# STUDY ON THE CHARACTERISTICS OF MOLTEN SALT HEAT STORAGE IN THE FAST PEAK REGULATION OF COAL-FIRED POWER UNIT


***Xiangyu ZHANG[a], Zhaoyao MA[a,b], Hainan WEN[a,b], Zhenshuai YANG[a], Hui LIU[a]***

[a] Xi'an Thermal Power Research Institute Co., Ltd, Xi'an, Shaanxi, China

[b] School of Low-Carbon Energy and Power Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, China

[*] Corresponding author; E-mail: zhangxiangyu214@163.com



*The load variation rate of the coal-fired power unit in China is generally around 2%, and the new technology is needed to further improve the load variation rate and to increase the peak regulation benefits. In this paper, the molten salt is utilized to constructed the "Carnot battery" based on the coal-fired power unit, in order to increase the load variation rate of the coal-fire power units, and the regulatory characteristics of the molten salt system during load variation processes and the coupling characteristics with the boiler and turbine are investigated. The results indicate that, the load variation rate in the 20-100% load can be improved to 6%Pe/min for a 300MW coal-fired power unit when molten salt system with power of 301MW and thermal storage duration of 83.6MWh is coupled, in which the maximum molten salt temperature is 420℃, and the steam produced by molten salt is added into the low-pressure cylinder of turbine. The average power generation efficiency of the "Carnot battery" constructed by the boiler and molten salt during the variable load regulation process is 38.72%, and the average power generation efficiency of the molten salt system is 24.57%. This study indicates that the small-scale molten salt systems can be used to improve the load variation rate of the coal-fired power units.*



*Key words: coal-fired power unit; molten salt; load variation rate; low-pressure cylinder; Carnot battery*


## 1. Introduction

Under the dual-carbon target, the new power system dominated by new energy sources such as wind and solar power are being rapidly constructed in China, however, the randomness, volatility and uncertainty of new energy will pose significant challenges to the safe operation of the power grid, and the electricity supply gap is expanding[1]. In order to ensure the reliable supply of electricity, a flexible power supply matched with new energy sources needs to be built. At present, the most economical and effective way is to promote the flexible transformation of coal-fired power, fully leveraging its role as a backup and ballast[2].

In China, the flexible transformation of coal-fired power units has been carried out since the 13th Five Year Plan, and nearly 90 million kilowatts of capacity having been renovated[3]. Domestic coal-fired power units are generally designed according to the rated load, and generally operated at

50-100% rated load and 1-2% load variation rate. After flexibility transformations, some units can achieve 20-30% rated load operation and a climbing speed of 2-3% Pe/min.[4]. For instance, the 660MW subcritical unit in Jingneng Daihai Power Plant can achieve a minimum peak shaving depth of 15% rated load, with a load variation rate of 2.8%Pe/min in the load range from 510MW to 610MW[5]. The minimum peak shaving depth of the 330MW supercritical unit in Changji Power Plant can reach 20% rated load, with a load variation rate of 2.3% Pe/min[6]. However, the cycle efficiency of the units decreases significantly at low load conditions. For example, the coal consumption of Qinling power plant increased by nearly 80% during deep peak-regulating operation at 10% load, and further increasing the load variation rate is constrained by pulverization and metal wall temperatures, so it is challenging to increase flexibility by relying solely on the conversion of coal-fired power units[7].

The coupled thermal energy storage technology for thermal power units provides a fresh approach for attaining flexible transformations, with the sensible heat and thermal storage technology based on melting salt shows a good application prospect in the fields of flexible operation of thermal power units, peak and frequency regulation, clean heating and so on[8]. In the past decade, many laboratories, research institutes and enterprises both domestically and internationally have dedicated to the theoretical analysis, experimental research and engineering application of molten salt thermal energy storage technology, and the significant progress has been made in areas such as molten salt working fluid research, molten salt heat transfer mechanisms and heat exchanger equipment research, and the coupling of molten salt thermal energy storage with power generation units. However, engineering demonstrations have primarily focused on solar-thermal power stations, and the coupling with coal-fired power units remains in the conceptual design stage[9]. Li et al. [10]from Huazhong University of Science and Technology designed a supercritical coal-fired power unit coupled with a molten salt thermal energy storage electric grid-level energy storage system, the detailed thermodynamic model is established using epsilon simulation software and the economic comparative analysis is conducted. Fan et al[11]. designed the ratio of steam and molten salt flow at different stages for 600MW sub-critical unit, and proposed a new heat storage system of "multi-tank - multi-heat exchanger". Li et al. [12]analyzed the flexible transformation technology of thermal power unit with high temperature molten salt heat storage and its application prospects. Wang et al.[13] established a theoretical model for the use of hundred-megawatt-level molten salt energy storage technology in deep load adjustment for thermal power unit, and provide evidence for thermal storage process parameters and overall efficiency. Zhang et al. [14] designed a coupling system scheme for a domestic 600MW coal-fired power unit with molten salt thermal storage, concrete thermal storage, and subcritical water thermal storage, and conducted a comparative analysis of the thermal and peak regulation performance of each coupling system. Zhou et al.[15] analyzed the peak regulation capacity of coal-fired power-physical thermal storage coupling system and its influencing factors, and established a calculation model of the peak regulation capacity of the coupling system and proposed a reasonable operation mechanism of the coupling system.

The traditional molten salt system is mainly used for photothermal power generation[16], or used in heat storage and peak regulation in the deep regulation stage of the unit to weaken the rigid boiler-turbine coupling, in which the scale of molten salt system is generally large. So far, few studies have focused on the role of molten salt systems in peak shaving flexibility[17]. In this paper, the molten salt is utilized to construct the "Carnot battery" based on the coal-fired power unit, participating in the flexible peak regulation of the units, and the regulatory characteristics of the molten salt system during load variation processes and the coupling characteristics with the boiler and turbine are investigated. Different from the traditional molten salt system for long-time heat storage, a small-scale molten salt system to assist in increasing the load variation rate of coal-fired power units is investigated in this study, and the molten salt system operates in a coordinated manner with the steam turbine in a constant-slide-constant mode, which can better fit the flexibility of the current coal-fired power units.

## 2. Calculation models

A 300MW unit is selected as the research object. The boiler is a subcritical drum boiler with natural circulation, single furnace, one intermediate reheating, solid slag discharge, all steel frame structure and tight closure. The turbine is a subcritical, single reheat, three cylinder and double exhaust, direct air cooled, extraction condensing steam turbine generator set. The main parameters of the unit are shown in Table 1, and the heat balance under THA(Turbine Heat Acceptance) condition is illustrated in Fig. 1.

**Tab. 1. Main parameters of the unit**

| Item | Unit | THA | 75％THA | 50％THA | 35％THA |
|---|---|---|---|---|---|
| Superheater outlet steam flow rate | t/h | 934 | 683 | 463 | 333 |
| Reheater outlet steam flow rate | t/h | 843.8 | 622.8 | 426.7 | 309 |
| superheater outlet pressure | MPa.a | 18.27 | 17.93 | 17.72 | 17.65 |
| Reheater inlet pressure | MPa.a | 3.83 | 2.84 | 1.95 | 1.42 |
| Reheater outlet pressure | MPa.a | 3.63 | 2.69 | 1.85 | 1.34 |
| Superheater outlet temperature | ℃ | 543 | 543 | 543 | 543 |
| Reheater inlet temperature | ℃ | 326.9 | 302.5 | 292.1 | 285.4 |
| Reheater outlet temperature | ℃ | 542 | 542 | 542 | 542 |
| Economizer inlet temperature | ℃ | 247.7 | 230.7 | 211 | 195.4 |

The depth of peak shaving and load variation rate of traditional coal-fired units are greatly restricted, and the thermal storage technology by molten salt has been gradually used to reduce the load adjustment burden [18], in which the more economical approaches is to participate in unit heating while assisting with load adjustment. When the load variation rate of unit needs to be increased, the boiler can be operated in parallel with molten salt to build a "Carnot battery", and the unit load is rapidly adjusted by extracted and generated steam by molten salt system. The design scheme is shown in Fig. 2. Different from the traditional "Carnot battery", the molten salt is heated by extracted steam, which has lower energy loss compared to the electric-thermal conversion process of heating molten salt by electric.

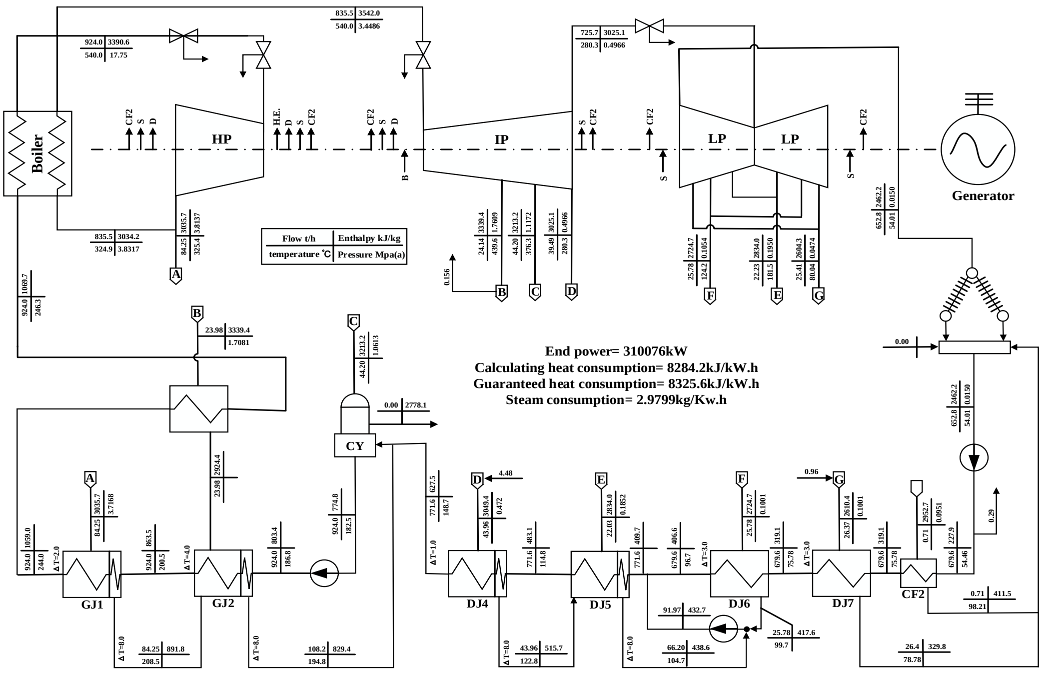


**Fig. 1. The heat balance diagram of unit at THA condition**

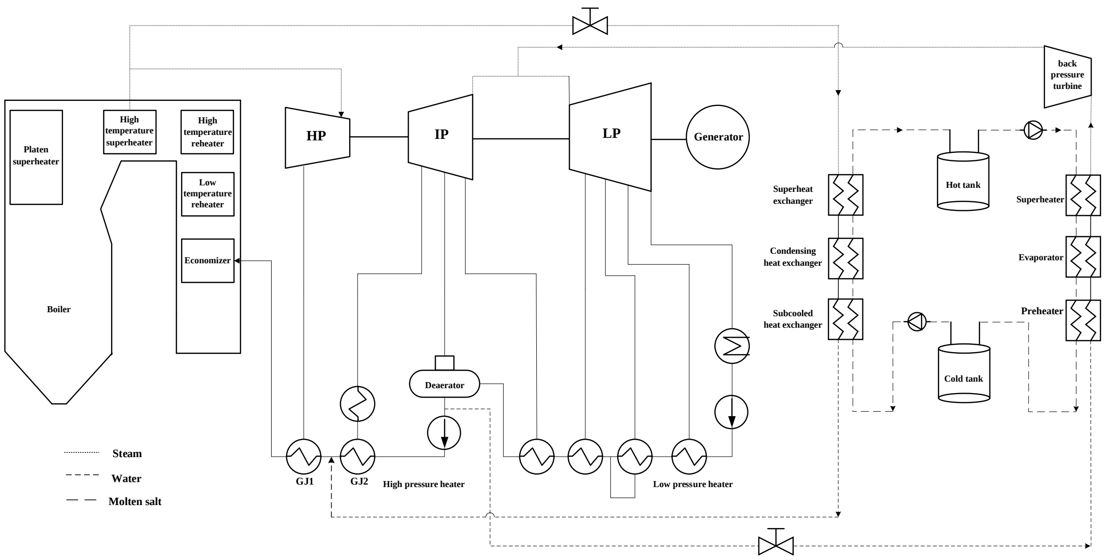


**Fig. 2. The schematic diagram of boiler molten salt coupling system**

The work process of the boiler and molten salt coupling system is as below: when the unit load needs to be increased, the boiler output is increased at a set rate, and the heat is transferred from the high-temperature molten salt to the steam-water system. The newly generated steam mixes with the exhaust steam from the intermediate-pressure cylinder, and the steam flow entering into the low-pressure cylinder is increased rapidly, assisting the boiler in achieving a higher load increase rate. When the unit load needs to be decreased, the boiler reduces its output at a set rate. Part of the main steam is extracted from the outlet of the superheater to heat the molten salt, the main steam after condensation and subcooling is returned into the No. 2 high pressure heater outlet, and some of the main steam reaches the steam turbine to do work, assisting the boiler in achieving a higher load decrease rate.

The mathematical model of the boiler-molten salt coupling system is established, when the boiler load is increased the molten salt undergoes a heat release process involving molten salt-steam heat transfer and steam work two stages, as represented by Eq. (1) and Eq. (2). When the boiler load is decreased, the molten salt undergoes a heat storage process involving steam-molten salt heat transfer and steam work two stages, as represented by Eq. (3) and Eq. (4). The power generation efficiency of the system is defined by Eq. (5)[19].

$$\int\int m_s C_p dT_s dt = \int m_w (h_{w1} - h_{w2}) dt \# (1)$$

$$\int \left(m_b \Delta h_{s,b} \eta_q \eta_e + m_w \Delta h_{s,w} \eta_{q,3} \eta_e + P_c\right) dt = \int P_e \left(1 + k_p\right) dt \#(2)$$

$$\int m_g \left(h_{g1} - h_{g2}\right) dt = \int\int m_s C_p dT_s dt \#(3)$$

$$\int (m_b \Delta h_{s,b}\, \eta_q \eta_e - m_g \Delta h_{s,g} \eta_q \eta_e) dt = \int P_e \left(1 - k_p\right) dt \#(4)$$

$$\mathrm{H}_f = \frac{\int P_e dt}{\int (Q_b / \eta_b + Q_s) dt} \times 100\% \#(5)$$

In the equations, $m_s$ represents the molten salt flow rate, [$kgs^{-1}$]; $C_p$ represents the specific heat capacity of molten salt,[ $kJkg^{-1}K^{-1}$]; $T_s$ represents the molten salt temperature, [K]; $t$ represents time, [s]; $m_w$ represents the cold fluid feed water flow rate, [$kgs^{-1}$]; $h_{w1}$ represents the inlet enthalpy value of feedwater; $h_{w2}$ represents the outlet enthalpy value of feedwater, [$kJkg^{-1}$]; $m_g$ represents the main steam flow of hot fluid, [$kgs^{-1}$]; $h_{g1}$ represents the main steam inlet enthalpy value, $h_{g2}$ represents the main steam outlet enthalpy value, [$kJkg^{-1}$]; $m_b$ represents the main steam flow rate of the boiler, [$kgs^{-1}$]; $\Delta h_{s,b}$ represents the isentropic enthalpy drop of the boiler's main steam, $\Delta h_{s,w}$ represents the isentropic enthalpy drop of steam generated by molten salt, $\Delta h_{s,g}$ represents the isentropic enthalpy drop of extracted main steam, [$kJkg^{-1}$]; $\eta_q$ represents the turbine efficiency, $\eta_b$ represents the boiler efficiency, $\eta_e$ represents the efficiency of the generator, $\eta_f$ represents the power generation efficiency of the boiler molten salt coupling system, [%]; $Q_b$ represents the boiler thermal load, $Q_s$ represents the molten salt system thermal load, [kW]; $P_c$ represents the power of the backpressure turbine, $P_e$ represents the generated power, [kW]; $k_p$ represents the unit load variation rate,[%].

## 3. Results and discussion

### 3.1. Determination of system parameters

When the "Carnot battery" is constructed by the boiler and molten salt, there are three options for the coupling inlet point of the steam generated by molten salt to the boiler: high-pressure cylinder, intermediate-pressure cylinder and low-pressure cylinder of turbine. The method of steam directly enter into the high-pressure and intermediate-pressure cylinders has higher cycle efficiency and less steam consumption, however, it is limited by the pinch point temperature of steam heating molten salt, so the auxiliary heating to increase the molten salt temperature is needed. The low-temperature molten salt, carbon steel tanks, and low-pressure heat exchangers can be used when the coupling inlet point is low-pressure cylinder[20], which is more economical and easier to realize in engineering.

The non-lithium binary nitrate salt is selected, its main components are the sodium nitrate and potassium nitrate. The melting point of molten salt is 115℃ and the permissible working temperature is 200-550℃, the specific heat capacity is about 1.46J/(g·k) and the density is 1.98g/cm$^3$[21]. The heat balance of heat storage and heat release for molten salt is shown in Fig. 3. During the heat storage process, the 543°C main steam extracted from the superheater is cooled to 220°C sub-cooled water, and the latent heat is completely releasing to heat the molten salt, so the molten salt temperature is increased from 210°C to 420°C. During the heat release process, the molten salt is cooled from 420°C to 210°C, and saturated water at 181.5°C (the outlet temperature of the deaerator at 100% load) is heated to superheated steam at 352°C. The minimum terminal temperature difference in heat storage process is 10℃, the pinch point temperature difference is 10.5℃, and the terminal temperature difference in heat release process is 28.5℃.

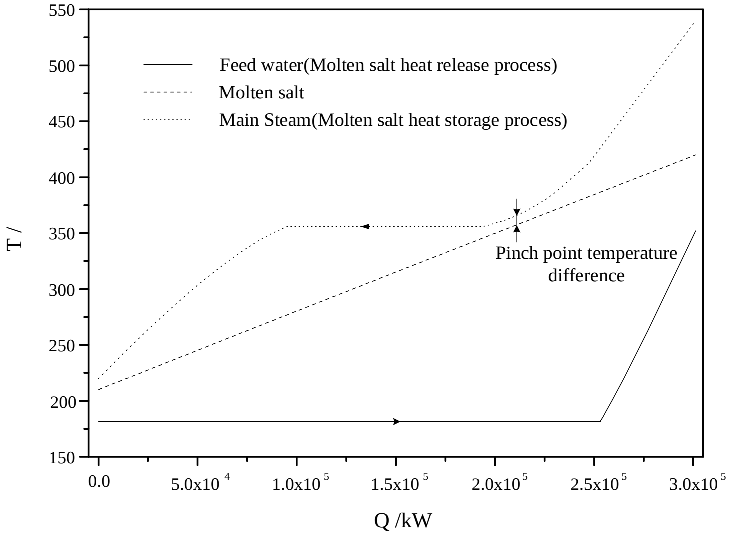


**Fig. 3. The heat balance diagram of heat storage and release process**

The steam flow generated is determined by the heat transfer temperature difference of molten salt, and the molten salt quantity can be reduced by increasing the molten salt temperature, but it is also limited by the pinch point temperature difference, as shown in Fig.4. When the temperature of high temperature molten salt increases from 360℃ to 420℃, the molten salt quantity decreases from 720t to 512t, and the pinch point temperature difference decreases from 49℃to 10.5℃. The permissible temperature for carbon steel materials is 420°C[22], and the material of the high temperature storage tank needs to be replaced if the molten salt temperature is to be further increased, so the maximum heating temperature of molten salt is 420℃.

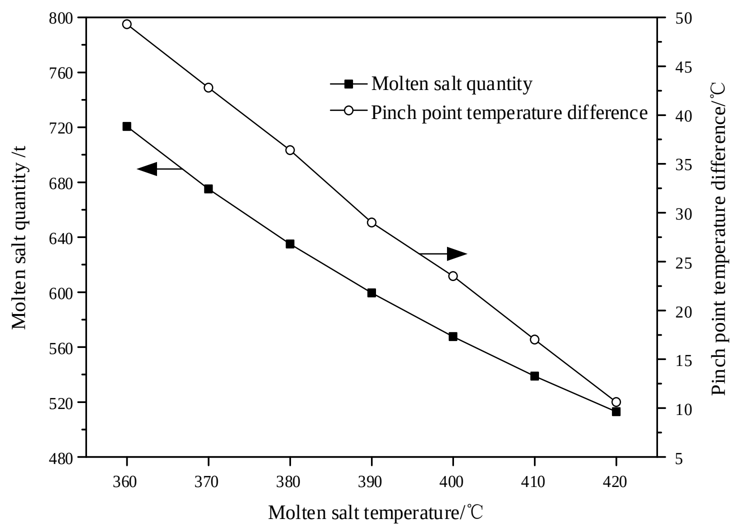


**Fig. 4. Relationship between maximum temperature of molten salt and molten salt quantity**

The steam generated by molten salt is imported into the low-pressure cylinder, however, the outlet pressure of the deaerator is slightly higher than the exhaust pressure of the intermediate-pressure cylinder, thus there are two methods for combining the steam from the molten salt with the exhaust from the intermediate-pressure cylinder: the first is to merge directly with the intermediate-pressure cylinder exhaust, and the second is to merge after working in a back-pressure turbine. The efficiency of added backpressure turbine is designed as 88%. The enthalpy-pressure variation curves for the two processes are shown in Fig. 5. It is evident that, the power of the molten salt heat exchanger decreases, and the cycle efficiency of the system is improved by increasing the backpressure turbine. Consequently, the approach of merging with the low-pressure turbine after additional work is performed by the back-pressure turbine is adopted in the subsequent calculation.

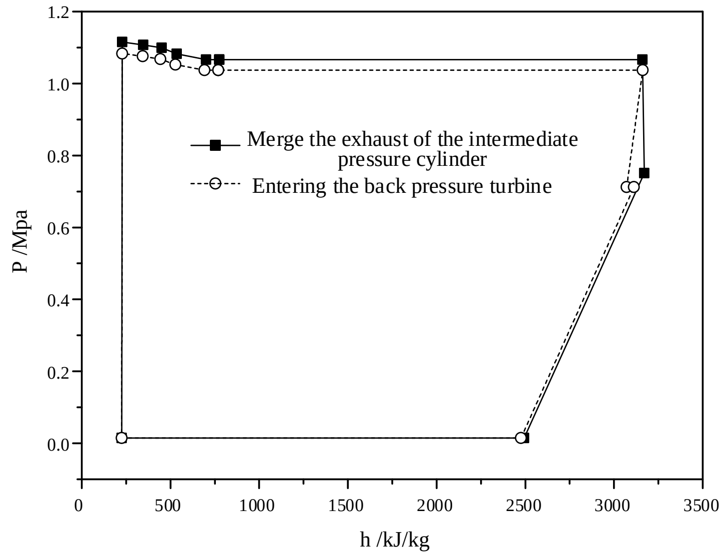


**Fig. 5. Enthalpy-pressure variation curve during heat release process**

### 3.2. Load increase process

The steam generated from molten salt is mainly used for load regulation of the power unit, taking the 50-100% THA load regulation process of the unit as an example, the target load variation rate of the unit is set to 6% Pe/min, and the corresponding AGC variation rate is 18 MW/min. In this process, the load variation rate of the boiler is set to 3% Pe/min, and the steam generated by the molten salt is supplemented to achieve a load variation rate of 3% Pe/min[23]. The boiler load can be changed from 50% to 100% through two operating modes: constant pressure operation and sliding pressure operation, and the outlet pressure of the deaerator and the required flow of molten salt in the two modes can be compared as shown in Figure 6.

It can be seen that the boiler operates under the two modes of constant pressure and sliding pressure, the deaerator outlet pressure and molten salt flow change little. In the subsequent calculation, the boiler operates according to the constant-slide-constant mode in the thermodynamic calculation book, which is constant pressure operation below 35%THA, sliding pressure operation at 35-90%THA and constant pressure operation at 90-100%THA, and the feed water temperature and pressure of the molten salt change with the temperature and pressure at the outlet of the deaerator.

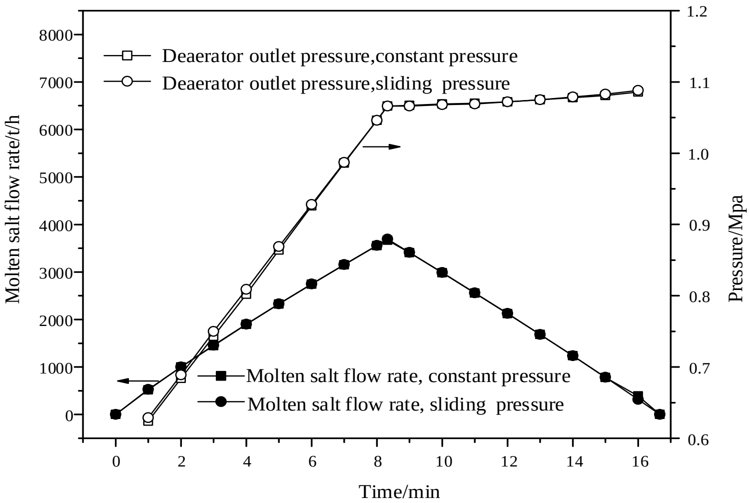


**Fig. 6. Comparison between constant pressure operation and sliding pressure operation of boiler**

The molten salt flow rate during the 50-100% THA load variation process is calculated according to the boiler load variation rate of 3%Pe/min and the turbine load variation rate of 6%Pe/min, without considering the pressure loss during heat transfer and flow, as shown in Fig. 7. The molten salt flow increases first and then decreases in a triangular distribution, the maximum molten salt flow rate is 3434.7t/h, the corresponding power of the molten salt heat exchanger is 301MW, the heat storage is 83.6MWh and the total molten salt quantity is 477t. Compared with merge directly with the intermediate-pressure cylinder exhaust, the total molten salt quantity can be reduced from 512t to 477t.

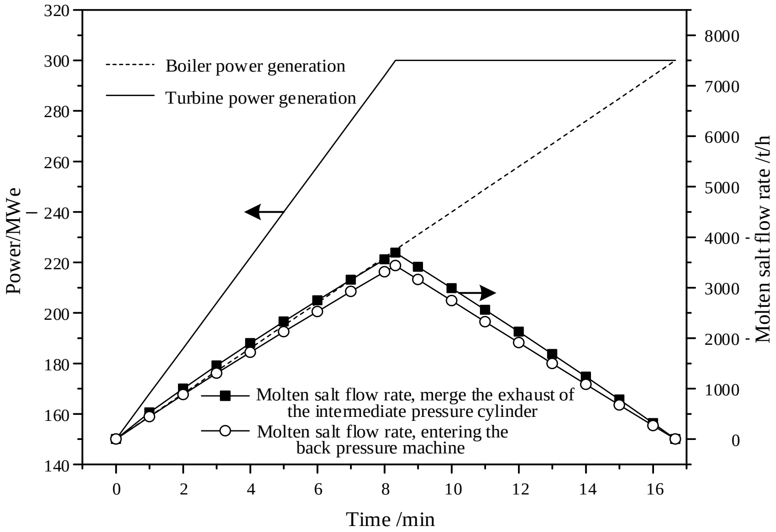


**Fig. 7. The load variation and molten salt flow rate variation curves from 50% THA to 100% THA**

There are two regulation modes can be selected in the 20-50%THA load increase process: the first is the boiler load variation rate of 1%Pe/min (molten salt supplement provides 5% Pe/min), the turbine load variation rate of 6%Pe/min. The second is the boiler load variation rate is 2%Pe/min (molten salt supplement provides 4% Pe/min), and the turbine load variation rate is 6%Pe/min. The molten salt flow change and molten salt quality are calculated, as shown in Fig. 8. It can be seen that the maximum molten salt flow under the two working conditions is 3693.3t/h and 3089.8t/h, and the total amount of molten salt required is 923.3t and 386.2t respectively. Compared with the 50-100%THA load variation process, the boiler load variation rate should be increased to 2%Pe/min, in order to achieve 6%Pe/min load variation rate in the process of the 20-50%THA load increase process.

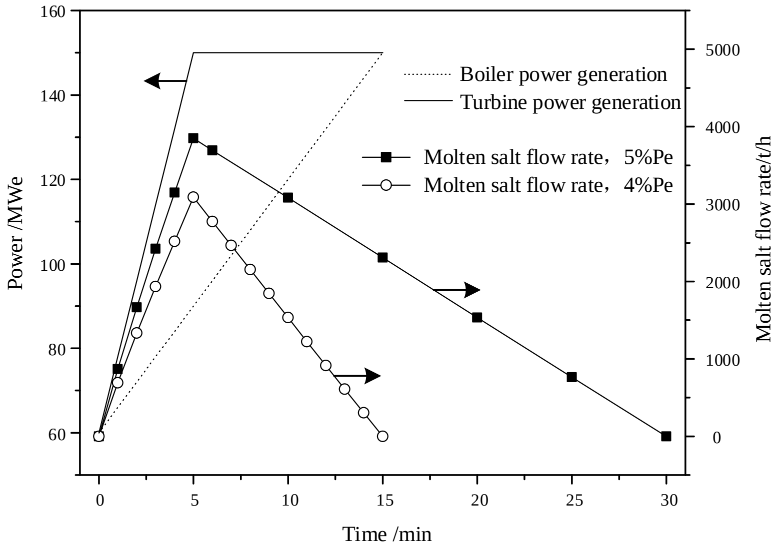


**Fig. 8. The load variation and molten salt flow rate variation curves from 20% THA to 50% THA**

### 3.3. Load reduction process

The unit load reduction includes 100-50%THA and 50-20%THA two processes, and the turbine load variation rate of 6%Pe/min is the goal to be achieved. According to the general AGC variation rate level of active boilers in the load reduction process, assuming the boiler load variation rate of 100-50%THA process is 4%Pe/min[24], and the boiler load variation rate of 50-20%THA process is 2%Pe/min. The excess main steam generated by the boiler is sent to the molten salt system to achieve thermal storage by heating cold molten salt.

The curve of 100-50%THA load variation and molten salt flow is shown in Fig. 9. The load regulation time is 12.5min, the maximum molten salt flow rate is 1693.3t/h, the power of molten salt heater is 102.9MW, and the amount of molten salt used is 176.4t. In the boiler load reduction process, the main steam pressure gradually decreases, the pinch point temperature difference is set to 10℃, the corresponding molten salt outlet temperature gradually decreases, and the average temperature after conversion is 363.1℃. This indicates that the molten salt is heated by extraction steam in the 100-50%THA load variation process, the molten salt accounting for 37% of the total amount can be heated from 210℃ to 363.1℃ when the turbine load variation rate is 6%Pe/min.

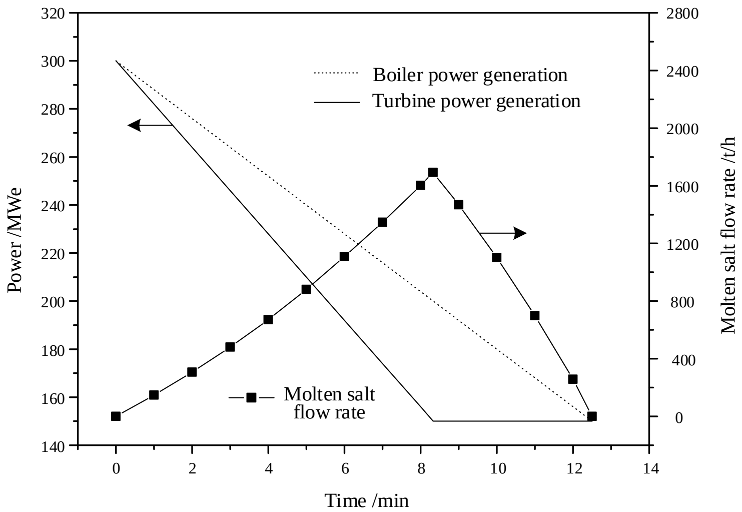


**Fig. 9. The load variation and molten salt flow rate variation curves from 100% THA to 50% THA**

The curve of 50-20%THA load variation and molten salt flow rate is shown in Fig.10. The load adjustment time is 15 min, the maximum molten salt flow rate is 3234.4 t/h, the power output of the molten salt heater is 127.8 MW, and the amount of molten salt used is 404.3t. When the pinch point temperature difference is set to 10℃, the corresponding average outlet temperature of molten salt is 301.1℃, which indicates that the molten salt is heated by extraction steam in the 50-20%THA load variation process, the molten salt accounting for 84.8% of the total amount can be heated from 210℃ to 301.1℃ when the turbine load variation rate is 6%Pe/min.

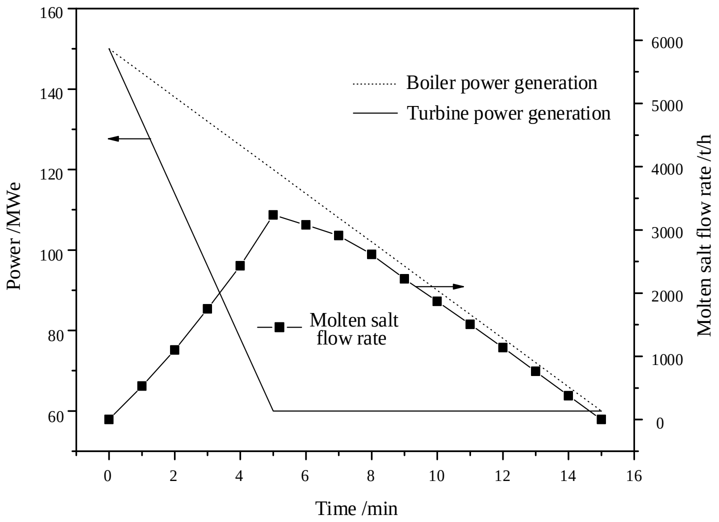


**Fig. 10. The load variation and molten salt flow rate variation curves from 50% THA to 20% THA**

From the above calculation, it can be seen that the molten salt heat storage and heat release processes do not match under the condition of the same load variation rate, and the steam heat extracted during the load reduction process cannot meet the demand for steam generated during the load increase process, so the heat storage of molten salt in the unit load deep regulation process can be considered. That is, under the 35%THA operation condition of the boiler, the main steam is extracted to heat the molten salt in the high-pressure heater, the cooled steam is returned to the reheater inlet, and then the molten salt in the low pressure heater is heated by steam extracted from the reheater outlet. The heat balance diagram is shown in Fig. 11. It can be seen that the extraction steam quantity is 143t/h, the turbine load is reduced to 75MW (25%THA), the high pressure heater power is 18.9MW, the low pressure heater is 13.9MW, and the heat storage time is 1.27h. The heat storage power of molten salt during low load operation of the unit is much lower than the heat release power of molten salt during load increase process, so as to realize the "slow charge and fast discharge" of molten salt system.

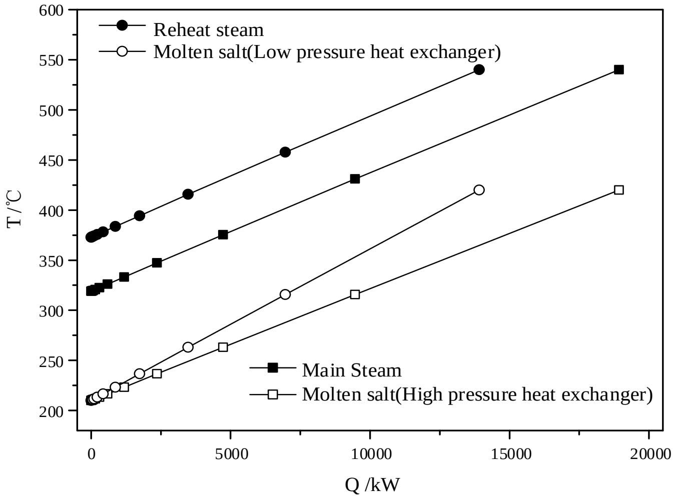

**Fig.11. The heat balance diagram of molten salt heat storage during deep load regulation process**

The power generation efficiency of the boiler-molten salt coupling system in the load variation process is calculated, as shown in Fig. 12, the efficiency curve of the 50-100% THA process is presented. The average efficiency of the steam generated by heat release from the molten salt entering the low-pressure cylinder for power generation is 24.57%, and the average power generation efficiency of the whole system is 38.72%.

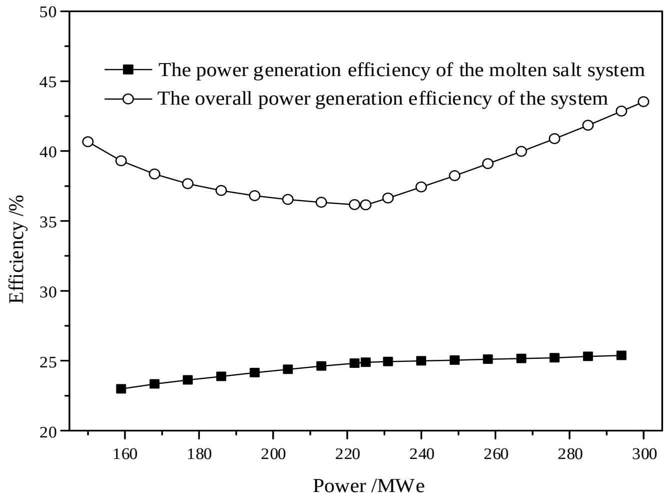


**Fig.12. System efficiency curve**

## 4. Conclusion

For the active coal-fired power unit, the method of generating steam by molten salt and incorporate into the low-pressure cylinder can be used to increase the load increase rate of the unit. A backpressure turbine is added into the molten salt steam circuit, which can improve the compatibility between molten salt steam and boiler steam, and reduce the amount of molten salt and improve the circulation efficiency of the system.

For a 300MW coal-fired power unit, the load variation rate can reach to 6%Pe/min during the 20-100% load variation range, when a molten salt system with heat transfer power of 301MW and heat storage of 83.6MWh is added, and the total amount of molten salt is about 477t.

The molten salt cannot be heated to design temperature by the extracted main steam in the load reduction process, so the steam can be extracted during the deep load regulation phase of the molten salt heating process in the boiler, and then the heat is released to the steam water system during the load increase process of the unit, achieving slow charge and fast discharge.

The average power generation efficiency of the carnot battery constructed by the boiler and molten salt during the load regulation process is about 38.72%, and the average power generation efficiency of molten salt system is about 24.57%.

## Nomenclature

$m_s$ - molten salt flow rate, [kgs$^{-1}$]

$C_p$ - specific heat capacity of molten salt, [kJkg$^{-1}$K$^{-1}$)]

$T_s$ - molten salt temperature, [K]
$t$ - time, [s]
$m_g$ - main steam flow of hot fluid, [kgs$^{-1}$]
$m_w$ - cold fluid feed water flow rate, [kgs$^{-1}$]
$Q_s$ - molten salt system thermal load, [kW]
$\Delta h_{s,g}$ - isentropic enthalpy drop of extracted main steam, [kJkg$^{-1}$]
$\Delta h_{s,b}$ - isentropic enthalpy drop of the boiler's main steam, [kJkg$^{-1}$]
$Q_b$ - boiler thermal load, [kW]
$k_p$ - unit load variation rate, [%].
$P_e$ - generated power, [kW]
$P_c$ - power of the backpressure turbine, [kW]
$m_b$ - main steam flow rate of the boiler, [kgs$^{-1}$]
$h_{w1}$ - inlet enthalpy value of feedwater, [kJkg-1]
$h_{w2}$ - outlet enthalpy value of feedwater, [kJkg$^{-1}$]
$h_{g1}$ - main steam inlet enthalpy value [kJkg$^{-1}$]
$h_{g2}$ - main steam outlet enthalpy value, [kJkg$^{-1}$]
$\Delta h_{s,w}$ - isentropic enthalpy drop of steam generated by molten salt, [kJkg$^{-1}$]

*Greek symbols*

$\eta_q$ - turbine efficiency, [%]
$\eta_e$ - generator efficiency, [%]
$\eta_b$ - boiler efficiency, [%]
$\eta_f$ - power generation efficiency of the boiler molten salt coupling system, [%]

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