Research on technical Optimization of solid regenerative electric Boiler

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Abstract—This paper briefly introduces the principle and device of solid heat storage in electric boiler, analyzes the advantages and necessity of solid heat storage boiler technology. The development status and application examples of heat storage technology for solid thermoelectric boiler are introduced, and the efficiency of solid heat storage device is verified through experiments.

1. Introduction
Regenerative electric boiler has the characteristics of low pollution, load transfer and high operating efficiency. It is a new type of energy storage system that can be widely used in power generation and electricity consumption. The time-shifting characteristics of load are utilized to assist the thermal power system to participate in peak adjustment, and electric energy is replaced by electric heating transformation at the user end and gradually adopting wind power heating \cite{1}.

This article first introduces the heat storage principle and device of solid heat storage electric boiler, analyzes the advantages of heat storage electric boiler technology and the necessity of developing solid heat storage electric boiler technology. Secondly, the development status of solid thermal storage electric boiler technology and related improvement research on existing technology are introduced. Finally, through the analysis of the results obtained in the actual engineering application, reasonable suggestions are put forward for the deficiencies in the technological development process.

2. Solid regenerative electric boiler technology
During the off-peak period, the heating wire increases the temperature of the regenerator to about 750\degree C, and stops heating and enters the exothermic stage during the non-off-peak period. The circulating fan is used to take the heat out of the energy storage body, and the circulating hot water (or other fluids) is heated through the air-water heat exchanger to achieve the purpose of cooling the energy storage body \cite{2}. The process flow is: heating \rightarrow solid heat storage \rightarrow heating \rightarrow heat exchange \rightarrow heating terminal. Solid form material has the characteristics of high melting point, high density and fast thermal conductivity. Solid heat storage technology is based on this property\cite{3}.

3. Research progress of solid regenerative electric boiler technology
M.M. Sorour\cite{4} studied a small-size heat storage unit with gypsum rock filling layer. Through experiments, it was concluded that the height of packed bed, the flow rate of heat exchange fluid, the input flow rate and the diameter of heat storage material particles all affect the efficiency of heat storage. Bai\cite{5,6} explained the distribution law of internal temperature field of heat accumulator under different
working conditions, the change law of heat storage and temperature in this process, and analyzed the factors affecting the efficiency of heat storage process. Jia Li et al. obtained the axial temperature distribution curve of heat exchange gas in the heat storage solid and distributed in the energy storage body by optimizing the heat storage and heat transfer process and the heat release duration of the ceramic honeycomb heat accumulator. The influence of inversion time, flue gas inlet temperature, height of regenerator and specific heat of regenerator material on thermal saturation time is obtained. Zhang et al. analyzed the economy of solid heat storage heating system and found that the centralized heating method using traditional energy of coal and natural gas has higher energy consumption and cost than the heating system of solid heat storage thermoelectric heater, and the latter has better economy. Based on the above-mentioned experimental research, the factors that affect the performance of the heat storage boiler are basically clear, and scholars have made further optimization explorations on different influencing factors.

3.1. Optimization of heat transfer effect of heat storage body
Tamme R et al. developed solid heat storage materials such as high-temperature concrete and cast ceramics by studying the properties of sand and basalt as heat storage materials. Doerte Laing and others conducted a large number of experiments on concrete heat storage technology, and developed and tested high-temperature concrete heat storage demonstration modules. Based on testing and verification, it is believed that high-temperature concrete is an ideal solid heat storage material. Because it has the characteristics of high strength, strong economic applicability, and low processing difficulty. After analysis, it is concluded that the use of high thermal conductivity materials can reduce heat exchange tubes by 60%.

3.2. Optimization of heat storage and release time
Roman Domanski et Gama Fellah studied the complete heat transfer process of the sensible heat storage system, used the analysis method of thermodynamic economics to obtain the optimal number of heat transfer units, heat storage time and exergy efficiency of the system using and the law of influence of “money value” at different times. Li Chaoxiang conducted experimental studies on the heat exchange process of the regenerative heat exchanger and proved that the heat exchange efficiency is affected by the length of the heat exchange time and the flow rate at the cross section of the heat exchanger.

Li Huijian studied the heat storage and release performance of solid heat storage radiators and came to the conclusion: The room temperature was maintained at 18°C through the power leveling for 2 hours during the day. Therefore, during the heat release stage, adding electricity for two hours is an effective way to increase the heat storage rate.

3.3. Optimization of heat storage and release time
In order to find the ideal heat transfer structure, Tang Zhiwei et al. came to the conclusion after a series of numerical simulations: The heat exchange effect of the heat storage module of the sawtooth plate shunt channel is better. Xing Zuoxia et al. conducted a study on the factors affecting the heat type of the heat storage module in the solid heat storage device and concluded that: The porosity ratio is a key factor that affects the temperature distribution of the regenerator, but it has a small effect on the thermal deformation. The regenerator structure with a porosity ratio of 20% has a smaller thermal deformation and a more uniform temperature distribution. The inlet temperature has a greater impact on thermal deformation. When non-metallic materials such as magnesium oxide are used as the heat storage body, the inlet temperature is set to 800°C.

4. Application example of solid regenerative electric boiler
The project is Shandong (Qingdao) International Shipping Center project, located in Qingdao Economic Development Zone, Located in Qingdao Economic Development Zone, 5A class. A super high-rise office building. The local government will reward 440 yuan per kW for the permanent power saving
and peak power load transfer achieved through the implementation of energy efficiency power plant and peaking and valley shifting technology [24].

Combined with the local actual situation, two alternative heat source schemes are proposed, by comparing the initial investment and the entire life cycle of all running costs, it is clear that using regenerative gas hot water boiler and solid investment in the early phase is similar as the electric boiler heating, operating cost, but years of solid regenerative electric boiler the gas vacuum hot water boiler can save 1,112,600 yuan a year, after the entire life cycle after the operation, A total of 21,829,500 yuan can be saved, and the economic benefit is quite remarkable.

5. Experimental verification

In order to verify the heat storage and release efficiency of the electric heat storage device, a small solid electric heat storage device is built in this paper. The system principle is shown in Fig.2. The external dimension (length × width × height) of this device is 2200×1680×2450 (mm), and the rated electric power is 50kW. The heating device uses electric heating wire to heat, and the heat storage material is magnesium oxide brick. In order to study the heat release efficiency of the device, the heat storage and release cycle is tested and calculated.

![System diagram of solid regenerative electric boiler installation](image)

**Fig. 1 System diagram of solid regenerative electric boiler installation**

5.1. Test results

In this test, the heat storage time was from 13:00 to 23:00 on the 11th, and the heat release time was from 23:01 to 18:00 on the 12th. The accumulated heat consumption from the beginning to the end of heat storage was 602kWh, and the average thermostatic power was 60.2kW. The temperature - time curves of heat storage and release are shown in Fig. 2 and Fig. 3 respectively. According to the calculation, the heat release in the heat storage process is 585.05MJ, the heat release process is 1486.93MJ, the total heat release is 2071.98 MJ. The average water flow rate in the heat storage process and heat release process is 15.35m³/h. The average temperature between the equipment during the test was 35.2°C.
5.2. Calculation of loss and heat balance

Fan power is 0.45kW, according to a cycle of 24h, power consumption =0.45*24*3600=38880kJ. The device surface test results are shown in the follow table.1-3.

Table 1. Test results of surface temperature of the device.

| Part         | Column A (t) | The surface temperature°C | The average temperature°C |
|--------------|--------------|----------------------------|----------------------------|
| The left wall | 35.2         | 41.2                       | 37.6                       | 36.2                       | 36.8                       | 38.0                       |
| The right wall| 35.2         | 41.2                       | 40.2                       | 37.5                       | 35.4                       | 38.6                       |
| The front wall| 35.2         | 38.3                       | 37.6                       | 38.5                       | 37.5                       | 38.0                       |
| The back wall | 35.2         | 38.7                       | 37.5                       | 41.5                       | 37.2                       | 38.7                       |
| Top          | 35.2         | 39.2                       | 38.5                       | 41.3                       | 38.3                       | 39.3                       |
| The average  | 35.2         | 39.7                       | 38.3                       | 39.0                       | 37.0                       | 38.5                       |
Table 2. Heat dissipation on the device body surface.

| Part        | Mean surface temperature °C | Mean surface temperature °C | Cooling area m² | Heat flow value kJ/m²h | Heat release kJ/h | ε  | A  |
|-------------|-----------------------------|-----------------------------|-----------------|------------------------|-------------------|----|----|
| left wall   | 38.0                        | 35.2                        | 5.49            | 89.2                   | 489.4             | 0.85| 9.2|
| right wall  | 38.6                        | 35.2                        | 5.49            | 111.8                  | 613.3             | 0.85| 9.2|
| Front wall  | 38.0                        | 35.2                        | 5.10            | 90.1                   | 459.8             | 0.85| 9.2|
| back wall   | 38.7                        | 35.2                        | 5.10            | 117.6                  | 600.1             | 0.85| 9.2|
| Top         | 39.3                        | 35.2                        | 5.20            | 154.4                  | 803.2             | 0.85| 11.72|
| A combined  |                             |                             |                 |                        | 2966              |     |    |
| Working time (h) |                 |                             |                 |                        |   24              |     |    |

Table 3. Test balance.

| Heat input | Heat output |
|------------|-------------|
| Heat MJ    | Heat MJ     |
| %          | %           |

| Input item                  | Heat MJ | % | Output item                                          | Heat MJ | % |
|-----------------------------|---------|---|-----------------------------------------------------|---------|---|
| Power consumption of heat storage device | 2167.2  | 100 | Heat release from the heat storage process         | 585.05  | 27.00 |
|                             |         |    | Heat release from the exothermic process           | 1486.93 | 68.61 |
|                             |         |    | Heat loss from the surface of the device           | 71.14   | 3.28 |
|                             |         |    | Power consumption of device fan                   | 38.88   | 1.79 |
|                             |         |    | Positive and negative balance difference         | -14.80  | -0.68 |
| A combined                  | 2167.2  | 100 | A combined                                          | 2167.20 | 100 |

6. Conclusion

Solid heat storage is a kind of technology that can effectively utilize wind power and photovoltaic power reasonably, so as to achieve the goal of peak cutting and valley filling. It has the advantages of environmental protection, energy saving and safety. It is found that high temperature resistant concrete and magnesia brick are good heat storage materials with comprehensive economic practicability, and magnesia brick is widely used in engineering tests. In the exothermic stage, with the reduction of the brick temperature, the heat dissipation power of the radiator is also reduced, which can be improved by adding flat electricity for 2 hours; in the heat accumulator, the thermal efficiency can be improved by dividing the heat accumulator, and the temperature distribution is more uniform when the pore ratio is 20%. And after practical engineering and experimental verification, the use of solid electric heat storage device is more economical in the long run. According to the calculation in the experiment in this paper, the tested positive balance efficiency is 27.00+68.61=95.61%. Inverse equilibrium efficiency =100-3.28-1.79=94.93%, the positive balance difference was 0.68%, and the positive balance efficiency was 95.61%. That is, the heat storage and release rate of the experimental solid electric heat storage device is 95.61%, which can achieve the goal of converting low valley electricity into heat energy efficiently for utilization.

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References

[1] Li Jianlin, Xie Zhijia, Li Dexin, et al. Research on key technology of regenerative electric Boiler to improve the absorption capacity of wind Power [J]. Electrical appliances and energy efficiency management technology,2018(01):1-7.

[2] Luo Yong, Chen Peng. Study on consistency of temperature drop of regenerator group during heat release of solid thermoelectric boiler. [J] Journal of Shijiazhuang Tiedao University (Natural Science Edition), 2020,33(01):116-121.

[3] Zhu Weidong, Ren Zhiyuan, Xiang Chengbing, et al. Solid heat storage technology and application[J] China comprehensive utilization of resources, 2018,36(09):77-79.

[4] Sorour M M. Performance of a small sensible heat energy storage unit[J]. Energy conversion and management, 1988, 28(3): 211-217.

[5] Li Han, Bai Shengxi, Huang Yimin. Heat storage principle and heat transfer analysis of electrothermal solid heat storage device[J] Power Plant Systems Engineering,2003, 19(3):29-30.

[6] Bai Shengxi, Zhu Changlin. Experimental study on thermal efficiency of solid electric heat storage Device [J]. Heilongjiang electric power,2005,27(4):257-259.

[7] Jia Li, Mao Ying, Yang Lixin. Numerical simulation of temperature distribution and thermal saturation time of heat storage and heat transfer [J]. Journal of basic science and engineering,2006,14(2):282-290.

[8] Zhang Bin, Wang Zhanjun. Research on the test of solid Regenerative Electric Heater heating system [J]. Low Temperature Building Technology,2010(010):103-104.

[9] Tamme R, Laing D, Steinmann W D. Advanced thermal energy storage technology for parabolic trough [J]. Journal of Solar Energy Engineering, 2004, 126(2): 794- 800.

[10] Laing D, Steinmann W D, Tamme R, et al. Solid media thermal storage for parabolic trough power plants[J]Solar energy,2006,80(10):1283-1289.

[11] Tamme R, Laing D, Steinmann W D. Advanced thermal energy storage technology for parabolic trough[C]/ ASME 2003 International Solar Energy Conference. American Society of Mechanical Engineers, 2003:563-571.

[12] Tamme R, Laing D, Steinmann W D, et al. Innovative thermal energy storage technology for parabolic trough concentrating solar power plants[C]. In: Proceedings of Euro Sun 2002, The 4th ISES Europe Solar Congress, Bologna, Italy.

[13] Laning D, Lehmann D, Fib M, et al. Test results of concrete thermal energy storage for parabolic trough power plants [J]. ASME Journal of Solar Energy Engineering, 2009, 131(4):410071-410076.

[14] Laning D,Steinmann W,Fib M,et al. Solid media thermal storage development and analysis of modular storage operation concepts for parabolic trough power plants [J]. ASME Journal of Solar Energy Engineering, 2008, 130(1): 11006.

[15] Laning D, Bahl C, Bauer T, et al. High-Temperature Solid-Media Thermal Energy Storage for Solar Thermal Power Plant [J]. Proceedings of the IEEE, 2012, 100(2): 516-524.

[16] Tamme R, Steinmann W D, Laing D. High temperature thermal energy storage technologies for power generation and industrial process heat[C]. In: Proceedings of FUTURES TOCK 2003,9th International Conference on Thermal Energy Storage, Warsaw, Poland.

[17] Domański R, Fellah G. Thermoeconomic analysis of sensible heat, thermal energy storage systems[J]. Applied thermal engineering, 1998, 18(8): 693-704.

[18] Domański R, Fellah G. Exergy as a tool for designing and operating thermal storage units[J] Journal of Power Technologies, 1995, 81: 23-45.

[19] Li Chaoxiang, Lu Zhongwu. Mathematical statistical analysis of heat transfer problem in packed Bed [J]. Journal of Northeastern University: Natural Science, 1998, 19(5): 484-487.

[20] Li Chaoxiang, Cai Jiuju. Experimental study on thermal characteristics of packed bed regenerative heat exchanger [J]. Metallurgical energy,1999,18(2): 39-44.
[21] Li Huijian, Jia Yugui, Zhang Hongxi, et al. Journal of hebei institute of civil engineering and architecture, 2017, 35(04): 76-78+89.

[22] Tang Zhiwei, Hu Mengdi, Zhang Xuefeng, et al. Journal of Beijing university of technology, 2019, 45(12): 1261-1268.

[23] Xing Zuoxia, Zhao Haichuan, Ge Weichun, et al. Solid electric energy storage system thermal deformation analysis and structure optimization research [J/OL]. Cheng for thermal energy and power, 2020 (01): 98-105 [2020-05-26].

[24] Hu Songtao, Song Renjiang, Liu Guangcheng, et al. Application of solid regenerative electric boiler in air conditioning system of an office building in Qingdao [J]. Hvac, 2015, 45(12): 25-29.