Experimental Study on a Solid-Storage Steam Generation System for Cascaded Thermal Energy Utilization

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Abstract: With the continuous and ongoing advancement of the national "dual carbon" goals, it has become an imperative task to accelerate the reform and adjustment of the energy structure. To achieve these "dual carbon" goals, we must drive the peaking of coal and oil consumption, vigorously develop non-fossil energy sources, and continuously increase the proportion of renewable energy in the overall energy structure. Traditional steam production methods, which have long been used in industrial production, are increasingly struggling to adapt to the current requirements of energy transition and environmental protection. Against this background, a solid thermal storage steam production system was proposed as an alternative solution; however, the existing solid thermal storage steam production systems still have obvious defects, mainly manifested in high return air temperatures and heat accumulation in the storage media, which ultimately lead to serious energy waste. To solve the problems of high return air temperatures and heat accumulation in the storage media of existing solid thermal storage steam production systems, this study proposes a solid thermal storage steam generation system based on cascaded thermal energy utilization. Specifically, this newly proposed system takes full advantage of the high-temperature thermal energy from the recirculated air to generate steam, and at the same time, it utilizes the low-temperature thermal energy of the recirculated air to preheat the feedwater. In this way, the system not only realizes the cascaded utilization of the recirculated air's thermal energy, but also effectively improves the overall efficiency of the system and the heat utilization rates, and also successfully addresses the heat accumulation problems that exist in the storage media of traditional systems. The key part of the cascaded thermal energy utilization strategy adopted by this system is to install a waste heat recovery device in the system's return air duct. In order to verify whether this strategy is effective and to study how it affects various parameters of the system, the research team built a special test bench for this solid thermal storage steam generation system. After carrying out a series of tests on this test bench and conducting detailed data analysis, the test results show that turning on the waste heat recovery device can significantly improve the thermal performance of the system. In detail, after the waste heat recovery device is activated, the return air temperature of the system can drop by as much as 28.7°C. When the system is operating under the condition of 0.5 MPa, the steam generation duration of the system can be extended by 29 to 42 minutes, and the usable temperature range of the heat storage medium can be increased by 43 to 54°C. These test results further confirm that activating the waste heat recovery device can effectively improve the system efficiency and the thermal utilization rate of the heat storage medium. Specifically, under the 0.5 MPa operating condition, the system efficiency is increased by 8.88%, and the thermal utilization rate of the heat storage medium is increased by 7.13%. Therefore, the installation of a waste heat recovery device in the return air duct of the solid thermal storage steam generation system can effectively alleviate the problem of heat accumulation in the heat storage medium, significantly improve the system efficiency and the thermal utilization rate of the heat storage medium, and ultimately achieve cascaded heat utilization. This research result can provide a valuable reference for the practical application and promotion of the solid thermal storage steam generation system based on cascaded thermal energy utilization in industrial production.

Keywords: Cascaded Thermal Energy

Utilization; Thermal Storage Medium Heat Utilization Rate; Solid Thermal Storage; Steam Generator

1. Introduction

With the continuous advancement of the "dual carbon" goals, China and other major global economies have entered a critical phase in their pursuit of these objectives. Substantial progress has been made in areas such as the energy revolution, industrial transformation, and carbon market development, while simultaneously facing multiple challenges, including energy security, cost balancing and global coordination. The 15th Five-Year Plan emphasizes accelerating the reform and adjustment of the energy structure, promoting the peak of coal and oil consumption, developing non-fossil energy sources, increasing the proportion of renewable energy, and advancing the energy system's shift from fossil fuel dominance to renewable energy reliance. Steam serves as an indispensable core heat source in industrial production. Traditional steam production models mainly depend on coal- and gas-fired boilers [1,2], which have long been troubled by prominent problems including low energy efficiency, high pollutant emissions, and poor operational stability. These models can no longer meet the strict requirements of energy transition and environmental protection policies in the new era. In this context, to satisfy the steam production needs of small- and medium-sized enterprises and conform to contemporary development requirements, the research team proposed a solid-state thermal storage steam generation system. This system makes use of surplus wind and solar power or electricity purchased during off-peak grid periods. Electrical energy is converted into high-temperature thermal energy through electric heating elements and stored in solid thermal storage materials. Then, according to the steam demand of industrial users, heat is transferred from the solid thermal storage material to low-temperature water via circulating air, turning it into steam for user supply.

In actual operation, existing solid thermal storage steam generation systems encounter challenges such as high return air temperatures, heat accumulation in storage media, and low system efficiency [3], which result in energy waste. Merely increasing the circulating air volume can no longer meet the system's operational needs. Taking both system efficiency and economic feasibility into account, this study proposes a solid thermal storage steam generation system that adopts cascaded thermal energy utilization. The system is equipped with a waste heat recovery device: high-temperature heat in circulating air is used for steam production, while low-temperature heat is employed to preheat the feedwater for the steam generator. This realizes the reuse of return air heat, thereby raising the feedwater temperature of the steam generator and reducing the return air temperature. The low-temperature return air entering the solid heat storage medium can absorb more heat, solving the problems of underutilized return air and insufficient heat utilization in the storage medium, and thus achieving cascaded heat utilization.

Domestic and international research on waste heat recovery shows that heat pipe heat exchangers are widely used for recovering waste heat from flue gas and other sources due to their high-efficiency heat transfer characteristics. Current research has mainly focused on system structural optimization, working fluid selection, and cascaded waste heat utilization, which enables efficient waste heat recovery, energy conservation, and carbon reduction [4-6]. Research on waste heat utilization methods includes conventional approaches as well as several new schemes, such as cascaded arrangement of heat exchangers, bypass flue technology, and the application of waste heat recovery devices [7-10]. Based on relevant domestic and international research, this study adopts a heat pipe heat exchanger as the waste heat recovery device.

2. Steam Production System for Cascaded Utilization of Thermal Energy

2.1 System Principle

This study focuses on the actual operation of existing solid-storage steam production systems. In the later stages of operation, the internal temperature of the solid-storage electric boiler gradually decreases, and the temperature difference between the circulating air and the thermal storage bricks inside the boiler narrows gradually. After the system operates for a period of time, the heat exchange efficiency between the circulating air and thermal storage bricks declines step by step. The circulating air can hardly absorb heat from the thermal storage bricks, which prevents the steam generator from obtaining sufficient heat. As a result, the rate of water vaporization inside the steam generator decreases, and the internal pressure drops gradually, failing to meet production demands. Therefore, this study proposes a solid thermal storage steam production system with cascaded thermal energy utilization. Specifically, a waste heat recovery device was installed in the return air duct between the steam generator and the circulation fan. This device is designed as a heat pipe heat exchanger, with an open water tank placed above the exchanger. The heat pipe exchanges heat with the return air and transfers the heat to the water in the tank. The cooled return air then passes through the circulation fan into the solid thermal storage unit, where it exchanges heat with the thermal storage bricks. The solid thermal storage steam production system equipped with this waste heat recovery device solves the problems of underutilized return air and unused residual heat in the thermal storage unit, achieves cascaded thermal energy utilization, and improves the system's operational efficiency. The components of the solid thermal storage steam generation system with cascaded thermal energy utilization are shown in Figure 1.

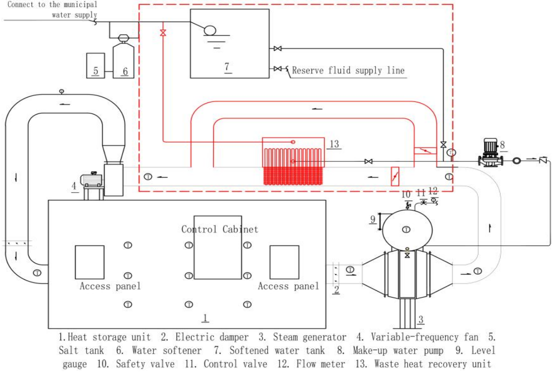

Figure 1. Solid Thermal Energy Storage-Based Steam Generation System with Cascade Utilization of Thermal Energy

Note: The sections outlined in red in the figure indicate the modifications made in this paper based on the existing system.

2.2 Design and Calculation of the Waste Heat Recovery System

Drawing on the principles of thermodynamics, fluid mechanics, and heat transfer, design and calculation work was carried out for the waste heat recovery system. Based on experimental data from an existing test bench, a heat pipe-type waste heat recovery system was designed. This system uses return air to preheat the feedwater of the steam generator, thus realizing the cascaded utilization of heat from circulating air. According to the operating strategy of the existing test bench, the steam generator was replenished in stages, with a replenishment frequency of once every 10 min. with a replenishment volume of approximately 0.015 m^3 per cycle. Owing to space constraints at the experimental bench site, the effective length of the heat pipe was set to 0.4 m, and the volume of the waste heat recovery system water tank was 0.15 m^3. The initial water temperature in the tank was 20°C. By using return air to preheat the feedwater for the steam generator, the water temperature is expected to reach 60°C. The formula for calculating the required heat transfer on the water side is as follows:

$$Q = c_{pw}\rho_w V_w\left(T_{wout} - T_{\text{win}}\right) \tag{1}$$

In the equation: c_{pw} --specific heat capacity of water;

The heat exchange efficiency of the waste heat recovery unit was set to 0.94. The heat recovered on the air side was calculated based on the law of conservation of energy using the following formula:

$$c_{pw}\rho_w V_w\left(T_{wout} - T_{\text{win}}\right) = c_{pa}\rho_a V_a (T_{aout} - T_{\text{ain}})t \times 0.94 \tag{2}$$

In the equation: c_{pa} -- specific heat capacity of air;

ρ_a -- density of air;

t -- heating time, min;

The heat transfer process between the circulating air and low-temperature water is a counter-current heat transfer. The formula for the logarithmic mean temperature difference [11] is:

$$\Delta T_m = \frac{\left(T_{ain} - T_{wout}\right) - \left(T_{aout} - T_{win}\right)}{\ln \dfrac{\left(T_{ain} - T_{wout}\right)}{\left(T_{aout} - T_{win}\right)}} \tag{3}$$

In the equation: ΔT_m --logarithmic mean temperature difference, °C;

The heat pipes in the waste heat recovery unit are made of red copper; the air side features annular flat fins, and the water side consists of smooth tubes. The correlation equation for convective heat transfer on the air side is as follows [11]:

$$N_{ua} = 0.1378 R_{ea}{}^{0.718} P_{ra}{}^{\frac{1}{3}} \tag{4}$$

In the equation: N_{ua} -- Nusselt number, $N_{ua}=\frac{h_a d}{\lambda_a}$, h_a is the heat transfer coefficient on the air side of the heat pipe, $\mathrm{W/(m^2 \cdot K)}$, d is the outer diameter of the heat pipe, m;

R_{ea} --Reynolds number for air, $R_{ea}=\frac{\rho_a v_a d}{\mu_a}$, v_a is the average flow velocity of air through the fins, m/s, and μ_a is the dynamic viscosity of air, Pa·s;

P_{ra} --Prandtl number;

Correlation equation for convective heat transfer on the water side:

$$N_{uw}=0.023R_{ew}^{0.8}P_{rw}^{0.4} \tag{5}$$

In the equation: N_{uw} -- Nusselt number, $N_{uw}=\frac{h_w d}{\lambda_w}$, h_a is the surface heat transfer coefficient on the water side of the heat pipe, $\mathrm{W/(m^2 \cdot K)}$, d is the outer diameter of the heat pipe, m;

R_{ew} -- Reynolds number of the water;

P_{ra} --Prandtl number;

Total heat transfer equation:

$$Q=K_T A_T \Delta T_m \tag{6}$$

Formula for the overall heat transfer coefficient:

$$\frac{1}{K_T}=\frac{1}{h_a}+\frac{\delta_{\text{Wall surfaces}}}{\lambda_{\text{Wall surfaces}}e}+\frac{1}{h_w}+R_{\text{grime}} \tag{7}$$

Calculations show that the required heat transfer capacity on the water side is 26.88 MJ, with an average heat transfer power of 22.4 kW, which classifies it as a small-to-medium power heat exchanger. In engineering applications, the typical heat pipe diameter range for such heat exchangers is DN15–DN25 [12]. Based on the calculation results and practical engineering experience, it was determined that the heat pipes for the waste heat recovery unit should be made of copper-aluminum finned heat pipes with a diameter of DN15. A total of 60 heat pipes will be used, arranged in 15 rows of four pipes each. The air side was equipped with aluminum fins with finned tube lengths of 280 mm, whereas the water side used smooth tubes. The dimensions of the water tank were 1210 mm × 477 mm × 336 mm. The waste heat recovery unit recovered approximately 22.4 kW of heat from the return air. The total heat transfer coefficient of the unit was determined to be 45 $\mathrm{W/(m^2 \cdot K)}$ with a total heat exchange area of 3.1 $\mathrm{m^2}$. The detailed design drawings of the waste heat recovery unit are shown in Figures 2 and 3.

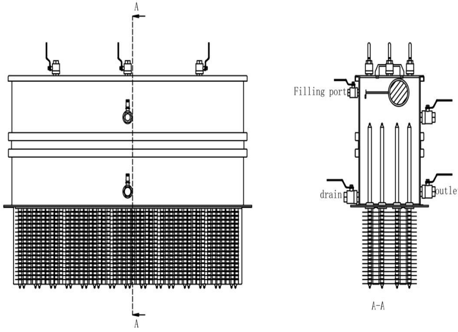

Figure 2. Front View and Cross-Section of the Waste Heat Recovery Unit

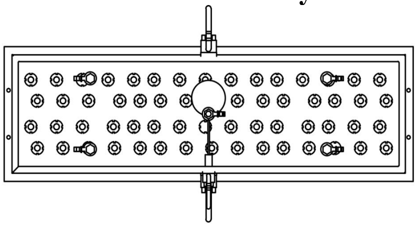

Figure 3. Top View of the Waste Heat Recovery Unit

3. Experimental Study

3.1 Objective of the Experiment

This experimental research on the solid-storage steam generation system with waste heat utilization was conducted to acquire key operational parameters during system operation, including the temperature of the heat storage medium as well as the pressure and temperature inside the steam generator. Additionally, it aimed to analyze how the circulating air temperature, steam generation efficiency, heat storage medium temperature, and system heat utilization rate change under different operating conditions after the installation of a waste heat recovery unit. The findings of this analysis are intended to provide a reference for the actual operation of the system.

3.2 Experimental Setup

The waste heat recovery unit was installed on the return air duct between the steam generator and the solid heat storage medium in the existing system. In practice, the waste heat recovery unit is only turned on during the later stages of system operation. After the circulation fan reaches full operating speed, the unit lowers the return air temperature, allowing more heat to be extracted from the storage medium and thus solving the problem of heat accumulation in the storage medium. The heat recovered by the unit was used to heat the water in the unit's tank, and this preheated water was then used to replenish the steam generator. For this reason, the inlet of the unit's tank should be connected to a water softener, while the outlet should be linked to the inlet of the original system's makeup water pump to supply water to the steam generator.

After installing the waste heat recovery unit, a bypass duct must be set up both before and after the unit. This bypass duct works alternately with the duct where the waste heat recovery unit is installed. Each duct should be equipped with a damper valve to make it easy to switch between the two ducts during system operation. A physical diagram of the waste heat recovery unit is presented in Figure 4, and the installation diagrams of the waste heat recovery unit and bypass duct are shown in Figure 5.

3.3 Experimental Protocol

To investigate the effects of adding a waste heat recovery unit to the system on operational parameters such as the temperature of the heat storage medium and the pressure and temperature within the steam generator, and to analyze the trends in system circulating air temperature, steam generation efficiency, heat storage medium temperature, and system heat utilization efficiency under different operating conditions before and after the addition of the waste heat recovery unit, various experimental conditions were established based on the actual conditions of the existing test bench by adjusting the steam parameters at the steam generator outlet and the operating time of the waste heat recovery unit, as shown in Table 1.

Figure 4. Inverted View of the Waste Heat Recovery Unit

Figure 5. Installation Diagram of the Waste Heat Recovery Unit and Bypass Duct

Table 1. Experimental Conditions

Test Conditions	Heat Storage Temperature (°C)	Steam Pressure (MPa)	Steam Flow Rate (kg/h)	Return Air Temperature When Waste Heat Recovery Unit Is On (°C)
1	750	0.5	100	202
2	750	0.5	100	198
3	750	0.5	100	194
4	750	0.5	100	Not activated

3.4 Analysis of Experimental Results

3.4.1 Analysis of solid heat storage media parameters

To analyze the patterns of change in the internal temperature of the solid heat storage media and the return air temperature when the waste heat recovery system is activated under 0.5 MPa operating conditions, the experimental data were organized as shown in Figure 6 below.

As can be seen from Figure 6, all test cases adopted 750°C as the initial central temperature of solid heat storage bricks. In the heat discharging process, circulating air kept exchanging heat with heat storage bricks, which steadily lowered the internal temperature of heat storage materials. Before the waste heat recovery unit was put into use, heat storage materials showed basically the same temperature falling rule in different tests. Their central temperature dropped sharply at the early experimental stage. After roughly 30 minutes of operation, the cooling speed slowed down obviously, and the temperature declined gently in the subsequent heat discharging period. In order to satisfy the steam production needs of the steam generator, researchers raised fan frequency in stages until the return air temperature hit 202°C, 198°C and 194°C respectively, and then started the waste heat recovery unit accordingly. After this equipment started working, the central temperature of heat storage bricks began to fall faster, and such trend lasted till the end of the test. It was found that the higher the return air temperature at startup, the lower the final temperature of heat storage bricks. Without adopting waste heat recovery measures in the whole experiment, the temperature of heat storage bricks decreased from 750°C to 385°C. The total heat discharging time was 202 minutes, and the effective steam production time was 174 minutes. When the recovery device was started at 194°C return air temperature, the final temperature fell to 342°C, with total heat discharge time of 239 minutes and steam production time of 211 minutes. When starting at 198°C, the final temperature dropped to 331.51°C, with 244 minutes of total heat discharge and 216 minutes of steam production. When starting at 202°C, the final temperature was 334.48°C, corresponding to 231 minutes of total heat discharge and 203 minutes of steam production.

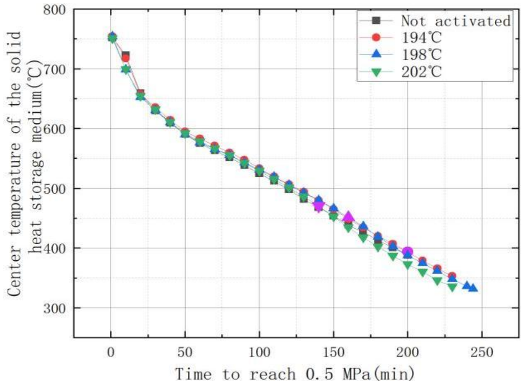

Figure 6. Temperature Profile of the Solid Heat Storage Medium at the Center under 0.5 MPa Operating Conditions

Note: The purple data points in the figure represent the time points when the waste heat recovery system was activated under each operating condition.

In practical application, waste heat recovery equipment can extend steam production time by 29 to 42 minutes, and expand the practical temperature scope of heat storage bricks by 43 to 54°C. Figure 7 displays the change law of inlet air temperature of heat storage materials after starting the waste heat recovery system under the working pressure of 0.5 MPa.

As shown in Figure 7, during the entire steam release process, the inlet air temperature of the heat storage unit was roughly the same under all operating conditions before the waste heat recovery system was activated, with a temperature deviation of less than 3°C. For this reason, it can be considered that the temperatures of the heat storage units were consistent prior to system activation. Under all test conditions, the inlet air temperature of the heat storage unit decreased gradually throughout the steam release process, starting from an initial 212°C.

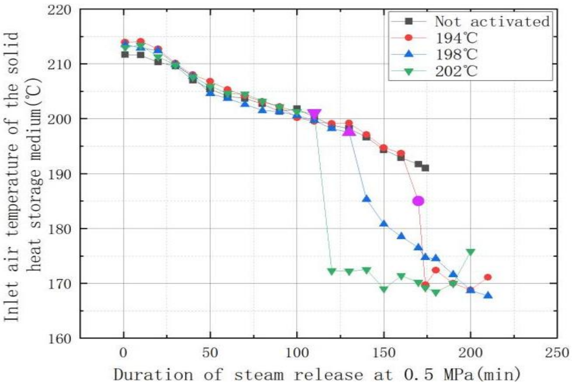

Figure 7. Variation in Inlet Air Temperature of the Heat Storage Medium at 0.5 MPa

Note: The purple data points in the figure represent the operating conditions under which the waste heat recovery system is activated.

In the test where the waste heat recovery unit was not activated at all, the lowest inlet air temperature at the end of the test was 191℃. When the return air temperature reached 202℃ and the waste heat recovery unit was turned on, the inlet air temperature dropped sharply from 201℃ to 172.3℃ immediately. After that, the inlet air temperature fluctuated around 172℃, and by 190 minutes, it started to rise again—increasing from 170℃ to 177.4℃, at which point the test came to an end. When the return air temperature reached 198℃ and the waste heat recovery unit was activated, the inlet air temperature dropped instantly from 196.9℃ to 180.8℃. Afterwards, the rate at which the inlet air temperature decreased slowed down, and the test ended after the temperature fell from 180.8℃ to 166.2℃. When the return air temperature reached 194℃, the activation of the waste heat recovery unit caused the inlet air temperature to drop suddenly from 191.8℃ to 172.4℃. Subsequently, the inlet air temperature fluctuated around 170℃ until the experiment was completed. The experimental results show that when the waste heat recovery unit was activated at a return air temperature of 198℃, the lowest inlet air temperature at the end of the experiment was 166.2°C. This represents a 24.8°C reduction in return air temperature compared to the condition where the waste heat recovery unit was not used. Under this operating condition, the waste heat recovery unit achieved the most effective utilization of return air heat.

3.4.2 Internal parameters of the steam generator

To analyze the patterns of change in the internal temperature of the solid heat storage medium and the return air temperature when the waste heat recovery unit was activated, the experimental data were organized as shown in Figures 8 and 9 below:

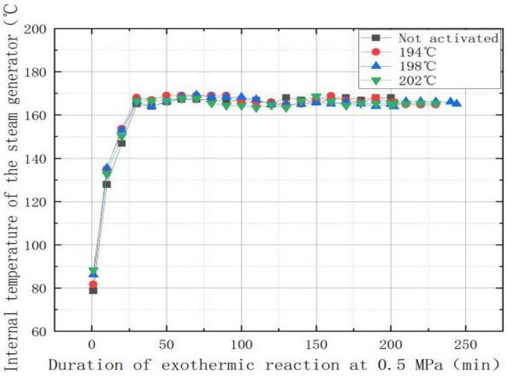

Figure 8. Temperature Distribution inside a Steam Generator Operating at 0.5 MPa

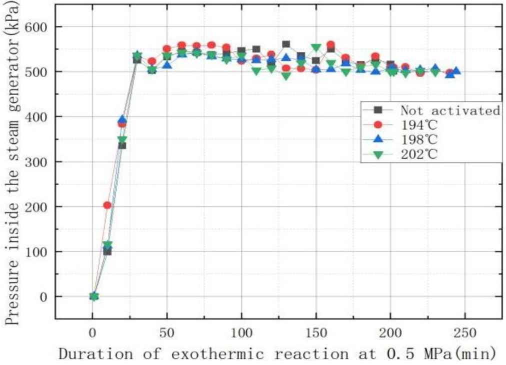

Figure 9. Internal Pressure Variation in a Steam Generator Operating at 0.5 MPa

As shown in Figure 8, at the start of heat release, the internal temperature of the steam generator under conditions where the waste heat recovery system is not operating is 78.76°C; under conditions where the waste heat recovery system is operating with return air at 202°C, the internal temperature of the steam generator is 88.32°C; under the condition of return air at 198°C with the waste heat recovery system activated, the internal temperature of the steam generator was 86.15°C; under the condition of return air at 194°C with the waste heat recovery system activated, the internal temperature of the steam generator was 81.70°C; during the system startup phase, the internal temperatures of the steam generators under all operating conditions rose rapidly and followed the same trend; 10 minutes after the fan started, the internal temperatures of the steam generators under all operating conditions exceeded 120°C; 30 minutes after fan startup, the internal temperature of the steam generator Under the condition without the waste heat recovery unit, the internal temperature of the steam generator was 165.01°C; the internal temperature of the steam generator under the condition with return air at 202°C and the waste heat recovery unit activated was 166.41°C; The internal temperature of the steam generator in the return air 198°C mode with the waste heat recovery unit activated was 166.28°C; The internal temperature of the steam generator in the return air 194°C mode with the waste heat recovery unit activated was 168.12°C; At this point, the steam discharge valve was opened to enter the steam discharge phase. The valve opening was controlled to maintain the steam outlet pressure and flow rate at 500 kPa and 100 kg/h, respectively. Immediately upon opening the steam discharge valve, the internal temperature of the steam generator began to decline. The most significant temperature fluctuation was observed under the condition where the waste heat recovery system was activated with a return air temperature of 198°C, with the internal temperature falling from 166.28°C to 164.01°C. Once steam production entered the stable phase, the internal temperature of the steam generator showed slight fluctuations up and down under all operating conditions, eventually stabilizing between 160°C and 170°C until the experiment finished.

As shown in Figure 9, during the system startup phase, the internal pressure of the steam generator rose rapidly from 0 kPa. The trend of pressure increase was consistent across all operating conditions. Thirty minutes after the fan started, the internal pressure of the steam generator was 525.59 kPa when the waste heat recovery unit was not activated. When the waste heat recovery unit was activated at a return air temperature of 202°C, the internal pressure of the steam generator reached 536.1 kPa. For the condition with the waste heat recovery unit activated at a return air temperature of 198°C, the internal pressure was 535.88 kPa. When the waste heat recovery system was activated at a return air temperature of 194°C, the internal pressure of the steam generator was 534.29 kPa. Notably, the internal pressure of the steam generator exceeded 500 kPa under all operating conditions.

At this point, the steam discharge valve was opened to enter the steam discharge phase. The opening degree of the control valve was adjusted to keep the steam outlet pressure and flow rate at 500 kPa and 100 kg/h, respectively. At the start of the steam discharge phase, the internal pressure of the steam generator dropped sharply the moment the steam discharge valve was opened. After 20 minutes, the steam pressure began to rise slowly under all operating conditions. After some time, the steam generator pressure undergoes four distinct cycles of decline and rise. Throughout the entire steam discharge process, the internal pressure of the steam generator remains above 500 kPa.

The 0.5 MPa test results indicate that, compared to operating without the waste heat recovery unit, activating it results in a longer steam generation duration and more stable temperature and pressure within the steam generator. Furthermore, activating the waste heat recovery unit promotes the utilization of solid heat storage media temperature and increases heat exchange capacity; the return air at 198°C with the waste heat recovery unit activated yields the best results in terms of heat storage media temperature utilization.

3.4.3 System efficiency analysis

The purpose of incorporating a waste heat recovery unit into the system is to achieve cascaded utilization of heat from the circulating air and to resolve the issue of heat accumulation within the heat storage medium. System efficiency and heat utilization rates of the heat storage medium were calculated using experimental data from various operating conditions. The experimental data for each operating condition are presented in Table 2, and the calculation formulas are shown in Equations (8) and (9):

$$\eta_1 = \frac{Q_S}{Q_E} \times 100\% \tag{8}$$

In the equation: Q_S --Heat output for steam production, kJ;

Q_E --Electricity consumption during the system's heat storage period, kW·h;

η_2 --Heat utilization efficiency of the heat storage medium, %;

$$\eta_2 = \frac{Q_U}{Q_{TS}} \times 100\% \tag{9}$$

In the equation: Q_U --Heat utilized by the thermal storage medium for steam production, kJ;

Q_{TS} --Total heat stored by the thermal storage medium, kJ;

η_2 --Heat utilization efficiency of the thermal storage medium, %.

Table 2. Experimental Data for Each Operating Condition

Operating Conditions	Steam Outlet Parameters	Steam Outlet Parameters Return Air Temperature When Waste Heat Recovery Unit Is On (°C)	Electricity Consumption (kW·h)	Initial Heat Storage Medium Temperature (°C)	Final Heat Storage Medium Temperature (°C)	Steam Production Duration (min)
1	500 kPa, 100 kg/h	202	610	750	334.48	202
2	500 kPa, 100 kg/h	198	614	750	331.51	216
3	500 kPa, 100 kg/h	194	628	750	342.85	211
4	500 kPa, 100 kg/h	Not activated	630	750	385.00	174

During the experiments under various operating conditions, the initial system parameters were kept consistent across all test conditions. Therefore, the calculated system efficiency and heat utilization rate of the thermal storage medium for each operating condition are shown in Table 3.

Table 3. Heat Utilization Data for the Thermal Storage Medium under Various Operating Conditions

Operating Condition	System Efficiency	Heat Utilization Rate of Heat Storage Medium
1	42.13%	55.40%
2	44.76%	55.80%
3	43.58%	54.29%
4	35.88%	48.67%

The calculation results indicate that the system efficiency and heat utilization rate of the heat storage medium are highest when the waste heat recovery unit is activated with return air at 198°C. The maximum system efficiency reached 44.76%, an increase of 8.88% compared to the condition where the waste heat recovery unit was not activated; the maximum heat utilization rate of the heat storage medium was 55.80%, an increase of 7.13% compared to the condition where the waste heat recovery unit was not activated.

4. Conclusions

This paper addresses the issue of low heat utilization efficiency in existing solid-storage steam generation systems by proposing a solid-storage steam generation system that employs cascaded heat utilization. Experimental results demonstrate that activating the waste heat recovery unit optimizes the system's thermal performance. Compared to the condition where the unit is not activated, the return air temperature can be utilized by an additional 24.8°C, steam production duration under 0.5 MPa conditions can be extended by 29-42 minutes, and the temperature utilization range of the heat storage medium increases by 43-54°C. Under conditions where the return air temperature is 198°C and the waste heat recovery unit is activated, the system efficiency and heat utilization rate of the heat storage medium are maximized, increasing by 8.88% and 7.13%, respectively, compared to conditions where the unit is not activated. Therefore, adding a waste heat recovery unit to a solid-storage steam generation system enables the cascaded utilization of heat from the recirculating air, thereby improving system efficiency and heat utilization rates and providing a reference for the practical operation of such systems.

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