sr(OH) <sub>2</sub> /SrO	Ni(OH) <sub>2</sub> /NiO
Decomposition temperature (°C)	515	265	1005	755	70
Reaction enthalpy (kJ/mol)	100.177	77.745	93.462	88.581	47.846



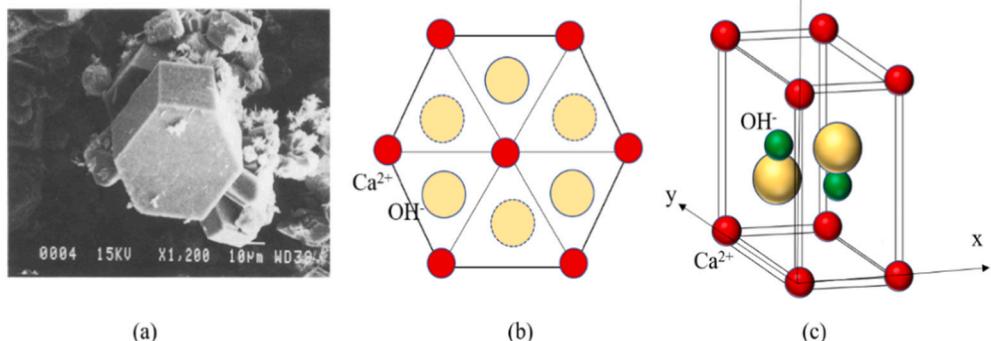
**Fig. 2.** Working flow diagram of calcium hydroxide/calcium oxide heat storage system.



**Fig. 1.** Necessary considerations for developing TES system based on chemical reaction [16].



**Fig. 3.** Structure of part II.

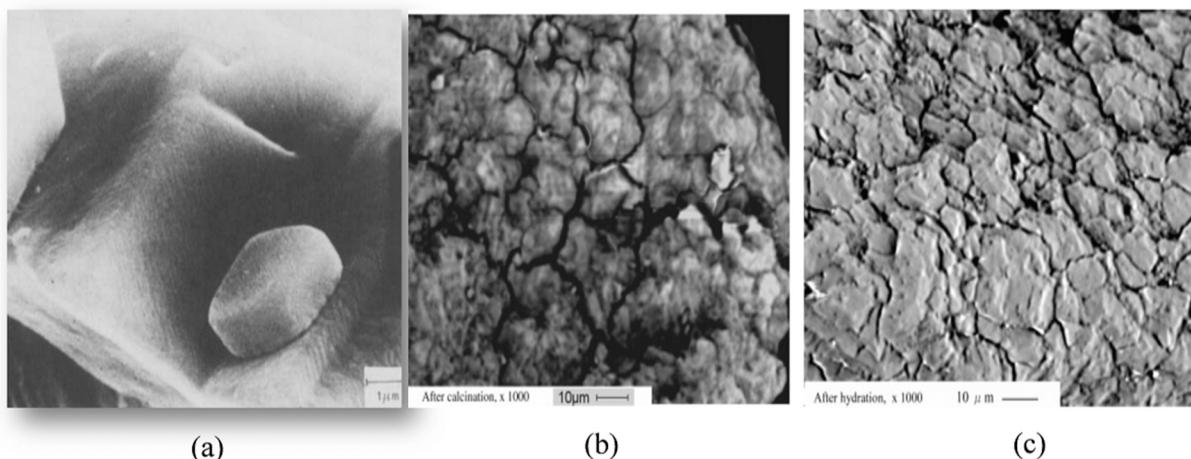


**Fig. 4.** Scanning electron micrograph of  $\text{Ca}(\text{OH})_2$  (a) [23]; Top view of the crystal lattice (b); Schematic diagram of crystal cell (c) [18,19].

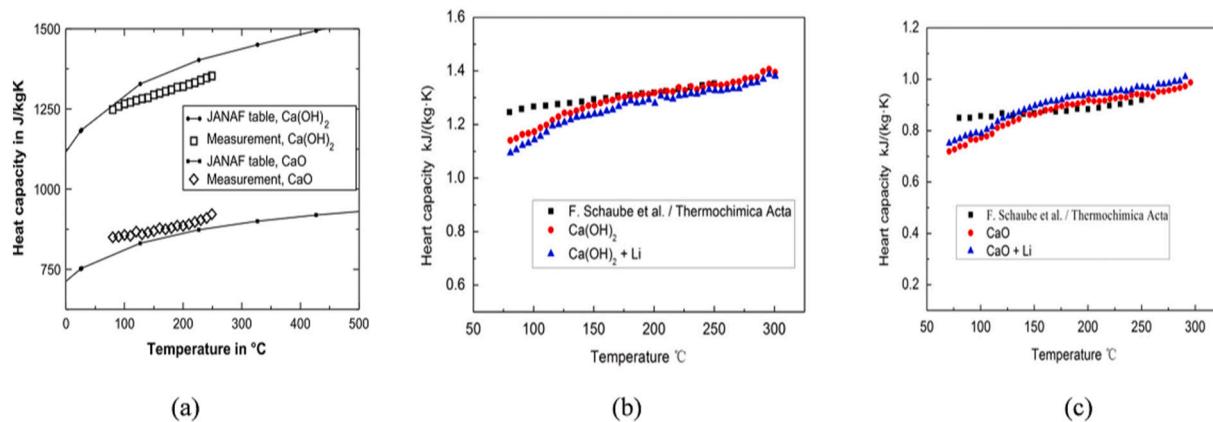
## 2. Physical and chemical properties

Many researchers have studied calcium hydroxide/calcium oxide thermal storage systems in simulations and experiments. The

outstanding advantages of the CaO/Ca(OH)<sub>2</sub> pair are high energy density, fast heat storage and release, and excellent reversibility during energy release and storage [17]. Indeed, for the better sense of the reaction process and apply the system on a large scale to practical



**Fig. 5.** SEM of CaO (a) [27]; SEM photographs of particle surfaces before the hydration (b) and after CaO hydration (c) [24].



**Fig. 6.** (a) Specific heat capacity of pure  $\text{Ca}(\text{OH})_2$  and  $\text{CaO}$  [30]; (b), (c) The results of specific heat capacity comparison [31].

applications, a deep comprehending of the physical and chemical properties of the material is indispensable. The contents of physical and chemical properties are shown in Fig. 3.

## 2.1. Structural analysis

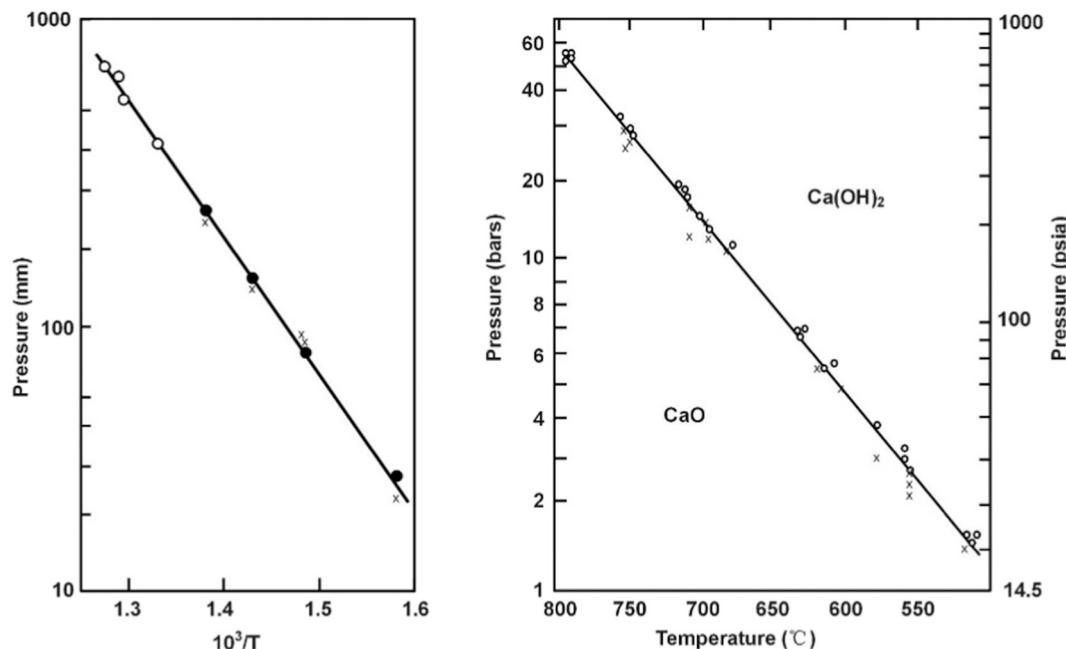
The crystal structure of calcium hydroxide is  $\text{CdI}_2$ -type, and its crystal is layered hexagonal structure [18,19]. The scanning electron micrograph and structural chart of  $\text{Ca}(\text{OH})_2$  are shown in Fig. 4. The Ca atom is located at the origin, and the O and H atoms are located at a fixed position of in space [20]. Chaix-Pluchery et al. [19] studied the proton transfer of crystals at different temperatures before reaching the dehydration temperature, and Desgranges et al. [18] did a similar study. Chaix-Pluchery et al. [21] thought that the decomposition reaction is classified into three procedures, and dehydration reaction is the process of eventually forming an interconnected network, thus opening a fast spread route for the migration of water molecules to the surface. In the research of Galwey et al. [22], they pointed out that during the decomposition of calcium hydroxide, there are only two states of calcium hydroxide and calcium oxide and the intermediates  $[\text{CaO} \cdot \text{H}_2\text{O}]$  inferred based on thermodynamics.

The crystal structure of calcium oxide is  $\text{NaCl}$ -type, and its crystal is cube structure. The scanning electron micrograph of  $\text{CaO}$  is shown in Fig. 5(a). From the above description, it can be expected that when the calcium oxide reacts with water vapor, its crystal structure will go from cubic to hexagonal. Lin et al. [24] studied the changes of calcium oxide before and after hydration, and the SEM photographs before and after hydration are shown in Fig. 5(b) and (c). It can be clearly seen from the pictures, there are many cracks on the surface of calcium oxide before hydration. After hydration, the width of the gap decreases because of the volume increases as calcium hydroxide formed. They believed that the cracks make it easier for water vapor to get in and out of the particles and reduce the gas's diffusion resistance. And it's these cracks that allow the  $\text{CaO}$  wholly converted to  $\text{Ca}(\text{OH})_2$  [25,26].

From the above summary, it is possible to deduce the order of the reactions from the changes in the structure of the material during the reactions. However, in future research, the structure should be continuously studied to better control its reaction process.

## 2.2. Heat storage capacity

The purpose of studying calcium hydroxide/calcium oxide heat



**Fig. 7.** The relation between  $\log p$  and temperature. (a) [33]; (b) [34].

**Table 3**

The reaction equation between temperature and pressure.

Temperature/pressure range	Reaction equation	References
350–530 °C	$\ln\left(\frac{P_{eq}}{10^5}\right) = -\frac{12845}{T_{eq}} + 16.508$	[30]
1–50 bar	$\ln\left(\frac{P_{H_2O}}{[bar]}\right) = -\frac{11375}{T[K]} + 14.574$	[36,37]
450–550 °C	$P_{eq} = 2.3 \times 10^8 \exp\left(-\frac{11607}{T}\right)$	[38]
530–800 °C	$\log_{10} P_{(bar)} = -\frac{22600}{4.575 T[^{\circ}C]} + 6.330$	[34]

storage systems is to be able to store heat and reduce energy consumption. Since the thermal storage performance is closely concerned with specific heat capacity, energy density and the reaction enthalpy, the analysis of the specific heat capacity, energy density and the reaction enthalpy will provide the better understanding to control over the progress of the direction of the reaction, and how to control different conditions to obtain the largest heat storage capacity.

### 2.2.1. Specific heat capacity

The specific heat capacities of calcium oxide and calcium hydroxide can usually be obtained by reference to a handbook or empirical formula. For example, for  $\text{Ca(OH)}_2$ : When the temperature is 273 K,  $C_p = 1141 \text{ J/(kg}\cdot\text{K)}$ ; When the temperature is from 276 K to 373 K,  $C_p = 1210 \text{ J/(kg}\cdot\text{K)}$  [28]; when the temperature is about 520 °C,  $C_p = 1660 \text{ J/(kg}\cdot\text{K)}$  [29]. In the research of Schabe et al. [30], the specific heat capacities of calcium hydroxide and calcium oxide at temperatures ranging from 25 °C to 250 °C. The specific heat capacity of pure calcium hydroxide and calcium oxide in the temperature range of 25 °C to 250 °C, shown in Fig. 6(a). Yan et al. [31] discussed the influence of doping lithium at 65 °C to 305 °C on the specific heat capacity of calcium hydroxide and calcium oxide, and compared the results with Schabe's study. The results of the comparison are exhibited in Fig. 6(b) and (c), it can be found that the specific heat capacity value of  $\text{Ca(OH)}_2$  slightly decreases and that of CaO slightly increases after doping with Li, but the overall effect on the specific heat capacity of the thermal storage material is not significant.

### 2.2.2. Energy density

In the article of Pardo et al. [16], according to the different calculation methods of energy density, it can be divided into two categories, one is volume energy density ( $\text{kJ}/\text{m}^3$ ), and the other is gravimetric energy density ( $\text{kJ}/\text{kg}$ ). For example, Fujii et al. [32] calculated the energy density is about 1400  $\text{kJ}/\text{kg}$  or  $1.2 \times 10^6 \text{ kJ}/\text{m}^3$ . This material has a higher energy density compared to sensible and latent heat materials and it requires a smaller volume of material to store the same amount of heat.

### 2.2.3. Reaction enthalpy

The reaction enthalpy can be calculated from Van't Hoff equation:  $\Delta H = -\frac{\Delta H}{RT} + \text{const}$ . Halstead et al. [33] plotted the relationship between the  $\ln P$  and the reciprocal of the absolute temperature  $T$ , are shown in Fig. 7(a), the average enthalpy of reaction calculated from the slope is 104.18  $\text{kJ/mol}$  in the temperature range of 300 °C to 510 °C. And a similar experiment made by Samms and Evans et al. [34], are shown in Fig. 7(b), by calculating the slope, they found that the enthalpy of the reaction in the temperature range of 530 °C to 800 °C is 94.56  $\text{kJ/mol}$ . Schabe et al. [30] measured the enthalpy of reaction is 104.4  $\text{kJ/mol}$  directly by DSC at a temperature of 505 °C.

### 2.3. Chemical equilibrium

The direction of the chemical reaction depended on the temperature and pressure during the reaction, according to Gibbs's free energy concept, when  $\Delta_f G_m = 0$ , the reaction reaches the maximum value and is

**Table 4**

Some of the kinetic models used for solid-gas reaction [39].

Reaction mechanism	Code	f( $\alpha$ )
Power law	P4	$\frac{3}{4\alpha^4}$
Power law	P3	$\frac{2}{3\alpha^3}$
Power law	P2	$\frac{1}{2\alpha^2}$
Avrami-Erofeev	A4	$4(1-\alpha)[-\ln(1-\alpha)]^{\frac{3}{4}}$
Avrami-Erofeev	A3	$3(1-\alpha)[-\ln(1-\alpha)]^{\frac{2}{3}}$
Avrami-Erofeev	A2	$2(1-\alpha)[-\ln(1-\alpha)]^{\frac{1}{2}}$
Avrami-Erofeev	A1.5	$1.5(1-\alpha)[-\ln(1-\alpha)]^{\frac{1}{3}}$

in equilibrium [35]. When the air pressure measured by different researchers arrived 101.325 kPa, there was a big difference in temperature. Therefore, Halstead and Moore et al. [33] verified which result was more accurate through experiments. The results showed that the air pressure reached a standard atmosphere, and the temperature was 512 °C. Because chemical equilibrium is related to temperature and pressure, many researchers have explored the relationship between temperature and pressure. Table 3 lists the relationship between temperature and pressure in different temperature or pressure ranges. And not only can the direction of the reaction be inferred from the formula, but the order of the reaction can also clearly seen from Fig. 7. If the temperature and steam pressure during the reaction are known, it can be determined at which point in Fig. 7. For example, if this point lies in the upper right-hand corner of the curve, the reaction proceeds in the direction of calcium hydroxide formation. Conversely, if this point lies in the lower left corner of the curve, the reaction proceeds in the direction of calcium oxide formation.

### 2.4. Kinetic studies

Kinetic research is an indispensable part of understanding the process of a chemical reaction. Through thermal analysis methods, a chemical change process can be studied and analyzed. The microscopic mechanism followed by the reaction is obtained, and the parameters of the reaction kinetics are obtained. The control equation of thermodynamics is received, and then the reaction process of this chemical heat storage process can be predicted.

In the kinetic analysis [23,39], the following formula is usually used to describe the reaction rate:

$$\frac{d\alpha}{dt} = f(\alpha)k(T) \quad (3)$$

$$k(T) = A \exp\left(\frac{-E}{RT}\right) \quad (4)$$

$$\frac{d\alpha}{dt} = A \cdot f(\alpha) \cdot \exp\left(\frac{-E}{RT}\right) \quad (5)$$

where  $f(\alpha)$  is the reaction mechanism function and  $\alpha$  represents the progress of the reaction, that is, the conversion ratio of reactants to products. And Table 4 displays some kinetic models for solid-gas reactions. Eq. (4) is the Arrhenius formula, where  $k(T)$  is the chemical reaction rate constant at temperature  $T$ ,  $A$  is the pre-exponential factor, which is determined only by the nature of reaction,  $E$  represents the activation energy,  $R$  is the gas constant, and  $T$  is the absolute temperature. The purpose of kinetics research is to solve and obtain three kinetic factors that can describe a certain reaction, namely activation energy  $E$ , pre-exponential factor  $A$  and reaction mechanism function  $f(\alpha)$ .

**Table 5**The different reaction kinetic models of the dehydration reaction of Ca(OH)<sub>2</sub>.

Reference	Gas	Result
[22]	Vacuum	$\frac{da}{dt} = k[Ca(OH)_2][P_{H_2O}]^{-0.5}$
[23]	Nitrogen	For commercial calcium hydroxide: E = 96.03–107.32 kJ/mol A = $1.70 \times 10^5$ – $1.23 \times 10^6$ s <sup>-1</sup> . For 0.1 M calcium hydroxide, E = 117.84–134.95 kJ/mol A = $4.041 \times 10^6$ ~ $2.997 \times 10^7$ s <sup>-1</sup> .
[43]	Air	$-\frac{dw}{dt} = k(T)f(w)$
[44]	Air	$\ln\left[\frac{P/(P-PA)}{T_0-T_c}\right] = \frac{ke}{CDeA(\Delta H_A)}$
[38]	Air	$\frac{dXDehy}{dt} = kDehy(T)(veq - vH_2O)f(XDehy)$
[30]	Nitrogen	For X < 0.2: $1.9425 \times 10^{12} \exp\left(\frac{-187.88 \times 10^3}{RT}\right) \cdot \left(1 - \frac{P}{Peq}\right)^3 \cdot (1-X)$ For X > 0.2: $\frac{dX}{dt} = 8.9588 \times 10^9 \exp\left(-\frac{162.62 \times 10^3}{RT}\right) \cdot \left(1 - \frac{P}{Peq}\right)^3 \cdot 2(1-X)^{0.5}$
[45]	Vacuum	$ade = \frac{74m_{H_2O}}{18m_{Ca(OH)_2}} \times 100\%$

X indicates the overall conversion rate.

#### 2.4.1. Kinetics of the dehydration

From the above analysis of the kinetic relationship, the activation energy and pre-exponential factor of the reaction need to be obtained. Matsuda et al. [40] and Kanamori et al. [41] took up research on the dehydration kinetics of calcium hydroxide and acquired the relevant governing equations very early. However, their mechanisms have not been studied in depth. The dehydration kinetics of calcium hydroxide has been finished in the air as well as in vacuum and nitrogen [22,23,42–44]. The results show that vacuum conditions contribute to the dehydration of calcium hydroxide. Table 5 lists the different reaction kinetic models of the dehydration reaction of Ca(OH)<sub>2</sub> based on the references.

#### 2.4.2. Kinetics of the hydration

The process of the hydration reaction is not yet transparent. The hydration kinetics of calcium oxide and water vapor have been studied both in indoor temperature [46,47] and high temperature [26]. Compared with room temperature, hydration at high temperature is closer to what happens in a reactor when a reaction occurs. In the study of Lin et al. [24], they found that when the vapor pressure was 3.8 MPa and the hydration temperature was 1023 K, the conversion rate from

CaO to Ca(OH)<sub>2</sub> reached 100%. However, as the hydration temperature further increases, the hydration conversion rate decreases. The results show that suitable temperature and pressure can enhance the hydration reaction of calcium oxide. Table 6 lists the different reaction kinetic models of the hydration reaction of CaO according to the references.

### 3. Problems to be solved in the application of Ca(OH)<sub>2</sub>/CaO thermochemical heat storage system in practice

At present, CaO/Ca(OH)<sub>2</sub> heat storage system is still in the laboratory stage and exists some drawbacks. In order to realize the industrial application of the system, abundant researchers have expounded the possible problems from different perspectives and put forward effective solutions. The specific shortcomings and solving strategies of CaO/Ca(OH)<sub>2</sub> heat storage system are illustrated in Fig. 8.

#### 3.1. High decomposition temperature

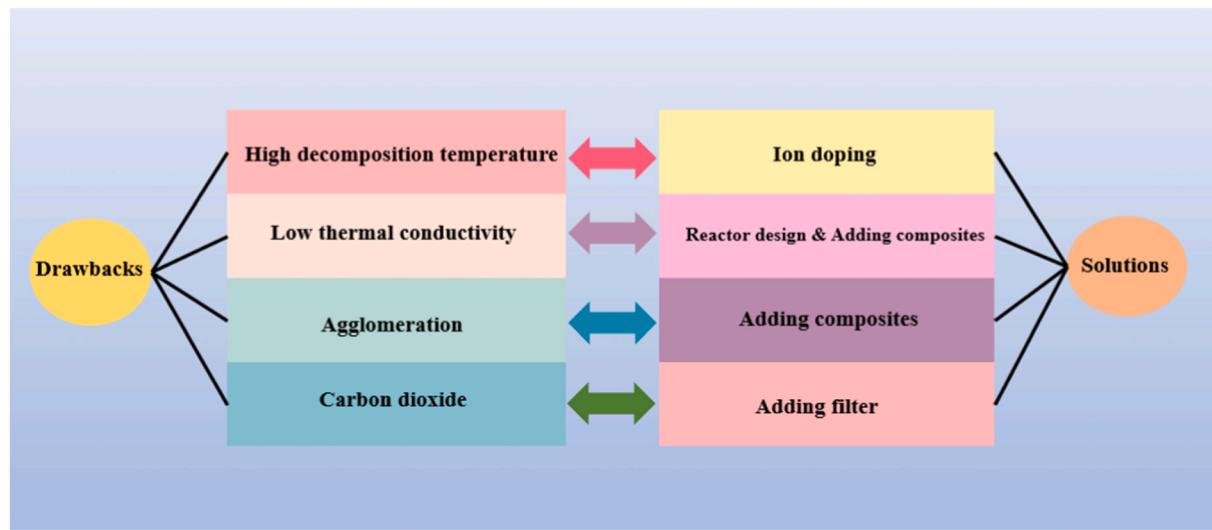
Although the heat storage capacity of this system is high, the dehydration temperature of calcium hydroxide is 500 °C approximately at atmospheric pressure. A variety of methods can be applied to reduce the decomposition temperature of Ca(OH)<sub>2</sub>, and thus a lower temperature heat source can be adopted. For instance, Murthy et al. [49] used a thermogravimetric analyzer to study the effect of calcium hydroxide doped with nickel hydroxide, aluminium hydroxide and zinc hydroxide on the decomposition temperature. It turns out that the decomposition temperature of the sample doped with aluminium hydroxide is much lower than that of pure calcium hydroxide. The experimental data also have shown that there are slightly different results in the samples doped with Zn(OH)<sub>2</sub>. Initially, the decomposition temperature decreases, but when doping exceeds about 3%, the decomposition temperature begins to increase. So, the right amounts of additives can lower the decomposition temperature. But the reason why the additive can lower the decomposition temperature is not explained. Moreover, the effect of lithium-ion and magnesium-ion doping on the decomposition temperature of calcium hydroxide has been studied by Yan and co-authors [8]. Lithium doping can complete the dehydration reaction at a lower temperature. The reason is the energy barrier for the dehydration reaction undoped is 0.40 eV, and the energy barrier for the dehydration reaction with Li added is 0.11 eV, meaning that Li doping can more easily complete the dehydration process, and can achieve the same heat storage efficiency at lower temperatures.

The current literature on how to reduce the decomposition temperature of calcium hydroxide is to add some metal ions. The experimental results show that not only the appropriate ions need to be found, but also the proportion of addition needs to be considered. In future research,

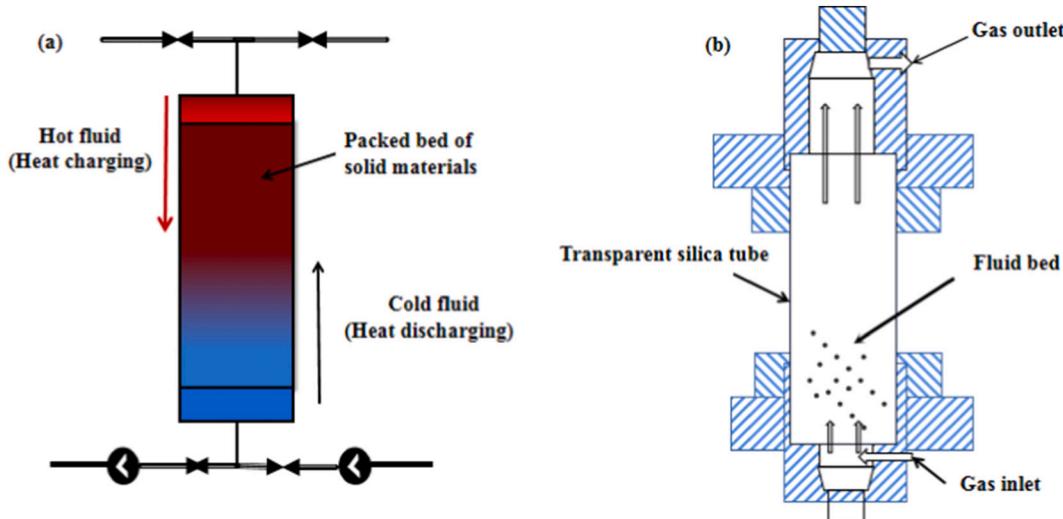
**Table 6**

The different reaction kinetic models of the hydration reaction of CaO.

Reference	Method	Results
[24]	High-pressure thermogravimetric	$R = \frac{1}{dp^{0.11}} \times 0.0069 \exp[-8400/(RT)] \times (PH_2O - P^*H_2O)^2$
[38]	Thermogravimetric analyzer	$\frac{dXHy}{dt} = KH_y(T) \cdot (vH_2O - veq)f(XHy)$
[30]	Thermogravimetric analyzer	$T_{eq} - T \geq 50$ K: $\frac{dX}{dt} = 13945 \times \exp\left(\frac{-89.486 \times 10^3}{RT}\right) \cdot \left(\frac{P}{Peq} - 1\right)^{0.83} \cdot 3(1-X)$ $\times [-\ln(1-X)]^{0.666}$ $T_{eq} - T < 50$ K: $\frac{dX}{dt} = 1.0004 \times 10^{-34} \exp\left(\frac{53.332 \times 10^3}{T}\right) \cdot \left(\frac{P}{10^5}\right)^6 \times (1-X)$ $ahy = \frac{56m_{H_2O}}{18m_{H_2O}} \times 100\%$
[45]	Vacuum pump steam mass flowmeter	$Rx = 0.1 \text{ or } 0.5 = \frac{dx}{dt(1-x)} \Big _{x=0.1 \text{ or } 0.5}$
[25]	Thermogravimetric analyzer	$\varphi = K2K1K4\sqrt{K3P_{H_2O}}$
[48]	Thermogravimetric analyzer	



**Fig. 8.** Existing drawbacks and solutions of the  $\text{Ca}(\text{OH})_2/\text{CaO}$  thermochemical heat storage system.



**Fig. 9.** Sketches map of two reaction beds: (a) Fixed bed reactor; (b) Fluidized bed reactor.

researchers need to be able to find suitable additives without reducing its heat storage capacity, and it is best to increase its heat storage capacity.

### 3.2. Low thermal conductivity

Thermal conductivity is closely related to the charge and discharge rate of the reaction. The greater the thermal conductivity performs, the faster the charging and discharging quality will be. Up to now, the simplest way to improve the thermal conductivity of  $\text{Ca}(\text{OH})_2$  is to compress the powder. Taking Ogura's work as an example [50], the thermal conductivity of pure calcium hydroxide particles in the reaction bed was measured by experiments to be  $0.12 \text{ W}/(\text{m}\cdot\text{K})$ . After compacting, the thermal conductivity of  $\text{Ca}(\text{OH})_2$  was up to  $0.4\text{--}0.55 \text{ W}/(\text{m}\cdot\text{K})$  [51]. However, since the reaction gas needs to flow uniformly, the powder cannot be packed beyond a specific limit. In another report, copper wire, copper fins and aluminium honeycomb were installed in the reactor to improve thermal conductivity, respectively [50]. Wang et al. [52] simulated a porous channel in the reactor, and simulated results showed that the thermal conductivity was significantly enhanced. Therefore, the heat transfer was effectively boosted, and the

vapor could be discharged as soon as possible, and the dehydration rate increased.

The reaction takes place in the reactor, in addition, to consider the inherent properties of the material, characteristics of the reaction bed also have an essential influence on the mass and heat transfer during thermochemical heat storage. Hence, the critical element is the heat transfer in the reaction bed on account of its low thermal conductivity. For a fixed bed reactor, the internal heat transfer performance is unsatisfactory. Besides, when the circulation process takes place in a fixed bed, agglomerates will form after several cycles, which will result in the formation of channels in the reaction bed, resulting in uneven reaction gas flow [53]. Compared to fixed beds, there is no problem of variable flow of reaction gas in fluidized beds. The problem is that a massive temperature difference will appear between the top and bottom of the reactor. Fig. 9 lists the schematic diagram of the two reaction beds.

Kuipers et al. [54] and Schaube et al. [53] calculated the thermal conductivity of the reaction bed. It consists of the thermal conductivity of the gaseous and the solid phase, as follows:

$$\lambda_r = \lambda_r g + \lambda_r s = \varepsilon \lambda g + (1 - \varepsilon) \lambda s = \left(1 - \sqrt{1 - \varepsilon}\right) \lambda g + (1 - \varepsilon) \lambda s \quad (6)$$

Especially for heat transfer in a fixed bed, Vortmeyer et al. [55]

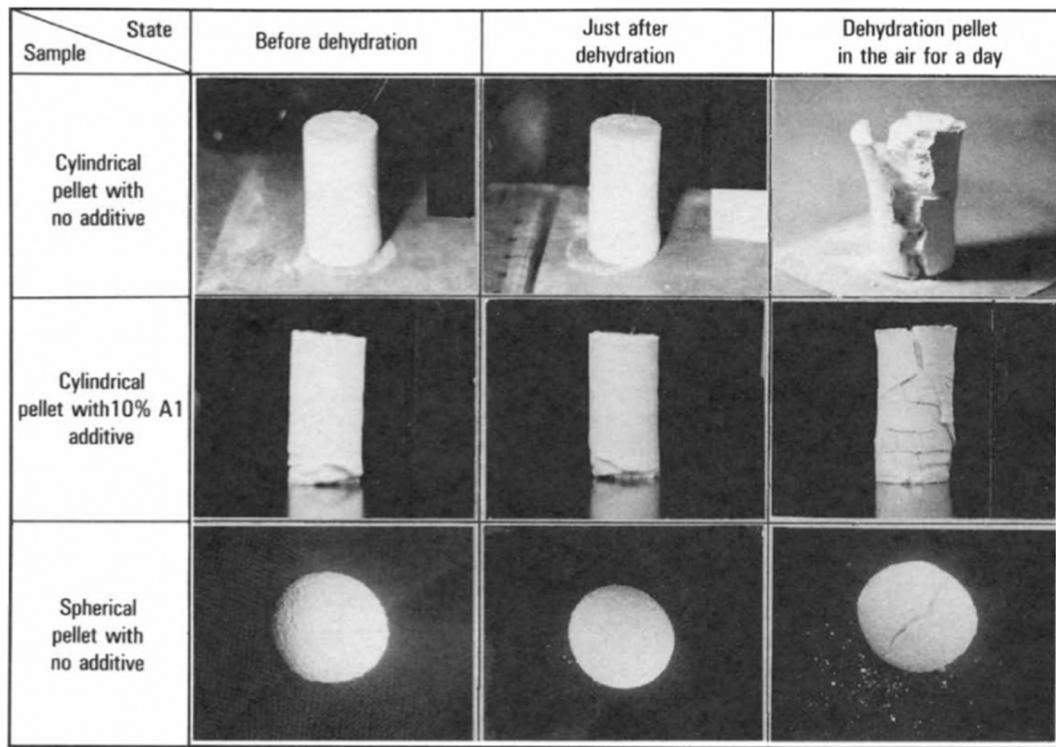


Fig. 10. The changes in pellet shape before and after reaction [32].

suggested that the effects of solid radiation need to be considered, but in general, the particle diameter is relatively small, so the radiation effect is negligible.

Druske et al. [56] prepared a composite material of salt hydrate and carrier. The results showed that the thermal conductivity of this composite material was significantly improved compared to the pure material. And Huang et al. [57] added hexagonal boron nitride to the heat storage material, and it turns out that the thermal conductivity could increase by 20 to 30%. This method gives us a hint of how to enhance the thermal conductivity in the article of Wu et al. [58], the authors explained the mechanism of heat conduction from a microscopic perspective. They analyzed how composite materials improve thermal conductivity. All of these methods and mechanisms support the researchers on how to improve the thermal conductivity of the heat storage materials. One thing to note is that the additive in the composite material cannot significantly reduce its heat storage capacity.

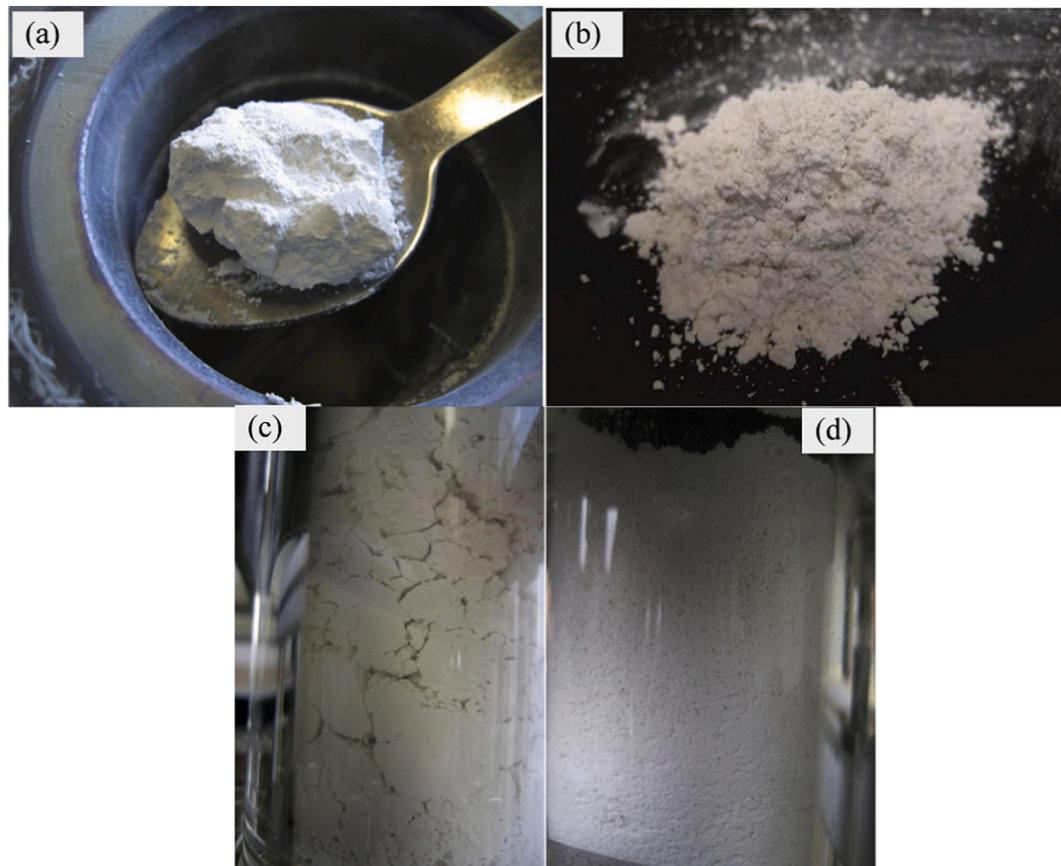
### 3.3. Agglomeration and crack

Many researchers have focused their attention on the problem that material accumulation and sintering will occur during cycling. This problem is due to the low mechanical properties of the material caused by particle wear during the reaction, which leads to a reduction in chemical activity, which in turn can cause the material to sinter. To be able to be applied in practice, the more the number of reaction cycles, the better. The treatment of powdered calcium hydroxide becomes very important. A large number of studies have shown that reducing the attraction between particles can effectively improve agglomeration. By summarizing the methods of many researchers, two ways are usually introduced to decrease the attraction between particles. The first method is to shape, which makes the powder into granulates or pellets. However, since the volume of the material will change during the thermochemical cycle, the granulates or pellets will crack during repeated dehydration and rehydration. Another method is to cover the particles with additives, which the surface roughness and the attractiveness of the particles will be augmented and reduced, respectively.

These added materials can be divided into zero-dimensional, two-dimensional and three-dimensional materials.

For the shape of the storage material, Fujii et al. [32] made calcium hydroxide powder into cylinders and spheres, and used copper, Zn, Al,  $\text{Al(OH)}_3$  powder as additives, and studied the kinetics of decomposition of  $\text{Ca(OH)}_2$  pellets. Data from the experiment, the reaction rate of sample doped with aluminium is faster than that of the sample doped with copper and zinc. In further investigations, it is found that the Al additive with 15% mass fraction had the best effect on the dehydration of pellets. For the samples doped with  $\text{Al(OH)}_3$ , the authors analyzed the pellets by X-ray diffraction. Looking at the graph of the results, there were both  $\text{Ca(OH)}_2$  and  $\text{Ca}_3\text{Al}_2(\text{OH})_{12}$  in the pellets, so they analyzed the chemical reactions may occur during the decomposition of calcium hydroxide. As the pellets are heated and dehydrated, it is inevitable that the volume of the pellets will change. For spherical and cylindrical pellets, the diameter and length of the pellets will be reduced, so cracking will occur. Fig. 10 shows the changes in pellet shape before and after reaction. The first two columns of the photo show the differences in the appearance of cylindrical pellets and spherical pellets before and after dehydration. The last column shows the change of the dehydrated particles staying in the air for a day. From the variation of the pellets, it can be seen that the pellets are severely cracked after a day's stay. This is due to the volume change caused by the absorption of moisture in the air. However, the aluminium-doped pellets still maintain its shape during the discharging process, possibly because the brittleness of the pellets is slightly improved. Therefore, for the sake of holding the shape unchanged when hydration occurs, the composition and size of the pellet need to be optimized. Sakellariou et al. [59] also studied the hydration of calcium oxide with different aluminium content. Concerning the mixture material with  $\text{Ca}/\text{Al}$  molar ratio of 81/19, it can maintain its structural integrity during hydration and dehydration. Still, with increasing the number of cycles, the cracking phenomenon will become more serious, so the presence of aluminium can not eliminate the fragmentation of the material.

$\text{SiO}_2$  nanoparticles are commonly used as flow agents in the industry to improve powder flowability. They can be perceived as a zero-

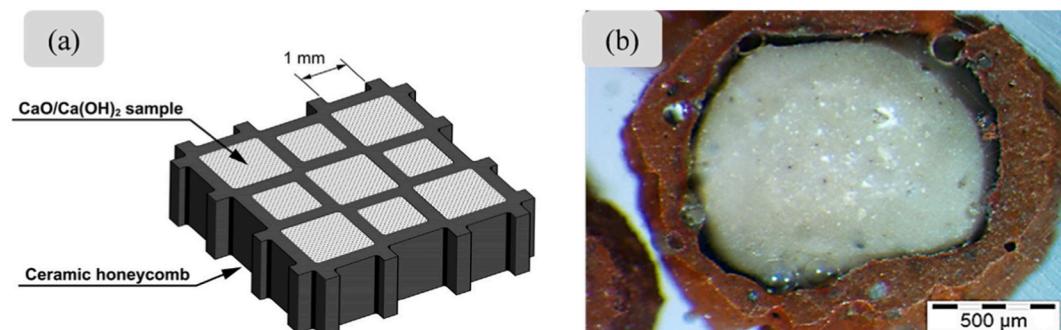


**Fig. 11.** The effect of adding nano silicon dioxide [60,61]. (a) and (b), (c) and (d) are the morphology of unadded nano silicon dioxide and nano silicon dioxide after cycles respectively.

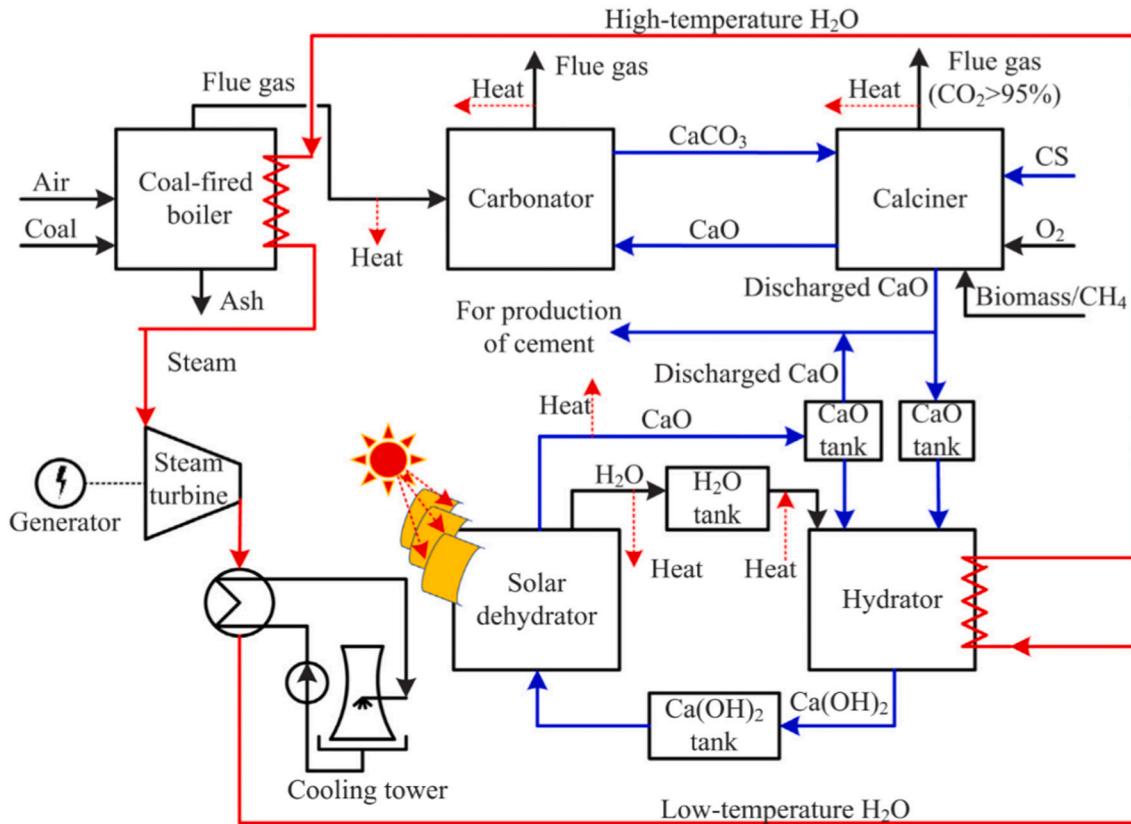
dimensional additive, to reduce the attraction between the reactant particles and reduce the sintering of the powder. Roßkopf et al. [60] studied the reaction of calcium hydroxide added with silica nanoparticles in the fixed bed reactor, and they observed that a small amount of nano-silica additive can prevent the occurrence of agglomeration, and can reduce the channel effect in the fixed bed reaction due to the poor permeability of calcium hydroxide particles. Fig. 11 shows the comparison between the reaction without the addition of nano-silica and the addition of nano-silica. And Roßkopf et al. [61] also studied the effect of adding silica nanoparticles in the fluid-bed reactor on the reaction and observed possible side reactions in the reaction. Xu et al. [62] revealed the reason for the mingle of silica particles could weaken the accumulation of particles. They considered that the addition of  $\text{SiO}_2$  could effectively prevent the sintering phenomenon because the addition of nano- $\text{SiO}_2$  particles creates a gap between  $\text{CaO}-\text{CaO}/\text{Ca}(\text{OH})_2-\text{Ca}(\text{OH})_2$

particles. Thus, the interaction between particles reduced.

Expanded graphite and vermiculite have similar properties and structures which is high thermal conductivity, high porosity, large surface area, low cost, chemical stability and moldability, due to its two-dimensional form, so it can be seen as a two-dimensional additive. Kariya et al. studied both calcium hydroxide and expanded graphite composites [63] and calcium hydroxide and vermiculite composites [64]. The results show that both composite materials enhance the reaction rate, improve the reaction performance, and improve the cyclic performance of the reaction. In addition to expanded graphite and vermiculite, kaolinite can also be regarded as a two-dimensional additive. Sakellariou et al. [17] prepared calcium oxide and kaolinite composites and studied the mechanical properties and cyclic performance of the composites. After 20 hydration/dehydration cycles, the mechanical stability of the composite improved. This method can effectively solve



**Fig. 12.** The internal structure of these two packages [68,69].



**Fig. 13.** The schematic diagram of coupled thermochemical heat storage system [77].

the problem of calcium oxide particle breaking after multiple cycles.

For three-dimensional additives, Criado et al. [65,66] made a composite material of sodium silicate and calcium oxide/calcium hydroxide. They studied the improvement of the mechanical properties of this composite material in comparison with the pure material. The test analyses show that the mechanical properties (crushing strength values) of the material have improved compared to the reference material. Xia et al. [67] prepared a new granular composite material composed of sodium carboxymethyl cellulose (CMC) and vermiculite and calcium oxide/calcium hydroxide powder to improve poor powder properties. The results show that after multiple dehydration/hydration cycles, the structure of the composite is still intact, and the heat storage rate of the mixture is faster than that of natural materials. Another vital additive is ceramic, which can also be seen as a three-dimensional additive. Afflerbach et al. [68] wrapped pre-made CaO/Ca(OH)<sub>2</sub> with ceramic shell, the results show that the mechanical stability of the spherical particles is much improved after ceramic encapsulation, and the strength remains unchanged during the ten-time hydration heat analysis. Funayama et al. [69] made a new compound using CaO/Ca(OH)<sub>2</sub> with ceramic honeycomb. The composite material also maintains high reactivity in repeated reactions. And the reaction output rate is much higher than pure particles. Fig. 12 shows the internal structure of these two packages. Funayama et al. [70] and Kariya et al. [71] employed calcium hydroxide and ceramic foam or porous silicon carbide, respectively, addressing the limitation of pure powder bed or granular bed. From their research, it can be seen that these composite materials have promising applications.

Some studies have analyzed the reasons why the addition of these materials helps to increase cycle stability from a microscopic perspective. Although the research on material agglomeration is relatively complete, these methods have their shortcomings, and it is still necessary to find different strategies to prevent material agglomeration. For example, in addition to the above materials, adding some one-

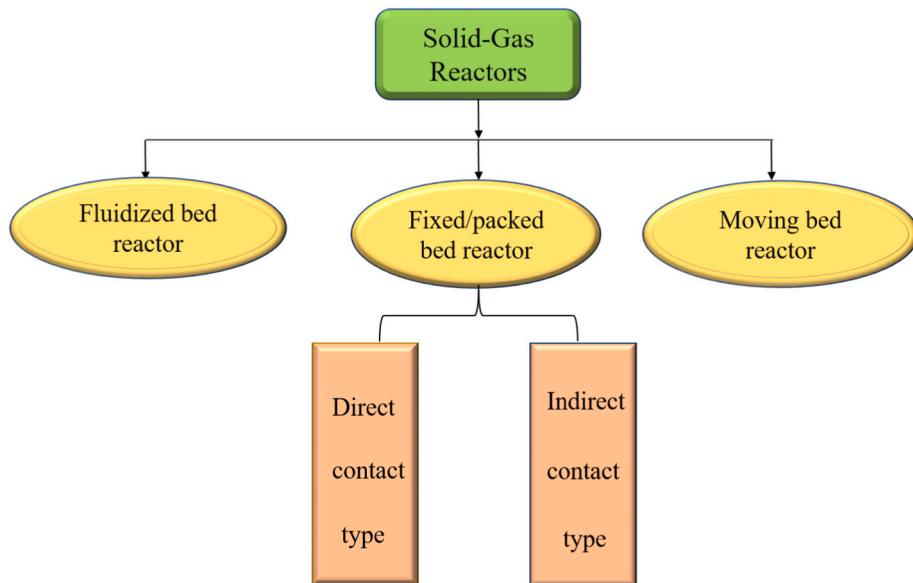
dimensional materials, such as carbon fibre, carbon nanotubes, etc., is also worth studying.

### 3.4. Effects of carbon dioxide

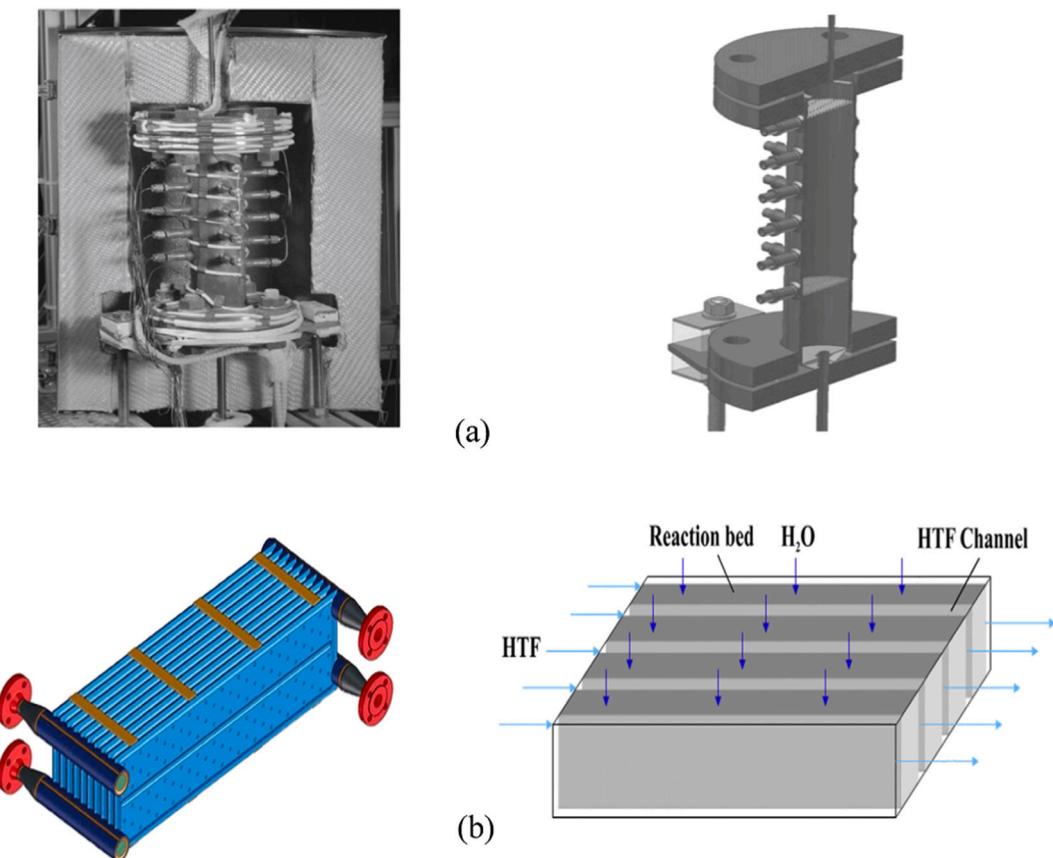
Another important factor affecting the Ca(OH)<sub>2</sub>/CaO thermochemical heat storage system is the CO<sub>2</sub> in the air, which the carbonation of calcium hydroxide/calcium oxide will occur. As a result, the material loses its heat storage capacity at the corresponding temperature. Yan and Zhao et al. [72] studied the harmful effects of CO<sub>2</sub> on this TCES system. The study revealed that under dry conditions, CO<sub>2</sub> and Ca(OH)<sub>2</sub> are more likely to react, forming agglomerates. Reacting in a humid environment, the side effects were more severe, and the amount of CaCO<sub>3</sub> increased by 10.7% and 28.7%, respectively. Also, this effect enlarges with the reaction cycles increases. Yan and Zhao et al. [73] studied the impact of dehydration temperature on reaction, and the consequences showed that higher dehydration temperature eliminated the effect of carbon dioxide on the material.

According to Anthony et al. [74] and Yu et al. [75], the process of CaO absorption of carbon dioxide needs to occur at high temperatures ( $> 600^{\circ}\text{C}$ ), and the method of releasing carbon dioxide needs to happen at temperatures higher than  $900^{\circ}\text{C}$ . And larger CaO surface area will result in higher CO<sub>2</sub> capture capacity. Hanak et al. [76] and Yuan et al. [77] designed the coupling thermochemical thermal storage system of Ca(OH)<sub>2</sub>/CaO and CaCO<sub>3</sub>/CaO. This schematic diagram of this coupled thermochemical thermal storage system shown in Fig. 13.

The side effects of carbon dioxide on the cyclic stability of Ca(OH)<sub>2</sub>/CaO thermochemical storage systems, is a serious problem, especially during heat release. Therefore, Ca(OH)<sub>2</sub>/CaO thermal storage systems are more appropriate for fixed bed reactors (closed systems) than for fluidized bed reactors (open systems). When this technology is used in open systems, precautionary measures need to be taken to avoid CO<sub>2</sub> contamination.



**Fig. 14.** Classification of solid-gas reactors.



**Fig. 15.** The schematic of the direct and indirect reactors. (a) directly operated reactor [85]; (b) indirectly operated reactor [37].

#### 4. Field of application

This reaction has been used for various purposes, such as heating food (calcium oxide hydration exotherm) and preheating internal combustion engines in motor vehicles [28,78]. Still, this thermochemical thermal storage system is geared more towards solar thermal applications [11,51,59,79–81] and use this chemical reaction to advance

the quality of factory exhaust heat, that is, chemical heat pump [82]. The applications of this reaction can be summarized in two categories: thermal energy storage and chemical heat pumps.

##### 4.1. The thermal heat storage

Wentworth et al. [83] and Ervin et al. [84] were the first two to try to

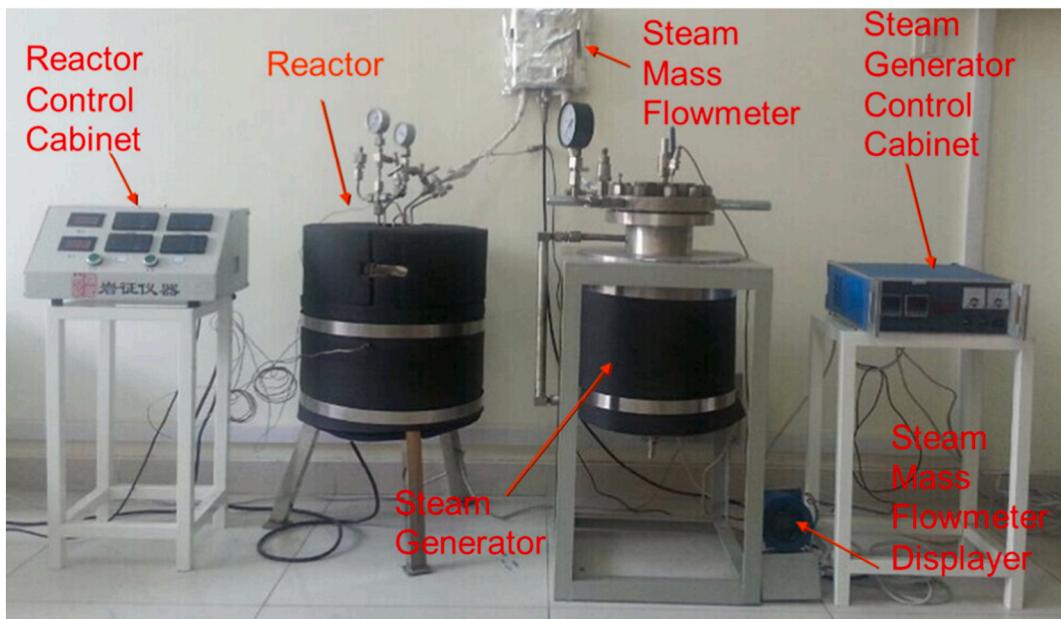


Fig. 16. Experimental setup diagram [45].

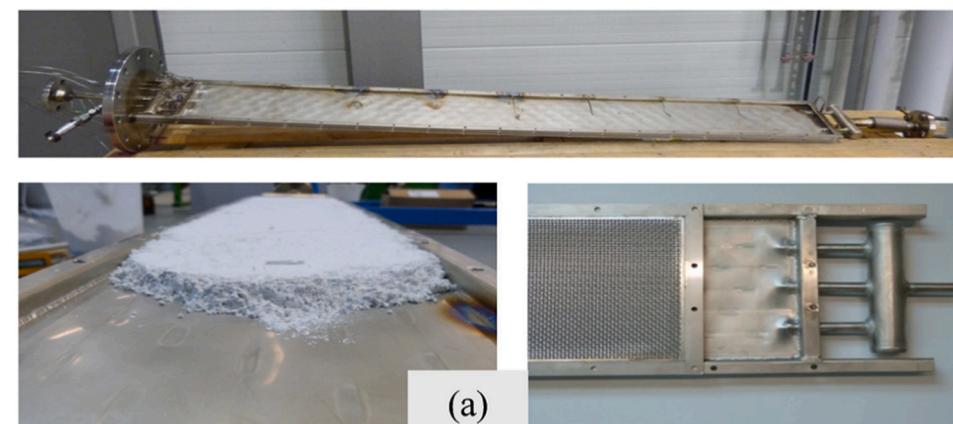
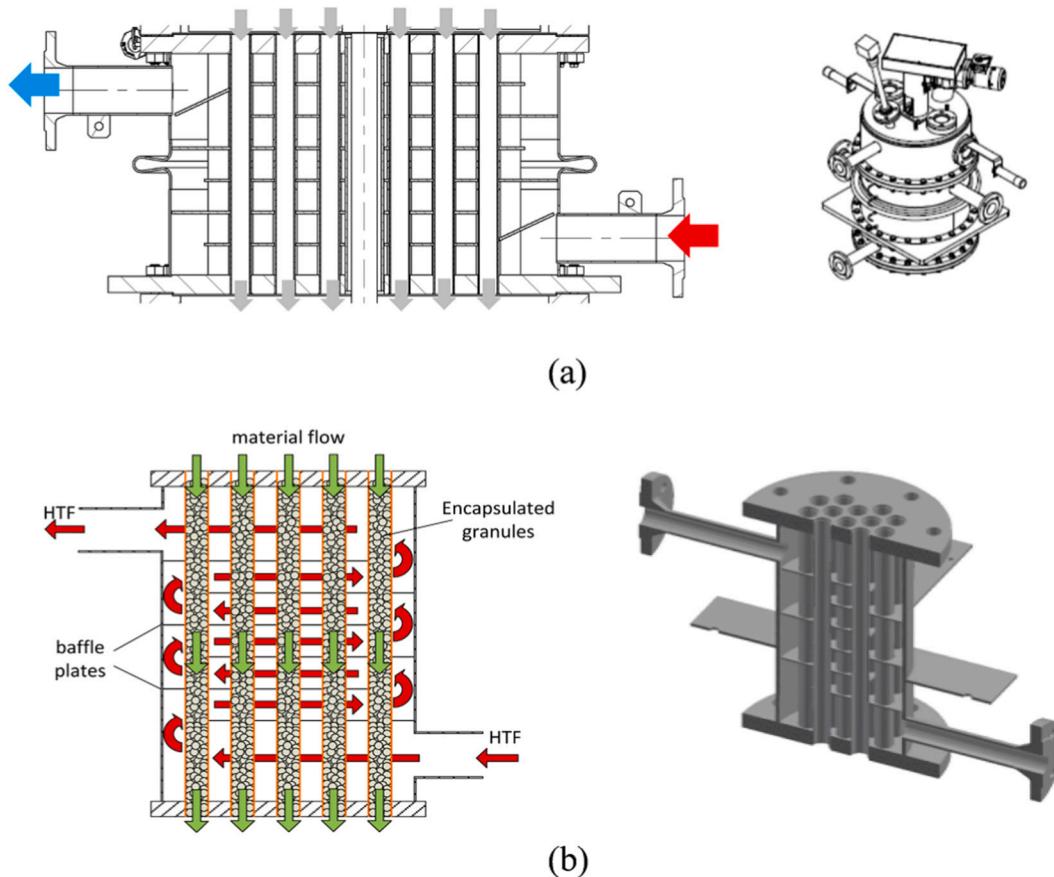


Fig. 17. (a) A new indirect reactor [86]; (b) Conceptual process design of indirect heating thermochemical reactor in CSP device [87].



**Fig. 18.** Diagram of a fixed bed reactor [89,90].

use these materials to store thermal energy. However, this research of  $\text{CaO}/\text{Ca}(\text{OH})_2/\text{H}_2\text{O}$  thermal storage system is still in the laboratory development stage, so the reactors are small-scale. The researchers studied the heat storage efficiency of different reactors, so it is crucial to choose the right reactor. Three kinds of solid-gas reactors used in the laboratory shown in Fig. 14.

#### 4.1.1. Fixed bed reactor

Since the research of thermochemical energy storage system has stayed in the laboratory stage, so the choice of the reactor is crucial. Fixed bed reactors have been extensively applied in the industry on account of their ease of operation. In this thermochemical heat storage system, fixed-bed reactors have always been the focus of research.

As can be seen from Fig. 14, there are two types of fixed bed reactors, one is direct contact type, and the other is indirect contact type. The schematic of the direct and indirect reactors shown in Fig. 15. Schabe et al. [51] compared the advantages and disadvantages of the direct and indirect forms of fixed bed reactors, and it is concluded that since indirect reactors are greatly restricted because of low thermal conductivity, direct heat transfer reactors are the better choice. And they also built a one-dimensional model of the direct reactor and calculated it with the advanced mathematical method.

Schabe et al. [85] studied some thermodynamic parameters of the direct heat transfer reactor, such as particle reaction rate, heat and mass transfer. Among these influencing parameters, they believe that the reaction rate is the dominant influencing parameter. The reactor of the system is shown in Fig. 15(a). Moreover, it was found in the experiment that although sintering still occurs, the overall conversion rate and reaction rate of the reaction show cycle stability within 25 cycles. They also built a two-dimensional model and compared the experimental and simulation results to verify the effectiveness of the model [53].

In Yan et al. [45] study, a direct-type fixed bed reactor was designed to study the heat storage and release process of the heat storage system. The experimental apparatus is shown in Fig. 16. Experimental results indicated that in charging stage, the higher the charging temperature, the faster the heat storage rate. Hence, the dehydration rate is higher in the same reaction time (47% at 510 °C and 65% at 540 °C after 300 min). During the heat release stage, the temperature decreases or the pressure increases, the hydration rate will increase (31.7% at 0.18 MPa, 60.9% at 0.24 MPa and 72.8% at 0.32 MPa).

Schmidt et al. [37] designed a 20 kg thermochemical storage reactor that operates indirectly. The charge-discharge characteristics of the storage reactor were studied, and it turns out that after ten cycles, the materials remained stable without degradation. It is also demonstrated that by adjusting the HTF (heat transfer fluid) mass flow rate, the reactor can achieve two operating modes, the peak power mode can reach 7.5 kW<sub>th</sub>, and the nominal power mode can reach 3 kW<sub>th</sub>. Schmidt et al. [86] developed a new indirect reactor (Fig. 17(a)) and studied the experimental demonstration of hydration-dehydration under low vapor pressure (1.4 kPa–20 kPa). The results show that it is possible to operate the storage system at low vapor pressure. And they [87] proposed the concept of applying this indirect heating thermochemical reactor to CSP (concentrated solar power) plant (Fig. 17(b)) and also carried out the thermodynamic analysis. Ranjha et al. [88] established a three-dimensional model to analyze the heat and mass transfer of an indirectly fixed bed reactor. The study discovered that the element of porosity and thermal conductivity have a greater impact on heat and mass transfer. Although increasing the reactor volume will enhance the heat storage capacity, it should be considered clearly before increasing the measure, owing to the augment of reactor height will limit the circulating of vapor; enhancing the length of the reactor requires a better heat transfer enhancement technology due to the low thermal

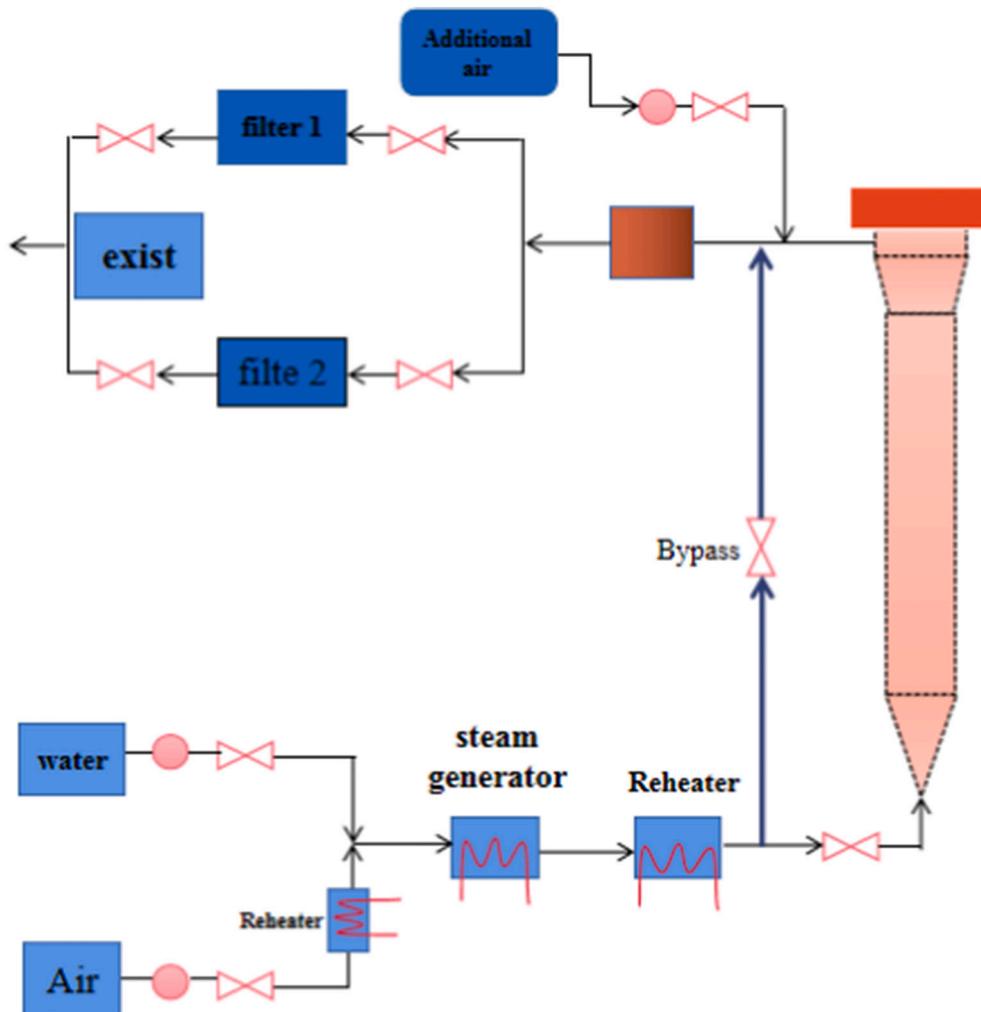


Fig. 19. Schematic view of the experimental setup [97].

conductivity.

#### 4.1.2. Moving bed reactor

The moving bed is believed to reduce the pressure drop and heat and mass transfer obstacles that occur in a fixed bed. Schmidt et al. [89]

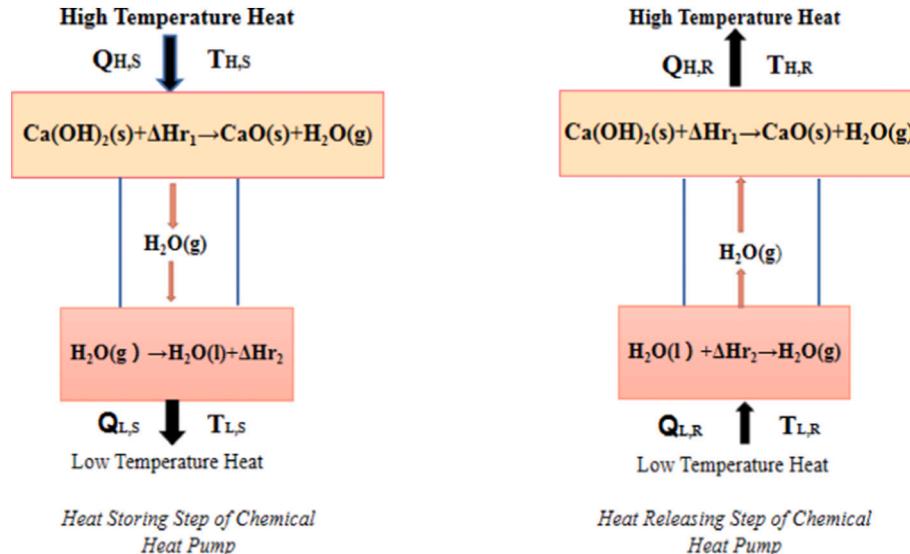
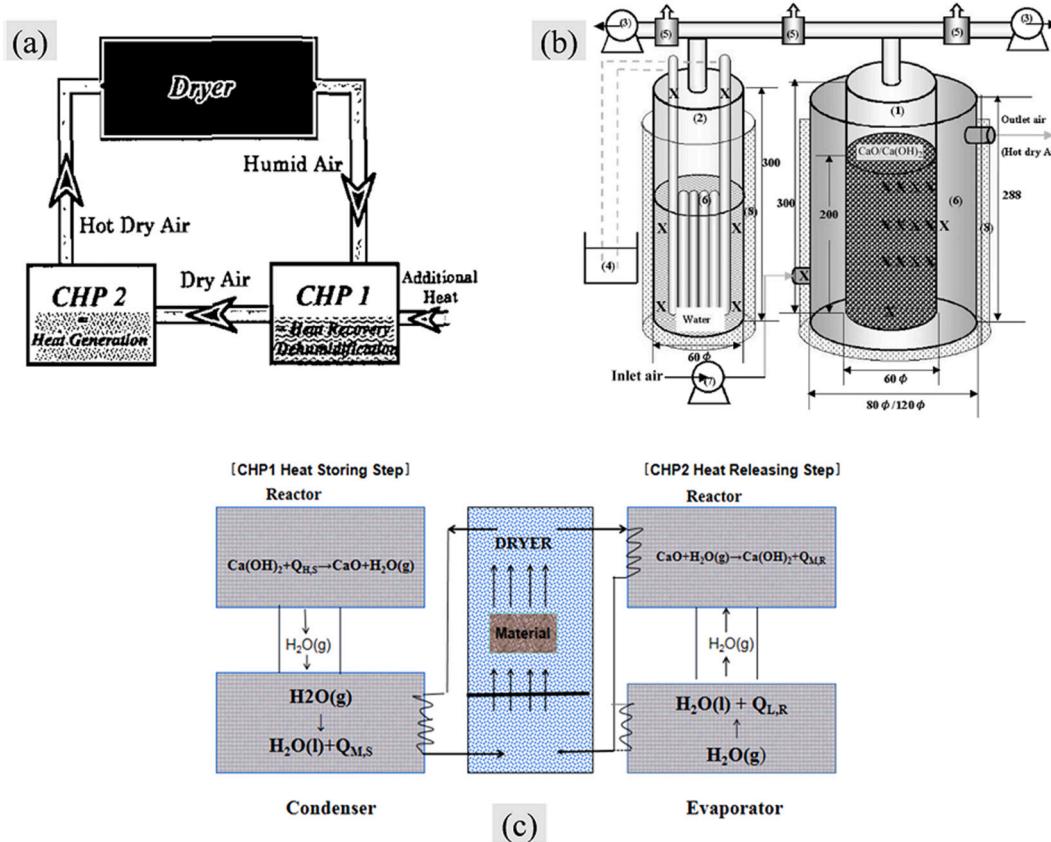


Fig. 20. Schematic diagram of chemical heat pump operation using  $\text{CaO}/\text{H}_2\text{O}/\text{Ca}(\text{OH})_2$  reaction [82].



**Fig. 21.** Schematic diagram of drying principle (a, c) [106,107]; The standard-type CHP unit (b) [104,105].

designed a novel moving bed reactor that can reach a scale of 10 kW/100 kWh (270 kg) and the reaction bed display in Fig. 18(a). And Cosquillo et al. [90] developed a similar moving bed reactor, and the reaction bed is shown in Fig. 18(b). This reactor adopts counter-current form, unreacted cold materials enter the pipeline from the top, and hot air enters the reactor from the bottom. Under the effect of gravity, the heat storage material flows through the tube. Heat is transferred by a hot fluid that flows on one side of the heat exchanger shell and is guided by a baffle. These plates ensure the rapid circulation of air, thus obtaining a preferable heat transfer coefficient between the airstream and surface of pipe.

#### 4.1.3. Fluidized bed reactor

The above researches conclude the thermal energy storage performance of the TCES system in fixed bed reactors and moving bed reactors. In addition to the above two reaction beds, some researchers have also studied the fluidized bed reactor, and this kind of reactors are being applied to thermal storage systems [91–93]. In order to work out the shortcomings of fixed bed heat and mass transfer, Darkwa et al. [94] proposed a fluid-bed reactor and established a model to simulate this reaction process. Results show that the reaction rate is significantly increased, and it also has reference value for future fluidized bed experiments. Criado et al. [95] put forward a flow design scheme based on the fluidized bed reactor and the energy density is 260 kWh/m<sup>3</sup> and the heat output is 100 MWt.

Pardo et al. [96] proved through experiments that it is feasible to carry out in a fluidized bed reactor. The weight of solid mixed reactant (Ca(OH)<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>) is 1.93 kg, so the mean energy density of the mixture is 60 kWh/m<sup>3</sup>, and it performs well within 50 cycles. Criado et al. [97] conducted hydration and dehydration experiments in a 5.5 kW<sub>th</sub> fluidized bed reactor and established a model to verify the correctness of the results. The experimental device is shown in Fig. 19.

However, due to the considerable temperature variation between the top and bottom of the reactor in a sizeable fluidized bed reactor, the CaO/Ca(OH)<sub>2</sub> reaction is insufficient. At present, this limitation has not resolved. Therefore, in the design and operation of the large-scale reactors for industrial applications in the future, more extraordinary efforts are needed.

#### 4.2. The chemical heat pump (CHP)

Chemical heat pumps store waste heat, solar energy and geothermal energy in the shape of chemical energy, and deliver heat at different temperature levels when the heat is needed. CHP can achieve four operating modes: temperature rise mode, heat storage mode, heat increase mode and cooling manner, which has been experimentally and theoretically confirmed [98–101].

Ogura et al. [82] assessed the efficiency of this chemical heat pump in different operating modes. Fig. 20 demonstrates a sketch map of CaO/Ca(OH)<sub>2</sub> heat pump system. There are two processes in the system, namely, the heat storage process (calcium hydroxide endothermic decomposition) and the heat release process (calcium oxide hydration exothermic). Under appropriate pressure, calcium oxide hydration can also be used for cooling purposes, but the cooling efficiency is not high. And To improve the efficiency of refrigeration, Cerkvenik et al. [102,103] proposed this chemical heat pump in series with other adsorption cooling devices, the results showed that the refrigeration efficiency was improved.

Ogura et al. [104–107] did a lot of researches on chemical heat pump dryer (CHPD) based on the dehydration and hydration of CaO/Ca(OH)<sub>2</sub>. The pump uses heat from the reaction or condensation of water to generate hot air for the drying chamber (Fig. 21(a, c)). Fig. 21(b) displays an abridged general view of the standard-type CHP unit.

## 5. Conclusion and perspective

In this paper, CaO/Ca(OH)<sub>2</sub>/H<sub>2</sub>O thermochemical heat storage system is addressed. CaO/Ca(OH)<sub>2</sub> thermochemical heat storage system has shown significant advantages compared to phase change heat storage and sensible heat storage, for instance, large heat storage capacity and long-term storage. In order to understand the reaction process of the chemical heat storage process, and lay a foundation for the application design and control of the chemical heat storage, we summarized its physical and chemical properties. By preparing composite materials, it can increase the heat transfer and improve the sintering phenomenon during the reaction. Although the system has made some progress, several issues still need to be resolved in future research, including the following key points.

- (1) In terms of heat transfer performance research, there are many methods to improve thermal conductivity and heat transfer performance, for example, some studies use metal fins, graphite and metal foam in chemical heat storage materials, but there are two issues to consider: the first one is to ensure that the heat storage performance does not drop significantly when using these improvement methods; the second problem is the coordination of the reaction temperature and the reaction direction, because the increase in heat transfer capacity may cause a sharp rise in heat and limit the reaction to a certain direction.
- (2) In terms of cycle stability, the failure of the heat storage system is mainly due to two reasons: one is the aggregation of the material, and the other is that the material is affected by CO<sub>2</sub>. There are relatively many studies on how to improve the sintering situation. However, the existing improvement methods are still not perfect, and it is necessary to find different strategies to prevent material agglomeration. As for the research on material carbonation, although this problem has been raised in some kinds of literature, no scholars have made detailed studies on the influence rule and degree between CO<sub>2</sub> and CaO/Ca(OH)<sub>2</sub>, so this is an urgent problem to be solved.
- (3) Regarding the research on thermodynamics, there have been some reports, and some studies have conducted more detailed isothermal, or non-isothermal lectures on the kinetics of the Ca(OH)<sub>2</sub>/CaO heat storage system, and even obtained the equivalent activation energy. Because each tester uses different parameters such as the purity and particle size of the material, and even the accuracy of the test equipment and test methods, the final thermodynamic equations are not all the same.
- (4) On the other hand, although there have been some studies on doping Al, Zn, and other atoms in the Ca(OH)<sub>2</sub>/CaO heat storage system to change its thermodynamic properties. However, the thermodynamic parameters of the doped substances have not been studied and calculated in detail. Given the problems in the thermodynamics research, it is urgent to analyze the Ca(OH)<sub>2</sub>/CaO heat storage system and before and after doping atoms.
- (5) In terms of application status, because the development stage of chemical heat storage itself is still in the laboratory research stage, the industrial application is not yet realistic. Therefore, it is necessary to design a new suitable reactor to apply this thermochemical heat storage system to actual production.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

This project is supported by the National Natural Science Foundation

of China (Grant No. 21546014) and Key Project of Shanghai Science and Technology Commission (Grant No. 18DZ1202502). The authors also wish to thank the reviewers and editor for kindly giving revising suggestions.

## References

- [1] T. Wang, C.Y. Zhao, J. Yan, Investigation on the Ca(OH)<sub>2</sub>/CaO thermochemical energy storage system with potassium nitrate addition, *Sol. Energy Mater. Sol. Cells* 215 (2020).
- [2] H. Zhang, H. Wang, X. Zhu, Y.-J. Qiu, K. Li, R. Chen, Q. Liao, A review of waste heat recovery technologies towards molten slag in steel industry, *Appl. Energy* 112 (2013) 956–966.
- [3] G. Hartfuß, M. Schmid, G. Scheffknecht, Off-gas waste heat recovery for electric arc furnace steelmaking using calcium hydroxide (Ca(OH)<sub>2</sub>) dehydration, *Steel Res. Int.* 91 (11) (2020), 2000048.
- [4] T. Bauer, N. Pfleger, N. Breidenbach, M. Eck, D. Laing, S. Kaesche, Material aspects of solar salt for sensible heat storage, *Appl. Energy* 111 (2013) 1114–1119.
- [5] Z. Khan, Z. Khan, A. Ghafoor, A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility, *Energy Convers. Manag.* 115 (2016) 132–158.
- [6] T. Yan, T.X. Li, R.Z. Wang, Thermochemical heat storage for solar heating and cooling systems, *Adv. Solar Heat. Cooling* (2016) 491–522.
- [7] D. Feng, Y. Feng, L. Qiu, P. Li, Y. Zang, H. Zou, Z. Yu, X. Zhang, Review on nanoporous composite phase change materials: fabrication, characterization, enhancement and molecular simulation, *Renew. Sust. Energ. Rev.* 109 (2019) 578–605.
- [8] J. Yan, C.Y. Zhao, First-principle study of CaO/Ca(OH)<sub>2</sub> thermochemical energy storage system by Li or Mg cation doping, *Chem. Eng. Sci.* 117 (2014) 293–300.
- [9] V. Palomba, A. Frazzica, Recent advancements in sorption technology for solar thermal energy storage applications, *Sol. Energy* 192 (2019) 69–105.
- [10] A. Gil, M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, L.F. Cabeza, State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modelization, *Renew. Sust. Energ. Rev.* 14 (1) (2010) 31–55.
- [11] A. Solé, X. Fontanet, C. Barreneche, A.I. Fernández, I. Martorell, L.F. Cabeza, Requirements to consider when choosing a thermochemical material for solar energy storage, *Sol. Energy* 97 (2013) 398–404.
- [12] J. Sunku Prasad, P. Muthukumar, F. Desai, D.N. Basu, M.M. Rahman, A critical review of high-temperature reversible thermochemical energy storage systems, *Appl. Energy* (2019) 254.
- [13] H. Shi, Y. Zhao, W. Li, Effects of temperature on the hydration characteristics of free lime, *Cem. Concr. Res.* 32 (5) (2002) 789–793.
- [14] J.M. Commandré, S. Salvador, A. Nzihou, Reactivity of laboratory and industrial limes, *Chem. Eng. Res. Des.* 85 (4) (2007) 473–480.
- [15] L. André, S. Abanades, G. Flamant, Screening of thermochemical systems based on solid-gas reversible reactions for high temperature solar thermal energy storage, *Renew. Sust. Energ. Rev.* 64 (2016) 703–715.
- [16] P. Pardo, A. Deydier, Z. Anxionnaz-Minvielle, S. Rougé, M. Cabassud, P. Cognet, A review on high temperature thermochemical heat energy storage, *Renew. Sust. Energ. Rev.* 32 (2014) 591–610.
- [17] K.G. Sakellariou, Y.A. Criado, N.I. Tsongidis, G. Karagiannakis, A. G. Konstandopoulos, Multi-cyclic evaluation of composite CaO-based structured bodies for thermochemical heat storage via the CaO/Ca(OH)<sub>2</sub> reaction scheme, *Sol. Energy* 146 (2017) 65–78.
- [18] L. Desgranges, D. Grebille, G. Calvarin, N. Floquet, J.C. Niepce, Structural transformations preparing the dehydration of Ca(OH)<sub>2</sub>, *Phase Transit.* 31 (1–4) (2006) 283–286.
- [19] O. Chaix-Pluchery, J. Pannetier, J. Bouillot, J.C. Niepce, Structural prereactional transformations in Ca(OH)<sub>2</sub>, *J. Solid State Chem.* 67 (2) (1987) 225–234.
- [20] L. Desgranges, D. Grebille, G. Calvarin, K. Chhor, C. Pommier, N. Floquet, J. C. Niepce, Structural and thermodynamic evidence of a change in thermal motion of hydrogen atoms in Ca(OH)<sub>2</sub> at low temperature, *J. Phys. Chem. Solids* 55 (2) (1994) 161–166.
- [21] O. Chaix-Pluchery, J. Bouillot, D. Ciosmak, J.C. Niepce, F. Freund, Calcium hydroxide dehydration early precursor states, *J. Solid State Chem.* 50 (2) (1983) 247–255.
- [22] A.K. Galwey, G.M. Laverty, A kinetic and mechanistic study of the dehydroxylation of calcium hydroxide, *Thermochim. Acta* 228 (1993) 359–378.
- [23] D. Chen, X. Gao, D. Dollimore, The application of non-isothermal methods of kinetic analysis to the decomposition of calcium hydroxide, *Thermochim. Acta* 215 (1993) 65–82.
- [24] S. Lin, M. Harada, Y. Suzuki, H. Hatano, CaO hydration rate at high temperature (~1023 K), *Energy Fuel* 20 (3) (2006) 903–908.
- [25] S. Lin, Y. Wang, Y. Suzuki, High-temperature CaO Hydration/Ca(OH)<sub>2</sub> decomposition over a multitude of cycles, *Energy Fuel* 23 (6) (2009) 2855–2861.
- [26] Y. Wang, S. Lin, Y. Suzuki, Effect of CaO content on hydration rates of ca-based sorbents at high temperature, *Fuel Process. Technol.* 89 (2) (2008) 220–226.
- [27] D. Beruto, L. Barco, A.W. Searcy, G. Spinolo, Characterization of the porous CaO particles formed by decomposition of CaCO<sub>3</sub> and Ca(OH)<sub>2</sub> in vacuum, *J. Am. Ceram. Soc.* 63 (7–8) (1980) 439–443.
- [28] K. Darkwa, Thermochemical energy storage in inorganic oxides: an experimental evaluation, *Appl. Therm. Eng.* 18 (6) (1998) 387–400.

- [29] M.N. Azpiazu, J.M. Morquillas, A. Vazquez, Heat recovery from a thermal energy storage based on the  $\text{Ca}(\text{OH})_2/\text{CaO}$  cycle, *Appl. Therm. Eng.* 23 (6) (2003) 733–741.
- [30] F. Schäube, L. Koch, A. Wörner, H. Müller-Steinhagen, A thermodynamic and kinetic study of the de- and rehydration of  $\text{Ca}(\text{OH})_2$  at high  $\text{H}_2\text{O}$  partial pressures for thermo-chemical heat storage, *Thermochim. Acta* 538 (2012) 9–20.
- [31] J. Yan, Z. C.Y., Thermodynamic and kinetic study of the dehydration process of  $\text{CaO}/\text{Ca}(\text{OH})_2$  thermochemical heat storage system with Li doping, *Chem. Eng. Sci.* 138 (2015) 86–92.
- [32] I. Fujii, M. Ishino, S. Akiyama, M.S. Murthy, K.S. Rajanandam, Behavior of  $\text{Ca}(\text{OH})_2/\text{CaO}$  pellet under dehydration and hydration, *Sol. Energy* 53 (4) (1994) 329–341.
- [33] P.E. Halstead, A.E. Moore, The thermal dissociation of calcium hydroxide, *J. Chem. Soc.* (1957) 3873–3875.
- [34] J.A.C. Samms, B.E. Evans, Thermal dissociation of  $\text{Ca}(\text{OH})_2$  at elevated pressures, *J. Appl. Chem.* 18 (1) (2007) 5–8.
- [35] A. Shkatulov, Y. Aristov, Modification of magnesium and calcium hydroxides with salts: an efficient way to advanced materials for storage of middle-temperature heat, *Energy* 85 (2015) 667–676.
- [36] L. Dai, X.-F. Long, B. Lou, J. Wu, Thermal cycling stability of thermochemical energy storage system  $\text{Ca}(\text{OH})_2/\text{CaO}$ , *Appl. Therm. Eng.* 133 (2018) 261–268.
- [37] M. Schmidt, C. Szczukowski, C. Roßkopf, M. Linder, A. Wörner, Experimental results of a 10 kW high temperature thermochemical storage reactor based on calcium hydroxide, *Appl. Therm. Eng.* 62 (2) (2014) 553–559.
- [38] Y.A. Criado, M. Alonso, J.C. Abanades, Kinetics of the  $\text{CaO}/\text{Ca}(\text{OH})_2$  Hydration/Dehydration reaction for thermochemical energy storage applications, *Ind. Eng. Chem. Res.* 53 (32) (2014) 12594–12601.
- [39] S. Vyazovkin, A.K. Burnham, J.M. Criado, L.A. Pérez-Maqueda, C. Popescu, N. Sbirrazzuoli, ICTAC kinetics committee recommendations for performing kinetic computations on thermal analysis data, *Thermochim. Acta* 520 (1–2) (2011) 1–19.
- [40] T. H.I. Matsuda, S.K. Lee, M. Hasatani, Kinetic study of  $\text{Ca}(\text{OH})_2/\text{CaO}$  reversible thermochemical reaction for thermal energy storage by means of chemical reaction, *Kagaku Kogaku Ronbun* 11 (1985) 542–548.
- [41] M.K.H.M. Hasatani, Heat storing/releasing characteristics of a chemical heat storage unit of electricity using a  $\text{Ca}(\text{OH})_2/\text{CaO}$  reaction, *Heat Transf. Jpn. Res.* 25 (6) (1996) 400–409.
- [42] A. Irabien, J.R. Viguri, I. Ortiz, Thermal dehydration of calcium hydroxide. 1. Kinetic model and parameters, *Ind. Eng. Chem. Res.* 29 (8) (1990) 1599–1606.
- [43] R.S. Mikhail, S. Brunauer, L.E. Copeland, Kinetics of the thermal decomposition of calcium hydroxide, *J. Colloid Interface Sci.* 21 (4) (1966) 394–404.
- [44] S. Dutta, T. Shirai, Kinetics of drying and decomposition of calcium hydroxide, *Chem. Eng. Sci.* 29 (9) (1974) 2000–2003.
- [45] J. Yan, C.Y. Zhao, Experimental study of  $\text{CaO}/\text{Ca}(\text{OH})_2$  in a fixed-bed reactor for thermochemical heat storage, *Appl. Energy* 175 (2016) 277–284.
- [46] S. Dutta, T. Shirai, Experimental investigation on a fast and exothermic solid-liquid reaction system, *Chem. Eng. Sci.* 35 (1–2) (1980) 209–216.
- [47] A. Irabien, A. Toquero, M.I. Ortiz, Kinetic behaviour of non-isothermal lime hydration, *Chem. Eng. J.* 40 (2) (1989) 93–99.
- [48] E. Serris, L. Favregeon, M. Pijolat, M. Soustelle, P. Nortier, R.S. Gärtnert, T. Chopin, Z. Habib, Study of the hydration of  $\text{CaO}$  powder by gas-solid reaction, *Cem. Concr. Res.* 41 (10) (2011) 1078–1084.
- [49] M.S. Murthy, P. Raghavendrachar, S.V. Sriram, Thermal decomposition of doped calcium hydroxide for chemical energy storage, *Sol. Energy* 36 (1) (1986) 53–62.
- [50] M.M.H. Ogura, H. Matsuda, M. Hasatani, M. Yanadori, M. Hiramatsu, Experimental study on heat transfer enhancement of the solid reactant particle bed in a chemical heat pump using  $\text{Ca}(\text{OH})_2/\text{CaO}$  reaction, *Kagaku Kogaku Ronbunshu* 17 (5) (1991) 916–923.
- [51] F. Schäube, A. Wörner, R. Tamme, High temperature thermochemical heat storage for concentrated solar power using gas-solid reactions, *J. Sol. Energy Eng.* 133 (3) (2011).
- [52] M. Wang, L. Chen, P. He, W.-Q. Tao, Numerical study and enhancement of  $\text{Ca}(\text{OH})_2/\text{CaO}$  dehydration process with porous channels embedded in reactors, *Energy* 181 (2019) 417–428.
- [53] F. Schäube, I. Utz, A. Wörner, H. Müller-Steinhagen, De- and rehydration of  $\text{Ca}(\text{OH})_2$  in a reactor with direct heat transfer for thermo-chemical heat storage. Part B: validation of model, *Chem. Eng. Res. Des.* 91 (5) (2013) 865–873.
- [54] J.A.M. Kuipers, W. Prins, W.P.M. Van Swaaij, Numerical calculation of wall-to-bed heat-transfer coefficients in gas-fluidized beds, *AICHE J.* 38 (7) (1992) 1079–1091.
- [55] V.D. Vortmeyer, Der energietransport durch warmestrahlung in festbetten mit exothermer reaktion, *Ber. Bunsen Ges.* 74 (1970) 127–134.
- [56] M.-M. Druske, A. Fopah-Lele, K. Korhammer, H.U. Rammelberg, N. Wegscheider, W. Ruck, T. Schmidt, Developed materials for thermal energy storage: synthesis and characterization, *Energy Procedia* 61 (2014) 96–99.
- [57] C. Huang, M. Xu, X. Huai, Experimental investigation on thermodynamic and kinetic of calcium hydroxide dehydration with hexagonal boron nitride doping for thermochemical energy storage, *Chem. Eng. Sci.* 206 (2019) 518–526.
- [58] S. Wu, T. Yan, Z. Kuai, W. Pan, Thermal conductivity enhancement on phase change materials for thermal energy storage: a review, *Energy Storage Mater.* 25 (2020) 251–295.
- [59] K.G. Sakellariou, G. Karagiannakis, Y.A. Criado, A.G. Konstandopoulos, Calcium oxide based materials for thermochemical heat storage in concentrated solar power plants, *Sol. Energy* 122 (2015) 215–230.
- [60] C. Roßkopf, M. Haas, A. Faik, M. Linder, A. Wörner, Improving powder bed properties for thermochemical storage by adding nanoparticles, *Energy Convers. Manag.* 86 (2014) 93–98.
- [61] C. Roßkopf, S. Afflerbach, M. Schmidt, B. Görtz, T. Kowald, M. Linder, R. Trettin, Investigations of nano coated calcium hydroxide cycled in a thermochemical heat storage, *Energy Convers. Manag.* 97 (2015) 94–102.
- [62] M. Xu, X. Huai, J. Cai, Agglomeration behavior of calcium Hydroxide/Calcium oxide as thermochemical heat storage material: a reactive molecular dynamics study, *J. Phys. Chem. C* 121 (5) (2017) 3025–3033.
- [63] J. Kariya, J. Ryu, Y. Kato, Reaction performance of calcium hydroxide and expanded graphite composites for chemical heat storage applications, *ISIJ Int.* 55 (2) (2015) 457–463.
- [64] J. Kariya, J. Ryu, Y. Kato, Development of thermal storage material using vermiculite and calcium hydroxide, *Appl. Therm. Eng.* 94 (2016) 186–192.
- [65] Y. Álvarez Criado, M. Alonso, J.C. Abanades, Composite material for thermochemical energy storage using  $\text{CaO}/\text{Ca}(\text{OH})_2$ , *Ind. Eng. Chem. Res.* 54 (38) (2015) 9314–9327.
- [66] Y.A. Criado, M. Alonso, J.C. Abanades, Enhancement of a  $\text{CaO}/\text{Ca}(\text{OH})_2$  based material for thermochemical energy storage, *Sol. Energy* 135 (2016) 800–809.
- [67] B.Q. Xia, C.Y. Zhao, J. Yan, A.A. Khosa, Development of granular thermochemical heat storage composite based on calcium oxide, *Renew. Energy* 147 (2020) 969–978.
- [68] S. Afflerbach, M. Kappes, A. Gipperich, R. Trettin, W. Krumm, Semipermeable encapsulation of calcium hydroxide for thermochemical heat storage solutions, *Sol. Energy* 148 (2017) 1–11.
- [69] S. Funayama, H. Takasu, S.T. Kim, Y. Kato, Thermochemical storage performance of a packed bed of calcium hydroxide composite with a silicon-based ceramic honeycomb support, *Energy* 201 (2020).
- [70] S. Funayama, H. Takasu, M. Zamengo, J. Kariya, S.T. Kim, Y. Kato, Composite material for high-temperature thermochemical energy storage using calcium hydroxide and ceramic foam, *Energy Storage* 1 (2) (2019).
- [71] J. Kariya, Y. Kato, Development of thermal energy storage material using porous silicon carbide and calcium hydroxide, *Energy Procedia* 131 (2017) 395–406.
- [72] J. Yan, C.Y. Zhao, Z.H. Pan, The effect of  $\text{CO}_2$  on  $\text{Ca}(\text{OH})_2$  and  $\text{Mg}(\text{OH})_2$  thermochemical heat storage systems, *Energy* 124 (2017) 114–123.
- [73] J. Yan, C.Y. Zhao, B.Q. Xia, T. Wang, The effect of dehydration temperatures on the performance of the  $\text{CaO}/\text{Ca}(\text{OH})_2$  thermochemical heat storage system, *Energy* 186 (2019).
- [74] E.J. Anthony, Ca looping technology: current status, developments and future directions, *Greenhouse Gases Sci. Technol.* 1 (2011) 36–47.
- [75] F.-C. Yu, N. Phalak, Z. Sun, L.-S. Fan, Activation strategies for calcium-based sorbents for  $\text{CO}_2$  capture: a perspective, *Ind. Eng. Chem. Res.* 51 (4) (2011) 2133–2142.
- [76] D.P. Hanak, C. Biliyok, V. Manovic, Calcium looping with inherent energy storage for decarbonisation of coal-fired power plant, *Energy Environ. Sci.* 9 (3) (2016) 971–983.
- [77] Y. Yuan, Y. Li, L. Duan, H. Liu, J. Zhao, Z. Wang,  $\text{CaO}/\text{Ca}(\text{OH})_2$  thermochemical heat storage of carbide slag from calcium looping cycles for  $\text{CO}_2$  capture, *Energy Convers. Manag.* 174 (2018) 8–19.
- [78] M.N. Vazquez, J.M. Morquillas, A. Vazquez, Evaluation of a Thermal Storage System on Warm-Up Exhaust Emissions, *SAE Mobilus*, 1992, 921459.
- [79] I. Fujii, K. Tsuchiya, M. Higano, J. Yamada, Studies of an energy storage system by use of the reversible chemical reaction:  $\text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{Ca}(\text{OH})_2$ , *Sol. Energy* 34 (4–5) (1985) 367–377.
- [80] J.K. Rosemary, G.L. Bauerle, T.H. Springer, Solar energy storage using reversible hydration-dehydration of  $\text{CaO}-\text{Ca}(\text{OH})_2$ , *J. Energy* 3 (6) (1979) 321–322.
- [81] G. Ervin, Solar heat storage using chemical reactions, *J. Solid State Chem.* 22 (1) (1977) 51–61.
- [82] H. Ogura, Efficiencies of  $\text{CaO}/\text{H}_2\text{O}/\text{Ca}(\text{OH})_2$  chemical heat pump for heat storing and heating/cooling, *Energy* 28 (14) (2003) 1479–1493.
- [83] W.E. Wentworth, E. Chen, Simple thermal decomposition reactions for storage of solar thermal energy, *Sol. Energy* 18 (3) (1976) 205–214.
- [84] G. Ervin, Solar heat storage using chemical reactons, *J. Solid State Chem.* 22 (1977) 51–61.
- [85] F. Schäube, A. Kohzer, J. Schütz, A. Wörner, H. Müller-Steinhagen, De- and rehydration of  $\text{Ca}(\text{OH})_2$  in a reactor with direct heat transfer for thermo-chemical heat storage. Part A: experimental results, *Chem. Eng. Res. Des.* 91 (5) (2013) 856–864.
- [86] M. Schmidt, A. Gutierrez, M. Linder, Thermochemical energy storage with  $\text{CaO}/\text{Ca}(\text{OH})_2$  – experimental investigation of the thermal capability at low vapor pressures in a lab scale reactor, *Appl. Energy* 188 (2017) 672–681.
- [87] M. Schmidt, M. Linder, Power generation based on the  $\text{Ca}(\text{OH})_2/\text{CaO}$  thermochemical storage system – experimental investigation of discharge operation modes in lab scale and corresponding conceptual process design, *Appl. Energy* 203 (2017) 594–607.
- [88] Q. Ranjha, A. Oztekin, Numerical analyses of three-dimensional fixed reaction bed for thermochemical energy storage, *Renew. Energy* 111 (2017) 825–835.
- [89] M. Schmidt, M. Gollsch, F. Giger, M. Grün, M. Linder, Development of a moving bed pilot plant for thermochemical energy storage with  $\text{CaO}/\text{Ca}(\text{OH})_2$ , in: *SolarPACES*, 2016.
- [90] A. Cosquillo Mejia, S. Afflerbach, M. Linder, M. Schmidt, Experimental analysis of encapsulated  $\text{CaO}/\text{Ca}(\text{OH})_2$  granules as thermochemical storage in a novel moving bed reactor, *Appl. Therm. Eng.* (2020) 169.
- [91] P.S. Fennell, R. Pacciani, J.S. Dennis, J.F. Davidson, A.N. Hayhurst, The effects of repeated cycles of calcination and carbonation on a variety of different

- limestones, as measured in a hot fluidized bed of sand, *Energy Fuel* 21 (4) (2007) 2072–2081.
- [92] Z. Ma, G. Glatzmaier, M. Mehos, Fluidized bed technology for concentrating solar power with thermal energy storage, *J. Sol. Energy Eng.* 136 (3) (2014).
- [93] Z. Ma, M. Mehos, G. Glatzmaier, B.B. Sakadjian, Development of a concentrating solar power system using fluidized-bed technology for thermal energy conversion and solid particles for thermal energy storage, *Energy Procedia* 69 (2015) 1349–1359.
- [94] K. Darkwa, A. Ianakiev, P.W. O'Callaghan, Modelling and simulation of adsorption process in a fluidised bed thermochemical energy reactor, *Appl. Therm. Eng.* 26 (8–9) (2006) 838–845.
- [95] Y.A. Criado, M. Alonso, J.C. Abanades, Z. Anxionnaz-Minvielle, Conceptual process design of a CaO/Ca(OH)<sub>2</sub> thermochemical energy storage system using fluidized bed reactors, *Appl. Therm. Eng.* 73 (1) (2014) 1087–1094.
- [96] P. Pardo, Z. Anxionnaz-Minvielle, S. Roug  , P. Cognet, M. Cabassud, Ca(OH)<sub>2</sub>/CaO reversible reaction in a fluidized bed reactor for thermochemical heat storage, *Sol. Energy* 107 (2014) 605–616.
- [97] Y.A. Criado, A. Huille, S. Roug  , J.C. Abanades, Experimental investigation and model validation of a CaO/Ca(OH)<sub>2</sub> fluidized bed reactor for thermochemical energy storage applications, *Chem. Eng. J.* 313 (2017) 1194–1205.
- [98] S. Fujimoto, E. Bilgen, H. Ogura, Dynamic simulation of CaO/Ca(OH)<sub>2</sub> chemical heat pump systems, *Exergy* 2 (1) (2002) 6–14.
- [99] H. Ogura, R. Shimojyo, H. Kage, Y. Matsuno, A.S. Mujumdar, Simulation of hydration/dehydration of CaO/Ca(OH)<sub>2</sub>chemical heat pump reactor for cold/hot heat generation, *Dry. Technol.* 17 (7–8) (2007) 1579–1592.
- [100] S. Fujimoto, E. Bilgen, H. Ogura, CaO/Ca(OH)<sub>2</sub> chemical heat pump system, *Energy Convers. Manag.* 43 (7) (2002) 947–960.
- [101] H. Ogura, S. Yasuda, Y. Otsubo, A.S. Mujumdar, Continuous operation of a chemical heat pump, *Asia Pac. J. Chem. Eng.* 2 (2) (2007) 118–123.
- [102] B. Cerkvenik, Y. Kato, F. Storkenmaier, Applicability of calcium oxide in a cascading sorption cooling system, *J. Chem. Eng. Jpn* 35 (10) (2002) 969–976.
- [103] B. Cerkvenik, P. Satzger, F. Ziegler, A. Poredos, High Efficient Sorption Cycles Using CaO/H<sub>2</sub>O and LiBr/H<sub>2</sub>O for Gas Cooling, 1999.
- [104] H. Ogura, H. Ishida, R. Yokooji, H. Kage, Y. Matsuno, A.S. Mujumdar, Experimental studies on a novel chemical heat pump dryer using a gas-solid reaction, *Dry. Technol.* 19 (7) (2001) 1461–1477.
- [105] H. Ogura, Effects of heat exchange condition on hot air production by a chemical heat pump dryer using CaO/H<sub>2</sub>O/Ca(OH)<sub>2</sub> reaction, *Chem. Eng. J.* 86 (1–2) (2002) 3–10.
- [106] H. Ogura, A.S. Mujumdar, Proposal for a novel chemical heat pump dryer, *Dry. Technol.* 18 (4–5) (2000) 1033–1053.
- [107] H. Ogura, T. Yamamoto, Y. Otsubo, H. Ishida, H. Kage, A.S. Mujumdar, A control strategy for a chemical heat pump dryer, *Dry. Technol.* 23 (6) (2005) 1189–1203.