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Design and optimization of a high-temperature Rankine Carnot battery

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ABSTRACT

As a low-cost grid-scale electrical storage, Carnot battery has attracted increasing interest due to the rapid growth of renewable energy. However, the low-grade efficiency and technological maturity are the problems in the development of the Carnot batteries. This paper proposes a technical approach to transform the thermal power stations into high-efficiency storage plants, combining existing equipment with new technologies. For this, a case study using a typical 1000MW supercritical coal-fired plant is investigated in this paper. The dynamic cycle and the high-temperature reservoir are comprehensively re-designed to enhance the round-trip efficiency of the Carnot battery. The results show that the optimization of the Rankine cycle increases the cycle efficiency by ~2% through rising the feedwater temperature. In the design of the high-temperature reservoir, volcanic rocks are used as the storage medium to be heated at 750~800 °C, combined with the cascade utilization of thermal energy, which makes a great contribution to the round-trip efficiency of 49.5%. Based on the obtained results, it is concluded that the high-temperature Rankine Carnot battery has the potential to become a promising grid-scale electrical storage in the coming future.

Keywords: Carnot battery, electrical storage, Rankine cycle, renewable energy, round-trip efficiency

NOMENCLATURE

Abbreviations	
A	Air preheater
B	Boiler
C	Condenser
D	Deaerator
E	Economizer
G	Generator
HE	Heat exchanger
HT	High-temperature
HP	High-prssure turbine
R	Regenerative heater
WHB	Waste-heat boiler
T	Turbine
DN	Smoking denitration absorber tower

1. INTRODUCTION

The scarcity of natural resources and global climate change promote the expansion of renewable energy share. In 2020, the total installed capacity of wind power and solar photovoltaics in Germany reached 117.2 GW, thus accounting for 55.5% of the entire energy mix. To cope with the changing climate and to achieve China's carbon neutrality goal, China has announced that by 2030 the installed capacity of wind power and photovoltaics will exceed 1,200 GW, accounting for 30-50% of the total installed power capacity. Grid balancing has become an important aspect for the power grid in matching the supply of energy to demand.

Except for the management of the demand and production sides, increasing the energy storage capacity in the grids is a proven strategy. However, lithium chemistry battery is a well-established technology but expensive to meet the requirement of grid-scale electric storage. Pumped hydro energy storage and compressed air energy rely on pre-existing reservoirs and caves. Compared to these, the Carnot battery can be installed everywhere, but it might have a lower efficiency[1].

Carnot batteries are used to store electric energy. In the charge, electric energy (input) is used to move the heat from the low temperature to the high-temperature reservoir, e.g., through a traditional heat pump, and an electric heater. Likewise, in the discharge, any heat engine technology may be used, ranging from Rankine, Brayton, or different thermodynamic cycles to

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thermoelectric generators. Improving the temperature of the HT reservoir is helpful to increase the compactness of a Carnot battery and enhance the efficiency of a thermodynamic cycle[2]. This may induce a low coefficient of performance (down to 1) if a heat pump is used for the charging process. Therefore, electric heaters seem cost-effective and simpler than heat pumps, and such a solution with a round-trip efficiency of around 45% is provided by Siemens Gamesa[3].

Nowadays, thermal power is still the major component of power generation in most countries; there is still a long way to go to squeeze coal out of the power sector. If the thermal plants can be retrofitted as the Carnot batteries during their lifetime to provide auxiliary services, which may compensate for their lower efficiency with a very low initial cost[4] and accelerate the progress of crowding out coal. For this, Carnot batteries called attention to alternative storage concepts, and become more and more popular. The round-trip efficiency improvement will be the guarantee for the thermal power plant to be transformed to a Carnot battery as its second life.

However, to the best of our knowledge, manufacturing and operation technologies of coal-fired power generation have been gradually improved, and it is now increasingly hard for any further significant energy conservation in this area. Due to the tremendous changes from the thermal power units to Carnot battery systems, it is intuitively believed that it provides a high potential for energy saving. For this, the main purpose of this paper is to design and optimize the structure of the Rankine Carnot battery system, thereby improving the round-trip efficiency. A 1000 MW supercritical coal-fired power plant is selected to be transformed into a Carnot battery in this paper. Through a thermodynamic system model established in this work, the system's performance is investigated and optimized.

2. SYSTEM DESCRIPTION AND METHODS

As presented in Fig. 1, a 1000 MW supercritical double-reheat unit is selected to be transformed into a Carnot battery system. As known, the simulation of thermodynamic systems can be calculated by many software (such as Aspen, Ebsilon, and so on) and calculating models established through Excel and Matlab[5]. Therefore, the detailed mathematical models, based on the conversion of the mass and energy, are not repeated herein. Certainly, the simulation results are verified by the rated parameters of the unit at design condition, as presented in Table.1. The results show all the simulation errors are less than one.

The total cycle efficiency of the unit is 50.93%, and the heat consumption and standard coal consumption rate for generation are 7067.53 kJ/kWh and 268.94 g/kWh, respectively. Increasing the feedwater temperature is helpful to reduce the exergy loss that occurs in the boiler. However, there exists a maximum feedwater temperature limited by many factors, including the safety of the water wall and economizer, the catalytic reaction occurs in the smoking denitration absorbed tower, the exhaust temperature of the flue gas, which mainly affects the boiler efficiency. Accordingly, the maximum feedwater temperature of a 1000 MW supercritical double-reheat unit is suggested within the range from 300 to 350 °C[6].

3. RANKINE CARNOT BATTERY

Retaining the steam turbine subsystem based on the Rankine cycle, and replacing the boiler with the HT and LT reservoirs and heat exchangers, can transform a coal-fired power station into a Rankine Carnot battery. Fig.2 gives the new construction of the transformed Carnot battery system. Through the electric heaters, the electric energy is stored as thermal energy in the HT reservoir, which may be composed of rock, sands, or some high-thermal-conductivity material. In the discharge, the air is driven by the fan/blower to carry the thermal energy from the HT reservoir and transfer them to feedwater for generating steam. In terms of improvement of thermal efficiency, a waste-heat boiler is equipped downstream of the blower. In the dynamic cycle, the generated steam drives the turbine to produce electric power through the supercritical Rankine cycle.

3.1 The power cycle

The temperature limitations of the feedwater in the original unit are all removed since the economizer and flue gas desulfurization are excluded. Therefore, the temperature of the feedwater can be increased as high as possible (within the cost-effective range) to improve the efficiency of the thermodynamic cycle. In the original unit, the 1# steam with 10.67 MPa pressure is extracted to preheat the feedwater to 315°C. In the transformed Carnot battery system, additional steam (Pre-1# of 13.58 MPa and Pre-2# of 24.25 MPa) is extracted from the Pre-HP to preheat the feedwater in the regenerative heaters Pre-R1 and Pre-R2, thereby increasing the feedwater temperature into 343 °C and 400 °C in order. According to the rated temperature difference between the

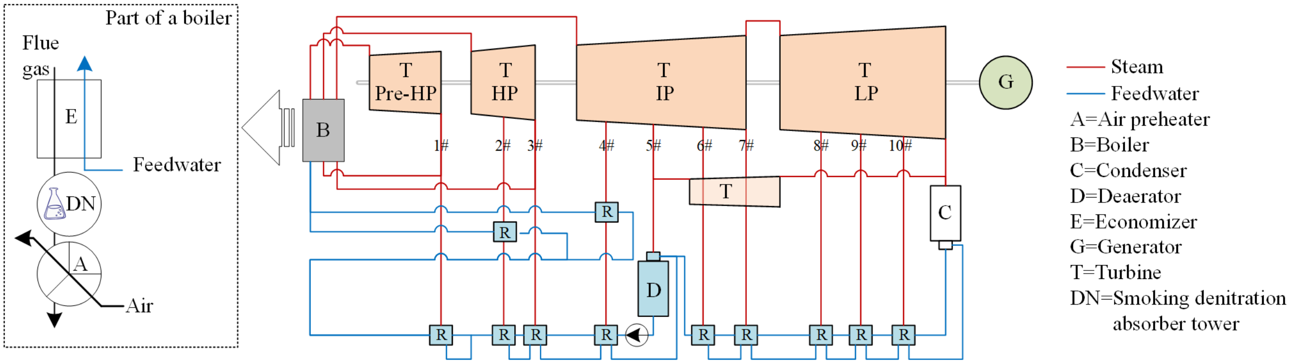

Fig. 1. The schematic diagram of the original unit

Table.1 Comparison between simulation and rated data of original plant.

	Item	Unit	Design data	Sim. results	RE (%)	Item	Unit	Design data	Sim. results	RE (%)
1	Power output	MW_e	1000.15	1000.15	0.00	**Extraction**				
2	Superheated steam	°C	600	600	0.00	1#	MPa	10.37	10.37	0.00
		MPa	30.12	30.12	0.00		kg/s	77.2	77.2	0.26
		kJ/kg	3445.72	3445.72	0.00	2#	MPa	5.95	5.95	0.00
		kg/s	719	718.9	-0.01		kg/s	50.1	50.1	0.20
3	1st Reheated steam	°C	610	610	0.00	3#	MPa	3.30	3.30	0.00
		MPa	9.98	9.98	0.00		kg/s	37.3	37.3	-0.53
		kJ/kg	3650.56	3650.56	0.00	4#	MPa	1.74	1.74	0.00
		kg/s	635	634.2	-0.13		kg/s	19.5	19.5	0.00
4	2nd Reheated steam	°C	610	610	0.00	5#	MPa	1.02	1.02	0.00
		MPa	3.055	3.055	0.00		kg/s	11.2	11.2	1.82
		kJ/kg	3705.17	3705.17	0.00	6#	MPa	0.71	0.71	0.00
		kg/s	550	551	0.18		kg/s	19.8	19.8	-1.00
5	Exhausts steam	kPa	4.5	4.5	0.00	7#	MPa	0.39	0.39	0.00
		kg/s	378.5	378.4	-0.03		kg/s	29.9	29.8	-0.67
6	Condenser water	°C	31	31	0.00	8#	MPa	0.122	0.122	0.00
		kg/s	457.5	457.5	0.00		kg/s	16.2	16.3	0.62
7	Deaerator	°C	180.28	180.28	0.00	9#	MPa	0.056	0.056	0.00
		kg/s	719	718.9	-0.01		kg/s	18.8	18.8	0.00
8	Feedwater	°C	324.42	324.42	0.00	10#	MPa	0.021	0.021	0.00
		MPa	36.49	36.49	0.00					
	Cycle efficiency	%	50.91	50.93	0.04					
	Heat Con.	kJ/kWh	7068	7067.53	-0.01					
	Coal Con.	g/kWh	2689	268.94	-0.02					

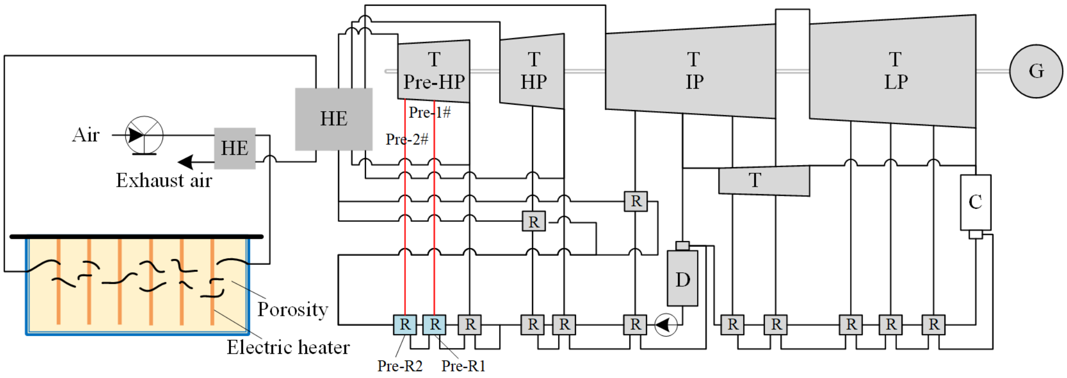

Fig. 2. The schematic diagram of the transformed Carnot battery system

Table. 2. The main parameters of the dynamic cycle in the Carnot battery

	Item	Unit	Original unit	Carnot battery	Item	Unit	Original unit	Carnot battery
1	Power output	MW$_e$	1000.15	**1052.62**	**Extraction**			
2	Superheated steam	°C	600	600	1#	MPa	10.37	10.37
		MPa	30.12	30.12		kg/s	77.2	76.27
		kJ/kg	3445.72	3445.716	2#	MPa	5.95	5.95
		kg/s	718.9	**1025**		kg/s	50.1	44.13
3	1st Reheated steam	°C	610	610.0	3#	MPa	3.30	3.30
		MPa	9.98	9.98		kg/s	37.3	37.20
		kJ/kg	3650.56	3650.56	4#	MPa	1.74	1.74
		kg/s	634.2	626.20		kg/s	19.5	17.86
4	2nd Reheated steam	°C	610	610.0	5#	MPa	1.02	1.02
		MPa	3.055	3.055		kg/s	11.2	11.24
		kJ/kg	3705.17	3705.17	6#	MPa	0.71	0.71
		kg/s	551	548.66		kg/s	19.8	19.82
5	Exhausts steam	kPa	4.5	4.5	7#	MPa	0.39	0.39
		kg/s	378.4	368.06		kg/s	29.8	29.87
6	Condenser water	°C	31	31	8#	MPa	0.122	0.122
		kg/s	457.5	457.48		kg/s	16.3	16.29
7	Deaerator	°C	180.28	180.28	9#	MPa	0.056	0.056
		kg/s	718.9	710		kg/s	18.8	18.76
8	Feedwater	°C	324.42	**401.50**	10#	MPa	0.021	0.021
		MPa	36.49	36.49	**Pre-1#**	MPa	-	**13.58**
						kg/s	-	**60.22**
					Pre-2#	MPa	-	**24.25**
						kg/s	-	**254.72**
	Cycle efficiency	%	50.93	**51.99**				
	Heat Con.	kJ/kWh	7067.53	**6924.50**				
	Coal Con.	g/kWh	268.94	**(263.50)**				

extracted steam and the regenerative heater, the specific heat transferred in the feedwater can be determined, thereby the flow rates of the additional extraction steam can be obtained. The main parameters of the dynamic cycle of the Carnot battery system are summarized in Table. 2.

As presented in Table .2, more flow rate of steam is extracted to preheat the feedwater, causing a higher steam consumption rate, which also boosts the power generation. Meanwhile, the increasing feedwater temperature increases the average heat absorption temperature from 324.4 to 401.5°C, improving the cycle efficiency from 50.93% to 51.99%, which is equivalent to a reduction of 5.44 g/kW·h of the standard coal consumption rate.

3.2 The high-temperature reservoir

The thermal energy converted from electricity is stored in an HT reservoir. As reported, in the 130MWh demonstration project, commissioned in Hamburg-Altenwerder, Germany, electrical energy is converted into hot air through a resistance heater and blower, heating the rock to 800 °C[7]. More than 1,000 tons of volcanic rocks are used as the medium for energy storage, with costs of about 80€/kWh of installed capacity. For comparison, lithium-ion batteries carry a cost of $200 per kWh or more and are limited in size. Additionally, in China, a carbon-based material is reported by the National Institute of clean and low-carbon energy[8], and the storage temperature of the demonstration facility has been achieved at 912 °C with an efficiency of 97%. The thermophysical properties of volcanic rock material and carbon-based material within 500~1000 °C are summarized in Table. 3.

Take the volcanic rocks as the storage medium for the system's performance investigation. If the working temperature is set to be within 500~800 °C, about 1~2×10^5 tons of volcanic rocks are needed to meet the requirement of the grid-scale electric storage to provide 4~8 hours electric supply (about 8 000~16 000 MWh). Since the HT reservoir can be built almost anywhere and easily be ramped up in size and capacity, the initial investment cost per capacity is expected to decrease significantly with the increase of scale.

Table 3. Thermophysical properties of the storage medium mentioned within 500~1000 °C[8,9,10]

Item	Spe. heat capacity (kJ·kg^{-1}K^{-1})	Density (g·cm^{-3})	Thermal cond. (W·m^{-1}K^{-1})
Volcanic rocks	1	2.5-2.7	1~1.2
Carbon-based material	1.3	1.9	70~100

According to the economic design of heat exchangers, the temperature difference at the outlet of the HT reservoir is assumed to be 50 °C. Therefore, the hot air temperature can be heated by the volcanic rocks from the ambient temperature of 20 °C to 750 °C and transfer the thermal heat to the feedwater (from 401 °C to 600 °C). Then, the exhaust air exits out from the heat exchanger at 450 °C. Based on conservation of energy and mass, approximately 5400 kg/s (or 14 000 m^3/s) of air is required. In terms of improvement of thermal efficiency, waste heat boilers are used to recover the exhaust thermal energy. Finally, the efficiency of the heat from the volcanic rocks to the steam can achieve about 96.1% theoretically.

In order to use the stored thermal energy in a higher efficient way, the HT reservoir is considered to be divided into several parts with various temperatures. Then, it is flexible to manage the power input for different electrical heaters to remain the HT reservoirs' temperatures. Furthermore, the heat exchanger also can be divided into several models, which is helpful in cascade utilization of thermal energy. Fig. 3 shows two options for the structure of the HT reservoir. It is believed that there exists interesting work on the optimization of the system design to maximize energy efficiency.

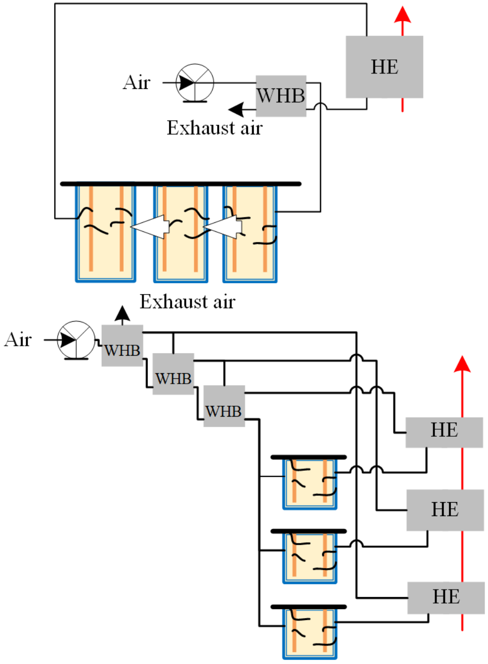

Fig. 3. Two options for the structure of the HT reservoir

4. DISCUSSION

As renewable energy grows rapidly, a low-cost grid-scale electrical storage is thereby urgently needed to balance the mismatch between energy supply and demand. When the electricity production is higher than the demand, the excess electrical power is stored in the volcanic rocks at 800 °C with an efficiency of close to 1. When electricity demand is higher than the production, the stored energy is discharged by using the hot air to carry the thermal heat from the volcanic rocks, which has an efficiency of 96.1%. Then, through the optimized supercritical Rankine cycle, the generated steam drives the turbine to produce electric power with a cycle efficiency of 51.99%. Generally, the round-trip efficiency can be achieved at 49.5%, which is 4.5% higher than the conventional case provided by Siemens Gamesa. Additionally, the use/share of the existing infrastructure leads to a low initial cost of the Rankine Carnot batteries, which highlights the economic competitiveness.

5. CONCLUSIONS

Grid-scale electrical storage technology is becoming more and more important with the development of renewable energy. On the other hand, a large number of thermal power generation is gradually eliminated during the world's energy revolution process. For this, a technical approach is proposed to transform the thermal fossil fuel power stations into a Carnot battery storage plant, combining existing equipment with the new technologies.

The dynamic cycle and the high-temperature reservoir are comprehensively re-designed to enhance round-trip efficiency. The results show that the optimization of the Rankine cycle is helpful to higher the cycle efficiency by ~2%. Additionally, the high-temperature reservoir is redesigned for the cascade utilization of thermal energy, which makes a great contribution to the round-trip efficiency of 49.5%. Based on the obtained results, it is concluded that the high-temperature Rankine Carnot battery has the potential to become a promising grid-scale electrical storage in the coming future.

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