

Applicability of coal slag for application as packed bed thermal energy storage materials

Zhenya Lai, Kefa Cen, Hao Zhou*

State Key Laboratory of Clean Energy Utilization, Institute for Thermal Power Engineering, Zhejiang University, Hangzhou 310027, China

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ABSTRACT

Refractory materials are considered as the most suitable high-temperature sensible heat storage materials due to their excellent thermo-mechanical resistance and superior thermophysical properties. Unfortunately, refractories are usually too expensive. To reduce the cost of energy storage materials, the recycling of refractory industrial solid wastes into storage materials is becoming increasingly prevalent. The paper innovatively proposes to use the slags from a liquid slagging furnace of a coal-fired power plant in China as packed bed sensible heat energy storage materials. This paper characterizes the chemical compositions and thermophysical properties of three typical coal slags (Fukang coal slag, Fukang coal granulated slag, Hongshaquan coal granulated slag) and evaluates their potentials as storage materials. The results show that the three kinds of coal slags have good thermophysical properties. At 380 °C, the energy storage densities per unit volume of the three materials are 1037 MJ/m³, 986 MJ/m³ and 920 MJ/m³, respectively. Fukang coal slag has good thermal stability and durability and can be directly used for ultra-high temperature energy storage at 1000 °C. Due to the low crystallization degree, the two granulated slags have poor thermal durabilities and need to be processed at high temperatures before using them for energy storage applications.

1. Introduction

Solar energy is the most promising renewable energy. However, solar energy has to face a mismatch between energy supply and demand. There are two solutions to this problem: the hybridation of solar energy with conventional fossil energy or the use of an energy storage system (Py et al., 2009, 2011). Since the former using fossil fuels exacerbates the shortage of fossil energy and undermines the renewable and sustainable characteristics of solar energy technology itself, energy storage systems have significant advantages.

Currently, the most mature energy storage system is the double-tank molten salt storage system. Nevertheless, molten salt has a high melting point with instability and corrosion at high-temperature (Py et al., 2009, 2011), which is not conducive to constructing an efficient and low-cost system. Thanks to the low cost and wide operating temperature range, the packed bed thermal energy storage (TES) system has been gradually favored by people in recent years.

Choosing low-cost and high-efficiency storage materials is the key to sensible heat storage research (Khare et al., 2013). During the operation of the heat storage system, the storage materials have to withstand the

harsh environment of high temperature and high pressure. Therefore, the primary candidates for high-temperature thermal storage are refractory materials with advantageous thermo-mechanical resistance and good thermophysical properties. Whereas, due to the high price of refractory materials, the recycling of refractory industrial solid waste into storage materials has become the best choice to develop new storage materials (Agalit et al., 2020a; Henry and Prasher, 2014; Calvet et al., 2013).

In the 1990s, Tayeb proposed using chemical and metallic industrial waste for solar energy storage (Tayeb, 1996). Up to now, more and more scholars are studying using industrial wastes or by-products as thermal energy storage materials. These recyclable waste materials mainly include wastes from the mining and metallurgical industry, asbestos-containing waste (ACW), municipal waste and fly ash (Gutierrez et al., 2016).

For wastes and by-products of the metallurgical industry, (Ortega-Fernández et al., 2015) characterized the thermophysical and structural characteristics of electric arc furnace (EAF) slag. The study shows that EAF slag is a successful sensible heat storage material. Furthermore, the material's thermal stability was verified at 1100 °C (Calvet et al., 2013).

* Corresponding author.

E-mail address: zhouhao@zju.edu.cn (H. Zhou).

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The compatibility tests showed that EAF slag was exposed to air directly at 1000 °C for 500 h without any corrosion issues (Ortega et al., 2015). (Grosu et al., 2018) compared the energy storage applicabilities of Basic Oxygen Furnace (BOF) slag, magnetite and river rock. Considering the thermophysical properties and prices of the three materials, the BOF slag is the best choice for storage materials. Agalit et al. (Agalit et al., 2017) claimed that induction furnace slag (IFS) has good thermophysical characteristics and thermal stability and is a good candidate material for high-temperature thermal energy storage applications (up to 1000 °C). Wang et al. (Wang et al., 2018) conducted wear tests on two kinds of EAF slags to evaluate the influence of temperature on friction characteristics. Agalit et al. (Agalit et al., 2020b) successfully synthesized IFS into crystalline material by the sintering method to meet the requirements of the high-temperature energy storage application. Calderon-vasquez et al. (Calderón-Vásquez et al., 2021) analyzed the thermophysical characteristics of copper slag to evaluate its applicability as a storage material. Naimi et al. (Naimi et al., 2015) evaluated the suitability of EAF slag, ladle furnace (LF) slag, aluminum pot skimming (APS) and aluminum white dross (AWD) as storage media for high-temperature Concentrating Solar Power (CSP) applications. The results show that EAF slag, LF slag and AWD are stable at high temperatures up to 1100 °C after one or two thermal cycles. APS is essentially carbon, and its degradation at high temperatures makes it unsuitable for high-temperature thermal storage. Besides, some by-products from the mineral industry have also been proposed to be used as energy storage materials (Ushak et al., 2013; Laia Miró et al., 2014; Navarro et al., 2012).

For ACW, (Py et al., 2009, 2011; Faik et al., 2012) characterized ACW treated by plasma torches. Due to heterogeneous cooling rates, the glassy ACW is produced close to the mold walls and crystallized ACW in the bulk. The results show that glassy ACW (amorphous materials) can be used in storage systems below 500 °C, while crystallized ACW (crystalline materials) can be used in storage systems up to 1100 °C. (Kere et al., 2014) further verified the stability of ACW in a high-pressure environment of 30 bars. Surprisingly, although the structural changes of the materials reduced the thermal capacity by 5%, the thermal conductivity increased by 19–30%, which is significant for improving the charging and discharging power of the energy storage module.

For urban waste, (Faik et al., 2012; Meffre et al., 2015) characterized municipal solid waste incinerator (MSWI) fly ashes. The results show that their thermophysical properties are equivalent to those of refractories. (Kocak et al., 2021) compared the thermophysical properties of demolition wastes (DW) and existing industrial wastes. The results show that DW can be used for high-temperature packed bed thermal energy storage. Kocak et al. (Koçak and Paksoy, 2019) prepared the sensible thermal energy storage (STES) material samples using binding additives with demolition waste dust. The DSC tests show that the specific heat capacity of the new sample is 1000–1460 J/(kg·°C) at 100–500 °C.

For fly ash, Agalit et al. (Agalit et al., 2020a) evaluated the potentials of coal fly ash (CFA), coal bottom ash (CBA) and coal bottom clinker (CBC) as storage materials. The results show that these materials exhibit good storage performances and can be used in solar tower power plants (up to 800 °C). (Ortega et al., 2015) successfully synthesized the waste materials (CFA, CBA and CBC) into potential storage materials by the sintering method. This method can overcome the shortcomings of high temperature and the uncontrollable crystallization process of the plasma torch. (Fu et al., 2015) found that the introduction of fly ash into aluminated cement can improve hardened pastes' mechanical and thermal properties. At the optimum dosage of 15%, the thermal conductivity and volume heat capacity increased by 17.2% and 60%, respectively.

Furthermore, the compatibilities of these recyclable waste materials with common heat transfer fluids (air, solar salts and hot oil) have also been studied (Calvet et al., 2013; Ortega et al., 2015; Laia Miró et al., 2014; Motte et al., 2015; Grosu et al., 2018; Ortega-Fernández et al.,

2015).

According to the literature review, studies on the valorization of industrial wastes and by-products as energy storage materials mainly focus on wastes from the mining and metallurgical industry, ACW and municipal solid waste. However, there are few studies on reusing wastes from coal-fired power plants as storage materials. As far as the author is aware, there is no relevant research on using the slags from a liquid slagging furnace of a coal-fired power plant as packed bed sensible heat energy storage materials. This research gap is precisely the novelty of this paper. Moreover, most of the wastes mentioned above need to be pretreated and shaped at high temperatures before being used as solid storage material, leading to additional heat consumption. However, furnace slags are lumpy or granular and can be used directly as storage material without additional reprocessing. Therefore, it is necessary to study the applicabilities of liquid slag as storage materials. Moreover, it is crucial to clarify the effects of coal types and slag morphology on the storage performances of coal slags. The above two aspects are the focus of this paper and represent the originality of the research. The research results will present useful reference sources for fellow researchers and practitioners in the energy community.

In this study, firstly we comprehensively characterize three coal slags by various methods and obtain their chemical compositions, thermo-physical properties, thermal stabilities and durabilities. Then, we assess the potentials of three coal slags as storage materials. Meanwhile, this paper analyzes the effects of coal types and slag morphology on the storage performances of coal slags.

2. Experimental

2.1. Materials

The Zhundong coalfield is China's largest integrated coalfield with estimated reserves of up to 390 billion tons. However, Zhundong coal has a high alkali metal content and is more likely to lead to ash deposition after combustion in the boiler. Fortunately, the liquid slag discharge furnace can increase the amount of slag discharge, reduce the deposition of coal ash on the heat exchange surface and thus improve the heat transfer efficiency. Fig. 1 shows the liquid flowing slag and granulated slag at the production site of a liquid slag discharge furnace in a coal-fired power plant.

In this study, two kinds of coal (Fukang coal and Hongshaquan coal) in Zhundong coalfield are selected as representative coals in China. The three kinds of coal slags tested are Fukang coal slag (FCS), Fukang coal granulated slag (FCGS) and Hongshaquan coal granulated slag (HCGS). The three slags are all from the slag conveyor of the 20 MW pilot-scale liquid slag discharge furnace in Xuzhou. Fig. 2 presents the morphology patterns of three coal slags. The three kinds of slags have apparent differences in morphology. FCS and FCGS are dark brown, while HCGS is black with an evident metallic luster. The FCS is coral-like, while the granulated slags are granular with irregular shapes. Table 1 shows the two coals' proximate analysis and ultimate analysis results. Compared with Fukang coal, Hongshaquan coal has more volatile and ash, and less fixed carbon content.

2.2. Characterization methods

The received coal slags contain a large amount of moisture and have wet surfaces. Therefore, the slags were first dried in an oven at 105 °C for 48 h to remove moisture in the slag samples. Moreover, due to the large particle size of Fukang coal slag, a manual hammer was used to break it into small particles before the tests. Before the characterization, the samples of three coal slags were ground (75 μm) with a ball mill and then dried in an oven at 105 °C for 24 h to remove moisture on the surface of the powders.

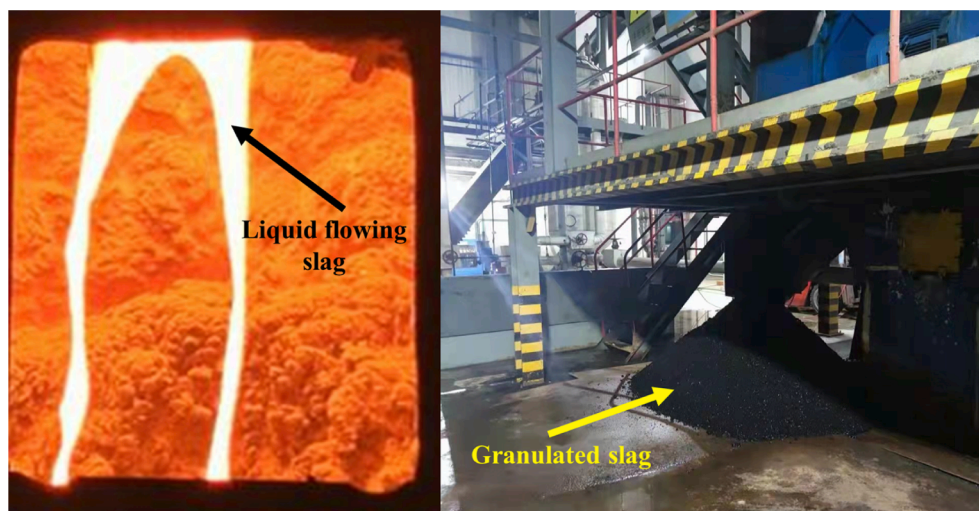


Fig. 1. Liquid flowing slag and granulated slag at the production site of a liquid slag discharge furnace in a coal-fired power plant.



Fig. 2. Three kinds of coal slags after drying.

Table 1

The analysis results of two coals.

Item	Fukang coal (FC)	Hongshaquan coal (HC)
Proximate analysis (% ad)		
Moisture	16.72	14.63
Ash	5.59	7.52
Volatiles	23.77	32.82
Fixed carbon	53.92	45.03
Ultimate analysis (% ad)		
C	61.98	61.52
H	1.63	3.59
O	13.07	11.48
N	0.52	0.84
S _t	0.49	0.42

2.2.1. Density

The apparent densities of three coal slags were measured by the Archimedes drainage method (Tian et al., 2015). Each sample was measured five times, and the average value of the results is present as the final result. In the test, the balance has an accuracy of 0.01 g.

2.2.2. Structural analysis and chemical compositions

The structural analysis of the raw materials was performed by X-ray powder diffraction (XRD) techniques with a PANalytical X'Pert PRO diffractometer under Bragg-Brentano geometry (θ - 2θ) using Cu ($K\alpha_1$ and $K\alpha_2$) radiation. Data were collected between 10° and 80° of 2θ with a step size of 0.02° and a count time of 20 s per step. The X-ray fluorescence spectroscopy (XRF) test was conducted on the powder samples of three coal slags using Shimadzu XRF-1800 to analyze their chemical compositions.

2.2.3. Differential scanning calorimetry (DSC)

Differential scanning calorimeter (TA Q200) was used to measure the specific heat of the three materials in the temperature range of 0–400 °C. The heating rate was 10 °C/min, and the atmosphere was nitrogen during the test. This test was applied on a sample mass of about 25 mg. The DSC has a heat flux sensitivity of 0.2 μ W and temperature accuracy of 0.1 °C.

2.2.4. Thermogravimetric analysis (TGA)

To evaluate the thermal stability of the materials, thermogravimetric tests (two heating and cooling cycles) were performed on three samples in the range of 50–1000 °C using a synchronous thermal analyzer (TGA/DSC3+, Mettler, Switzerland). During the test, the heating and cooling rates were 10 °C/min, and the atmosphere was air. This test was applied on a sample mass of about 28 mg. The synchronous thermal analyzer has a mass accuracy of 0.1 mg.

2.2.5. Thermal durability test

Thermal durability tests were performed on several samples (granular) using a muffle furnace. The tests contained 100 cycles between 300 and 500 °C. The heating rate was 5 °C/min, and the cooling rate was 2 °C/min. The morphology and weight changes of the samples before and after the tests were compared. In the test, the balance has an accuracy of 0.01 g. Before the experiment, the samples were dried in an oven at 105 °C for 24 h to remove the moisture in the samples.

2.3. Experimental uncertainties

The major parameters' maximum uncertainty was evaluated via the error propagation theory (Moffat, 1988), as given in Table 2.

Table 2
Experimental uncertainties of the major parameters of interest.

Property/parameter (unit)	Uncertainty (%)
Apparent density (kg/m ³)	0.17
Specific heat capacity (J/(g·°C))	1.43
Heat capacity (kJ/(m ³ ·°C))	1.44
Energy density per volume unit (MJ/m ³)	1.44
Energy density per mass unit (kJ/kg)	1.44
Mass of the TGA test (mg)	0.21
Mass of the thermal durability test (g)	0.02

$$\delta R = \left[\sum_{i=1}^N \left(\frac{\partial R}{\partial X_i} \delta X_i \right)^2 \right]^{1/2} \quad (1)$$

Where δR is the total uncertainty, X_i is the measurement parameter, δX_i is the uncertainty of each independent variable, which can be calculated according to the accuracies of measuring instruments and measured values.

3. Results and discussion

3.1. Chemical compositions

Figs. 3–5 show the XRD test results of three coal slags. It can be seen from the figure that the FCS has a high degree of crystallization, and its main mineral components are Akermanite ((Ca_{1.53}Na_{0.51})(Mg_{0.39}Al_{0.41}Fe_{0.16})Si₂O₇) and Diopside ((Fe_{0.35}Al_{0.2}Mg_{0.44})Ca_{0.96}(Fe_{0.08}Si_{0.7}Al_{0.2})₂O_{6.12}). However, FCGS and HCGS have wide amorphous phase distributions and hardly significant material fronts, showing an amorphous nature. They have low degrees of crystallization, which is due to the rapid cooling rate of granulated slags (Agalit et al., 2020b).

Table 3 shows the XRF test results of three coal slags. Meanwhile, Table 3 also gives the chemical compositions of two kinds of coal ashes (Fukang coal ash, FCA; Hongshaquan coal ash, HCA) for comparative analysis. As shown in the table, all coal slags have similar chemical compositions, and their main components are CaO, Fe₂O₃, SiO₂ and

Al₂O₃. This result is consistent with the literature (Agalit et al., 2020a, 2020b). The total content of the above four components exceeds 90%, which is consistent with most coal slags, proving the representativeness of the coal slags in China (Chen et al., 2017). It is noteworthy that the granulated slags have significantly higher Fe₂O₃ contents and lower CaO contents compared with the FCS, which explains the lower crystallization degrees of granulated slags to a certain extent (Chen et al., 2017; Hu et al., 2022). Besides, compared with the two fukang coal slags, Hongshaquan coal slag has higher Al₂O₃ content and lower CaO content. This result is because of the different chemical compositions in the two kinds of coals, which is demonstrated by the chemical compositions of FCA and HCA in Table 3.

3.2. Thermophysical characteristic

3.2.1. Apparent density

Fig. 6 shows the apparent densities of three kinds of coal slags. Fig. 6 also gives the densities of other common energy storage materials (Agalit et al., 2020a) for comparative analysis. The apparent densities of coal slags in the current experiment are between 2750 and 3050 kg/m³, comparable to other energy storage materials. Notably, compared with the waste (CFA, CBA and CBC) from coal-fired power plants in Morocco (Agalit et al., 2020a), the coal slags in this study have significantly higher densities. This difference may be related to different coal types and discrepant combustion and cooling conditions. The higher density can increase the heat capacity of the material, allowing more energy to be stored in the same tank volume. Alternatively, the same amount of heat can be stored in smaller tanks and reduce the cost of the storage system. Besides, the apparent densities of fukang coal slags are significantly higher than that of Hongshaquan coal slag. Meanwhile, FCS has a slightly higher apparent density than FCGS, which is attributed to the high content of low-density ash of the latter (Agalit et al., 2020a).

3.2.2. Specific heat capacity

Fig. 7 shows the specific heat capacities of three coal slags with temperature. It can be seen from the figure that the specific heat

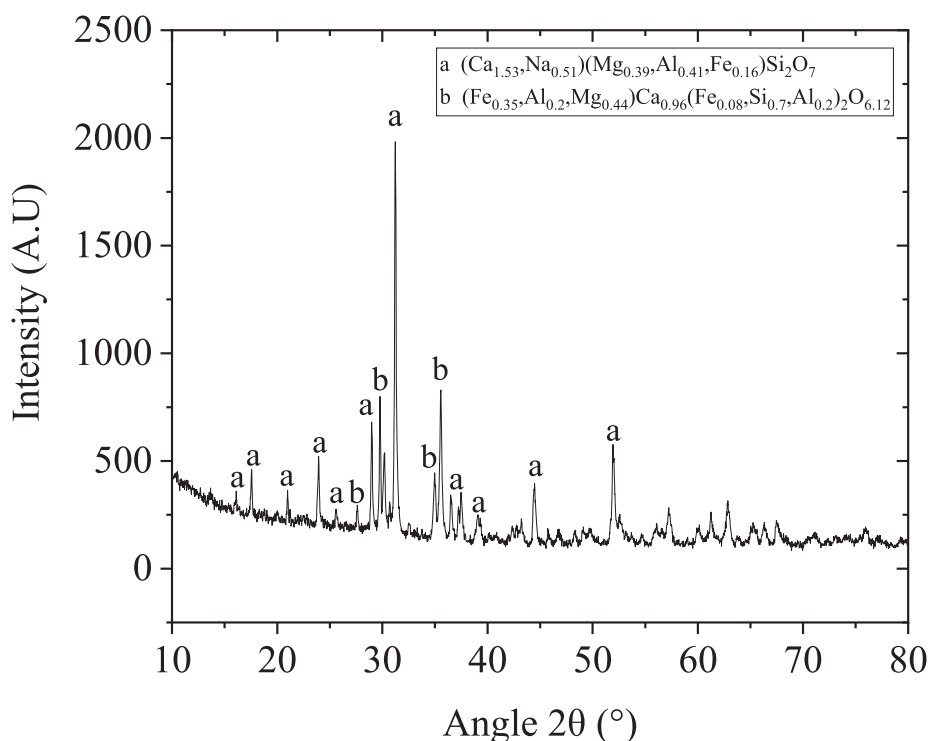


Fig. 3. XRD pattern of FCS.

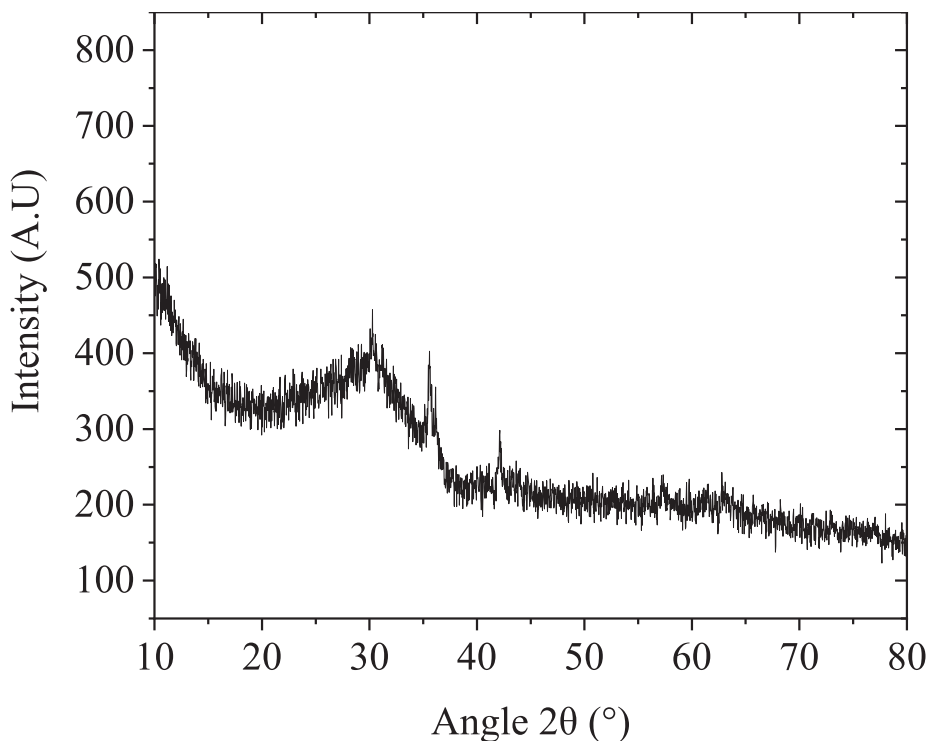


Fig. 4. XRD pattern of FCGS.

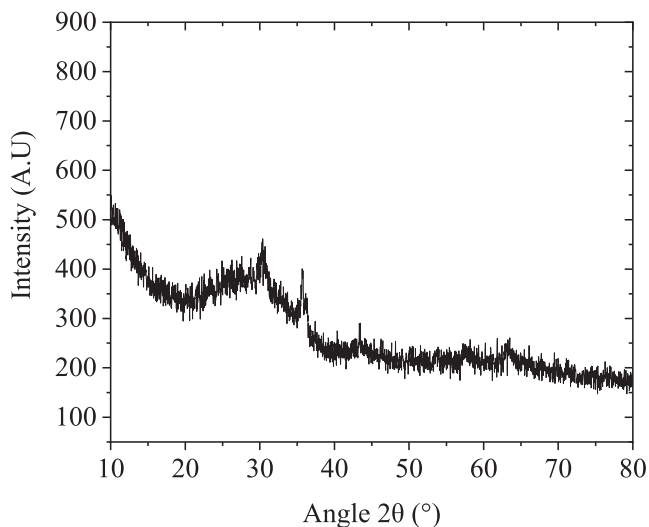


Fig. 5. XRD pattern of HCGS.

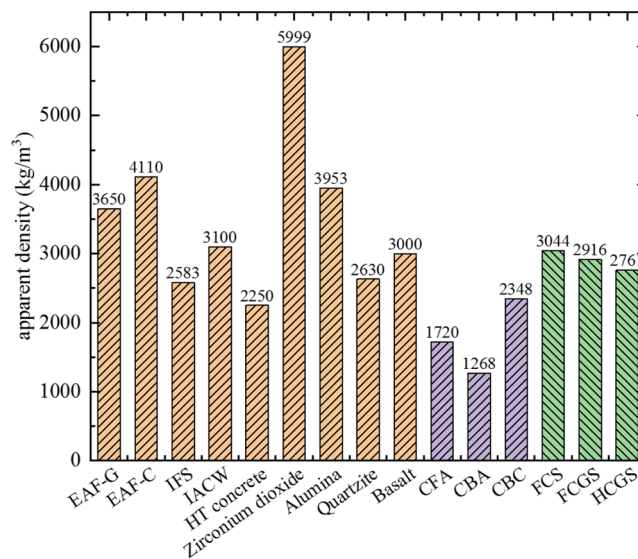


Fig. 6. Apparent densities of the coal slags and common storage materials reported from literature.

Table 3
Chemical compositions of three kinds of coal slags.

Wt (%)	CaO	Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	MgO	SrO	BaO
FCS	27.96	27.46	24.22	9.94	4.18	1.38	1.36
FCGS	20.69	37.64	22.10	10.38	3.27	1.17	1.08
HCGS	14.62	38.44	25.68	14.13	2.80	0.66	0.83
FCA	35.59	12.36	10.37	5.27	10.01	-	-
HCA	16.63	18.68	31.52	13.32	6.19	-	-

capacities of the three coal slags increase monotonically with the increase of temperature, and the increase rate decreases gradually, which is consistent with the results in the literature (Agalit et al., 2020a, 2020b). At the same temperature, there is little difference in the specific

heat capacities of the three coal slags. When the temperature increases from 10 °C to 380 °C, the specific heat capacities of the three coal slags increase from 0.70 J/(g.°C) to 1.00 J/(g.°C). Compared with similar solid waste energy storage materials (0.5–1.0 J/(g.°C)) (Gutierrez et al., 2016), the three coal slags have good specific heat capacities. According to Debye’s theory, the specific heat capacity increases as the temperature rises and gradually approaches a maximum value. Due to the temperature limitation of the measuring equipment, the current test is only carried out up to 380 °C. When the material is heated to more than 400 °C, it will exhibit greater specific heat capacity.

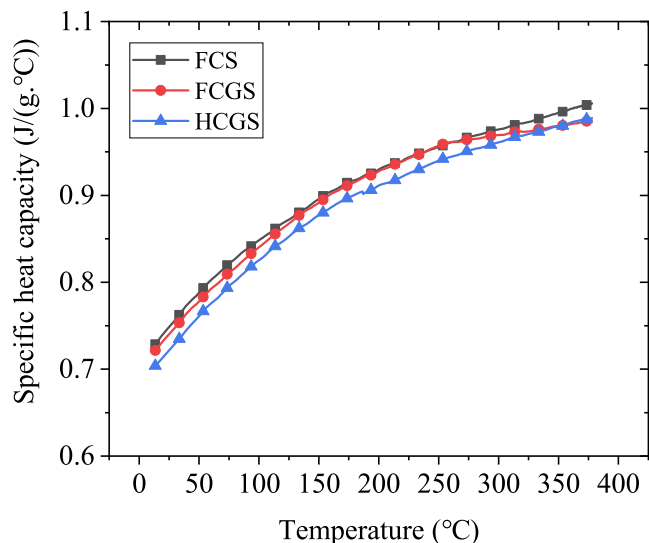


Fig. 7. The specific heat capacities of the three coal slags.

3.2.3. Heat capacity

Heat capacity is the product of density and specific heat capacity. For thermal energy storage systems, the heat capacity of the storage material is a critical index for evaluating storage performances. Figs. 8–10 show the heat capacities of the three coal slags with temperature. As the density of the material keeps almost constant with the increasing temperature under the current tests, the heat capacity and specific heat capacity of the material have a similar changing trend. When the temperature increases from 10 °C to 380 °C, the heat capacities of FCS, FCGS and HCGS increased from 2218 kJ/(m³·°C), 2104 kJ/(m³·°C) and 1943 kJ/(m³·°C) to 3062 kJ/(m³·°C), 2876 kJ/(m³·°C) and 2730 kJ/(m³·°C), respectively. Meanwhile, Figs. 8–10 also show the changes of energy storage densities per unit volume and unit mass of the three materials with temperature. The energy density per volume unit is the total amount of heat required to raise one unit of volume of the material from 0 °C to a specific temperature (Agalit et al., 2020a, 2017). The energy density per mass unit is the total amount of heat required to raise one unit of mass of the material from 0 °C to a specific temperature (Agalit et al., 2020a, 2017). For example, the energy storage density per unit volume of the FCS is 1037 MJ/m³ at 380 °C. It means that the total heat required to raise FCS per cubic meter from 0°C to 380 °C is 1037 MJ. As shown in the figure, the energy storage density of the three materials increases with temperature and energy storage capacity. At 380 °C, the three materials’ energy storage densities per unit volume are 1037 MJ/m³, 986 MJ/m³ and 920 MJ/m³, respectively. According to the energy storage density of similar industrial by-products reported in previous studies (750–1550 MJ/m³) (Agalit et al., 2020a; Ortega-Fernández

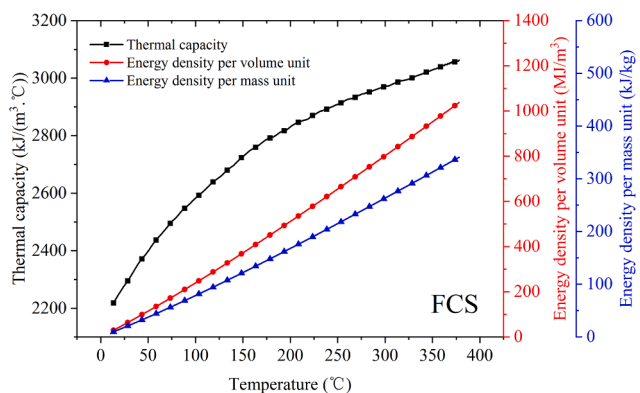


Fig. 8. Heat capacity and energy storage density of FCS.

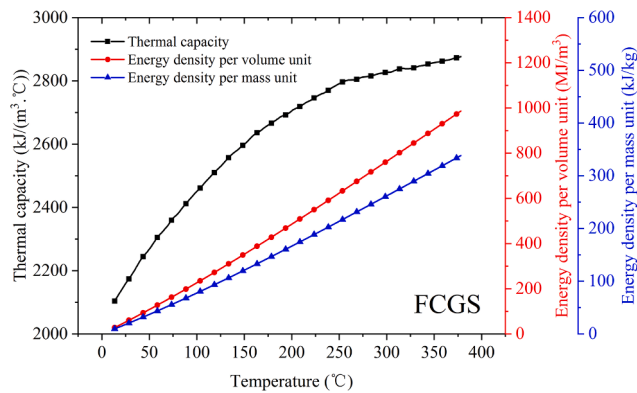


Fig. 9. Heat capacity and energy storage density of FCGS.

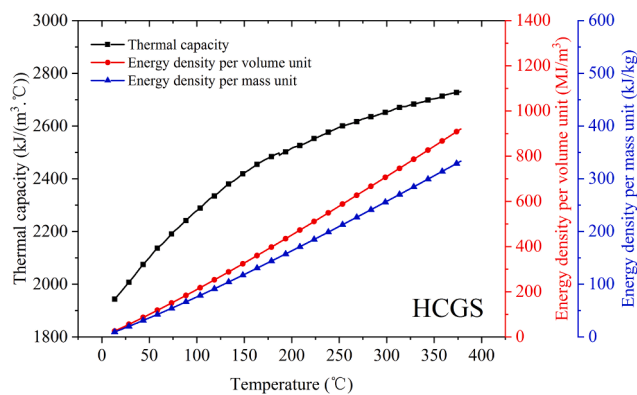


Fig. 10. Heat capacity and energy storage density of HCGS.

et al., 2015; Agalit et al., 2017), the current energy storage materials have good energy storage densities.

3.2.4. Thermal stability

Figs. 11–13 show the thermogravimetric test results of three coal slags. Two heating and cooling cycles were performed at 50–1000 °C. And the heating and cooling rates were 10 °C/min. The three samples showed no significant mass loss during thermal cycles, indicating that the combustion of the coals is sufficient, and no organic matter and combustible matter remained in the coal slags. Among them, the weight change of FCS in the thermal cycle is negligible, which has excellent thermal stability. This result can be attributed to the FCS’s high degree

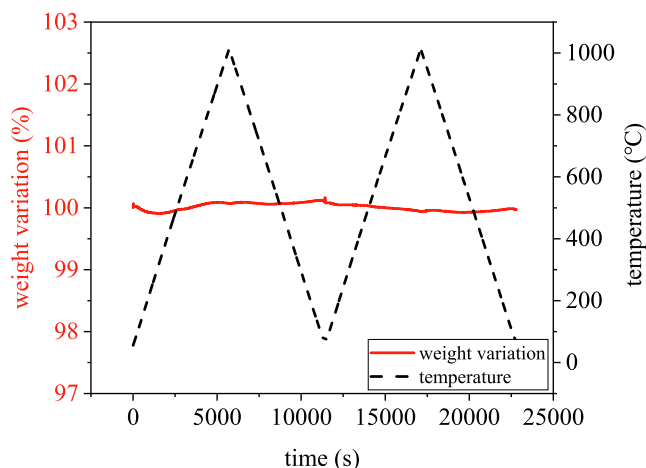


Fig. 11. TGA curve of FCS for two thermal cycles (50–1000 °C).

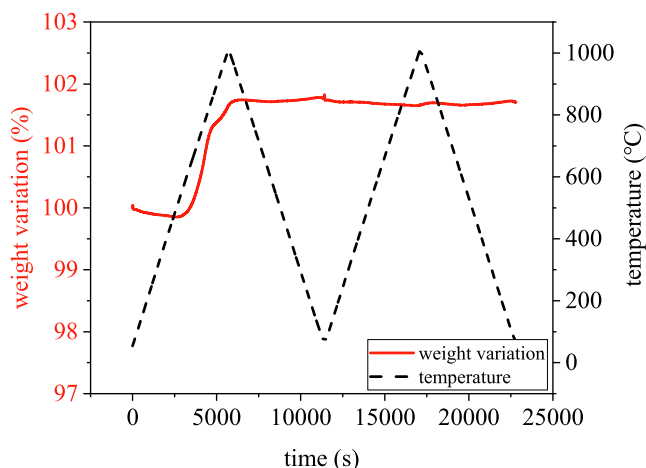


Fig. 12. TGA curve of FCGS for two thermal cycles (50–1000 °C).

of crystallization (Py et al., 2011; Faik et al., 2012; Meffre et al., 2015). However, FCGS and HCGS have worse thermal stability, attributed to the glass characteristics and low degree of crystallization of granulated slags (Py et al., 2011; Faik et al., 2012; Meffre et al., 2015).

It is noteworthy that the thermogravimetric curves of the two granulated slags have similar variation patterns. During the first thermal cycle, the sample's weight decreased slightly below ~470 °C due to the evaporation of water on the surface of the powder sample and the removal of bound water inside the powder (Agalit et al., 2020a; Jemmal et al., 2016). From 470 °C to 1000 °C; the mass of the sample increases by 1.5–2%, attributed to the oxidation of the metal components and the formation of new phases under the air atmosphere (Agalit et al., 2020a, 2017). Above 1000 °C; the sample mass tends to be stable. This result is consistent with previous studies (Py et al., 2011; Faik et al., 2012; Meffre et al., 2015). The original material has an unstable structure; changing from amorphous to crystalline form during the first heating process. Afterward, the crystalline structure formed in the first thermal cycle is quite stable, and the chemical composition and microcosmic structure hardly change in the second cycle (Py et al., 2011; Faik et al., 2012;

Meffre et al., 2015).

In reference (Agalit et al., 2020a), the mass of the coal cinder decreased at 550 °C due to carbonate decomposition, but no similar phenomenon occurred in the three coal slags in the current study. This difference shows that coal slags' chemical compositions and thermal stabilities are different due to different coal types and diverse combustion conditions, which proves the necessity of current research. According to the thermogravimetric test results, FCS has good thermal stability between 50 and 1000 °C, and can store heat in ultra-high temperature of 1000 °C. However, FCGS and HCGS have worse thermal stability and are only suitable for heat storage at low temperatures below 500 °C. Besides, if granulated slag is required to store heat at high temperatures above 500 °C, it should be pre-treated to form a stable crystalline phase before heat storage (Py et al., 2011; Faik et al., 2012; Meffre et al., 2015).

3.2.5. Thermal durability

Good thermal durability is very significant for energy storage materials. The thermal tolerance of materials is affected by the composition and size of materials, the operating temperature, and the heating and cooling rates. Figs. 14–16 show the morphology changes of three coal slags before and after the heat resistance test. Table 4 shows the mass changes of three coal slags before and after the heat resistance test.

The above experimental results show that before and after the heat tolerance test, the FCS remains in a mechanical stable state without the significant morphology change and mass loss. For the two kinds of granulated slags, the slag particles were broken with the mass loss after 100 thermal cycles. Moreover, it is worth noting that some slag fragments were found in the muffle furnace. It is speculated that two types of granulated slags were broken, and the slag fragments splashed out of the porcelain boat during heating. These slag fragments may explain the mass loss of the two granulated slags to a certain extent. Fig. 17 shows the pattern of slag fragments. In conclusion, FCS shows excellent thermal durability, while the two granulated slags show poor heat tolerance under the current test conditions (300 °C–500 °C). To improve the thermal stability and thermal tolerance of granulated slags, it is an excellent choice to conduct the reforming process after high-temperature crystallization treatment (Agalit et al., 2020b).

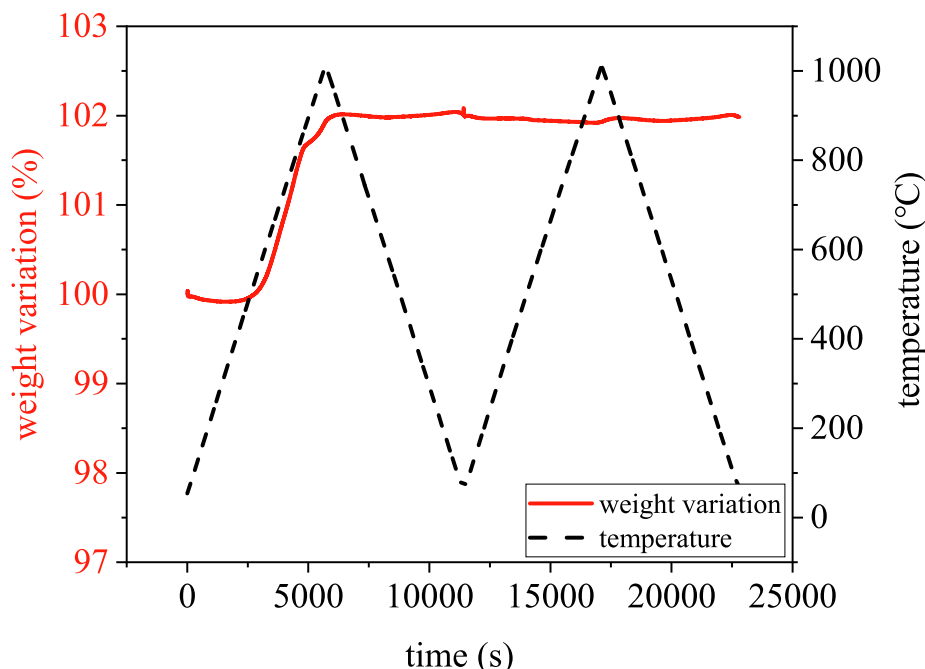


Fig. 13. TGA curve of HCGS for two thermal cycles (50–1000 °C).

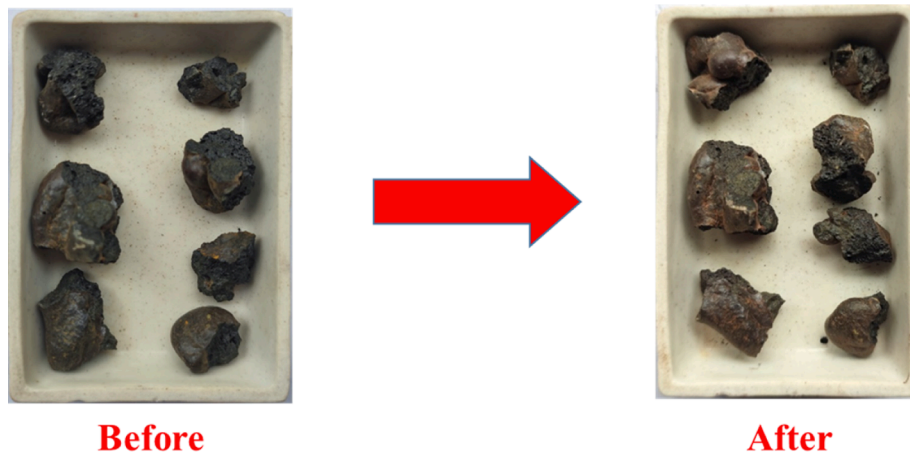


Fig. 14. Morphology change of FCS before and after thermal cycle test.

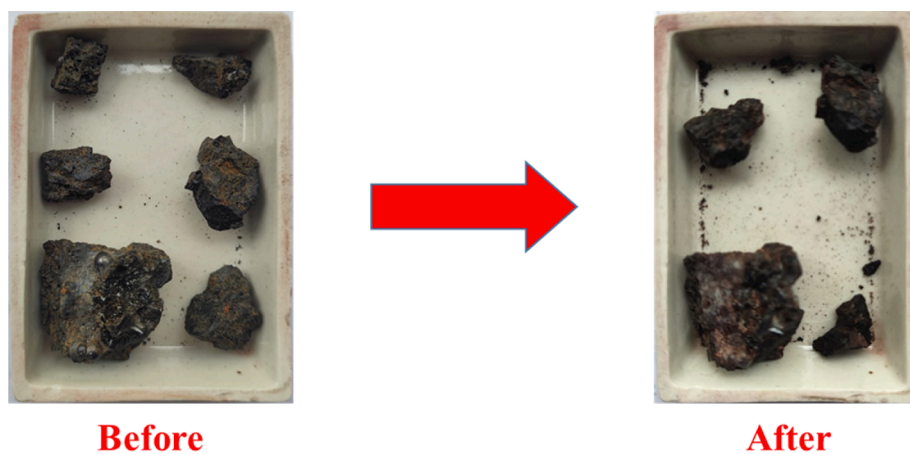


Fig. 15. Morphology change of FCGS before and after thermal cycle test.

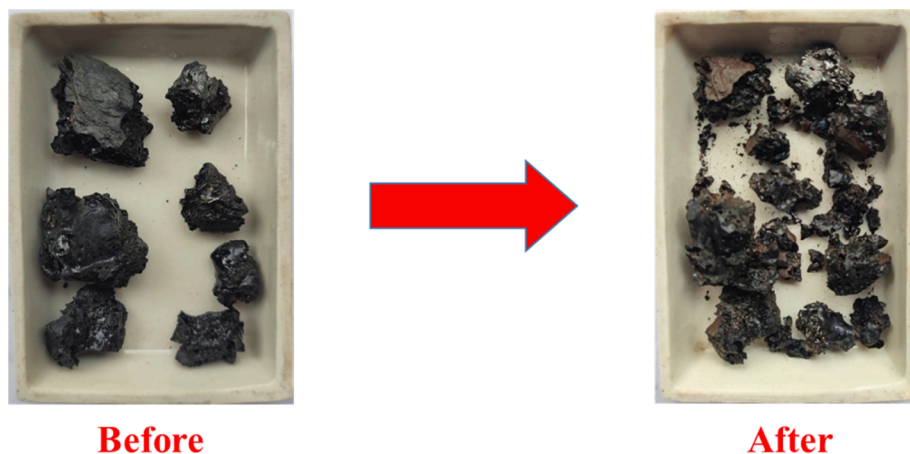


Fig. 16. Morphology change of HCGS before and after thermal cycle test.

3.3. Applicability of coal slag as thermal energy storage material

In conclusion, the three kinds of coal slags have excellent thermo-physical properties. Among them, FCS is a successful sensible heat storage alternative material with superexcellent thermal stability, which can be directly used for the packed beds storage application. Meanwhile, its wide operating temperature range makes the new generation of

1000 °C ultra-high temperature storage system more competitive and attractive. The granulated slags need to be treated at high temperatures to improve thermal stability and thermal tolerance before being used as energy storage materials.

The application of coal slag in energy storage systems has multiple benefits (Henry and Prasher, 2014; Calvet et al., 2013; Ortega-Fernández et al., 2015). First, recycling waste reduces the costs of TES systems

Table 4

Mass and morphology changes of three slag samples before and after thermal cycle test.

Materials	Mass change (%)	Morphology change
FCS	0.05	No sign of disintegration or friability
FCGS	−12.04	grain breakage
HCGS	−3.09	grain breakage



Fig. 17. The slag fragments in the muffle furnace during the thermal cycle test.

and electricity generation. Second, using recycled materials rather than new raw materials (other sand and rocks) avoids the depletion of natural resources and use conflicts. Third, the valorization of coal slags can relieve the pressure of landfills to a certain extent, resulting in environmental benefits.

4. Conclusions

In this paper, the density characteristics, thermophysical characteristics, thermal stabilities and thermal durabilities of three kinds of solid wastes from coal-fired power plants (Fukang coal slag, Fukang coal granulated slag, Hongshaquan coal granulated slag) were characterized by a series of tests to evaluate their applicabilities as sensible heat storage materials. The main conclusions are as follows:

The apparent densities of the three slags are 2761–3044 kg/m³. When the temperature increases from 10 °C to 380 °C, the specific heat capacities of the three slags increase from 0.70 J/(g·°C) to 1.00 J/(g·°C). At 380 °C, the energy storage densities per unit volume of the three materials are 1037 MJ/m³, 986 MJ/m³ and 920 MJ/m³, respectively, which are considerable energy storage densities.

Thanks to the high degree of crystallization, fukang coal slag has excellent thermal stability and durability, and can be directly used to store energy in the high temperature of 1000 °C. However, the two granulated slags' thermal stabilities and thermal durabilities are worse due to the low crystallization degree. After 100 thermal cycles at 300–500 °C, the particles of both granulated slags degraded with mass loss, which is not suitable to be directly used as energy storage materials. To improve the thermal stabilities and thermal durabilities of granulated slags, it is an excellent choice to conduct a reforming process after high-temperature crystallization treatment.

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.

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