RECENT PROGRESS IN WASTE HEAT RECOVERY TECHNOLOGY FOR BOILER FLUE GAS
A Comprehensive Review

by

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With the urgent need to improve energy utilization efficiency and reduce pollutant emissions, developing advanced technologies of flue gas waste heat recovery from coal-fired and gas-fired boilers has become a key issue in industrial green transformation. This paper systematically reviews the current research progress on the boiler flue gas waste heat recovery technologies. The working principles, key characteristics, and application status of sensible heat waste heat recovery, latent heat recovery, and synergistic recovery have been thoroughly analyzed. It is summarized that sensible heat recovery technologies are focused on coupling and optimizing them with existing thermal systems. Low temperature economizers and bypass flue gas design are adopted to improve overall utilization efficiency. Heat pumps exhibited significant advantages in latent heat recovery technologies due to their capability of upgrading the low grade thermal energy. Synergistic recovery technologies, utilizing innovative processes such as ceramic membrane condensers, heated and humidified air denitrification, and heat pump-coupled CO_2 *capture, have been demonstrated to achieve not only waste heat recovery but also reduce water consumption, pollutant emissions, and energy consumption for* CO_2 *capture. Therefore, the multi-objective collaboration in flue gas waste heat recovery presents significant potential for future work. To further enhance the utilization level of boiler flue gas waste heat, future research is recommended to focus on the following issues: constructing a full-temperature-range cascade utilization system for sensible and latent heat, optimizing the design of synergistic recovery processes, and improving the performance of thermal equipment for synergistic recovery.*

Key words: *flue gas waste heat, flue gas temperature, sensible heat recovery, latent heat recovery, heat pump, synergistic recovery, ceramic membrane condenser*

Introduction

Amidst the consistently rising global energy demand and escalating climate change, enhancing energy efficiency and reducing carbon-based energy use have become key strategies for industrial sectors to achieve a green and low carbon transition. As a ubiquitous energy carrier in the power industry and industrial processes, the flue gas from coal-fired or gas-fired boilers contains substantial amounts of medium to low temperature waste heat that is not effectively utilized. To prevent acid dew point corrosion from damaging thermal equipment and

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pipe-lines, boiler exhaust gas temperatures are typically restricted to 120-150 °C or even higher. The resulting exhaust heat loss accounts for 50%-80% of boiler heat losses and 3%-8% of the total input energy in power plants [1]. Directly releasing flue gas into the environment not only represents significant energy waste but also exacerbates greenhouse gas and pollutant emissions. Therefore, deeply exploiting the waste heat recovery potential of boiler flue gas and constructing high efficiency waste heat recovery systems are of paramount importance for advancing the dual carbon strategic goal [2].

Boiler flue gas contains a significant amount of sensible and latent heat. Sensible heat recovery aims to lower the flue gas temperature to recover energy, and it encounters fewer technical challenges due to the temperature limitation imposed by the acid dew point. Existing technologies include air preheaters, low temperature economizers, and bypass flues, which are crucial for boosting energy efficiency in coal-fired power plants. In contrast, latent heat recovery targets the heat released by water vapor in flue gas, posing greater challenges, especially with the growing use of hydrogen co-firing, which increases vapor content and makes recovery more essential [3]. Current technologies, such as condensing heat exchangers and heat pump systems, are still primarily in the research, validation, or pilot testing phases and have not been widely adopted by the industry. Furthermore, there is a growing interest in optimizing flue gas waste heat recovery to integrate it with water resource recovery, reduce pollutants, and capture carbon, resulting in improved energy efficiency and environmental benefits, making it a key area of research.

This paper reviews recent advances in boiler flue gas waste heat recovery, especially deep recovery efforts. It systematically examines the principles, application scenarios, and energy efficiency challenges of sensible heat recovery, latent heat recovery, and synergistic recovery technologies. Additionally, it highlights future directions in deep flue gas waste heat recovery. The goal is to provide useful references for the technological advancements and industrial applications of deep waste heat utilization from coal-fired and gas-fired boilers in China and worldwide.

Sensible heat recovery technology

Sensible heat recovery involves transferring high temperature sensible heat from boiler flue gas to feedwater or air through heat exchangers, thus lowering the exhaust gas temperature. Current sensible heat recovery technologies for boiler flue gas are relatively well-developed both in fundamental theory and component design. The primary research focus is on coupling sensible heat recovery processes with the overall thermal system, such as boilers and steam turbines in coal-fired power plants, to modify or optimize existing processes through efficient cascade utilization. This approach aims to enhance power generation output and decrease specific heat consumption.

Wang *et al.* [4] evaluated the technical feasibility of installing a low temperature economizer between the booster fan and wet flue gas desulfurization (FGD) unit in a 600 MW coal-fired power plant. By further recovering flue gas heat through the low temperature economizer to heat condensate water from low pressure heaters, the steam extraction from turbines for feedwater heating was reduced. Simultaneously, the lowered flue gas temperature decreased the spray cooling water consumption in the subsequent wet FGD unit. Analysis revealed minimal negative impacts on the power plant, resulting in a standard coal savings of 2-4 g/kWh and water savings of 25-35 tonne per hour during full-load operation. Wang *et al.* [5] further theoretically proved the superiority of this solution, emphasizing improvements in both the second-law efficiency and the thermal balance efficiency of the system.

Since the inlet flue gas temperature entering the low temperature economizer is relatively low, it can only be used to heat condensate water from low pressure heaters, resulting in limited energy savings. To address this, Xu *et al.* [6] and Yang *et al.* [7] proposed a novel boiler flue gas waste heat recovery design that relocates the low temperature economizer upstream of the electrostatic precipitator (ESP). In this system, the air preheater is divided into three-stages: the high temperature air preheater (HTAP), the main air preheater (MAP), and the low temperature air preheater (LTAP). The HTAP is positioned in a bypass flue parallel to the economizer in the main flue passage. Flue gas in the main flue passage sequentially passes through the economizer, MAP, low temperature economizer (LTE), LTAP, ESP, booster fan, FGD unit, and finally exits via the stack, fig. 1. Compared to the conventional design, this configuration enables the low temperature economizer to partially replace steam extraction from the No. 5 low pressure heater (RH5), thereby increasing air temperature through the HTAP by 16 °C. Thermodynamic calculations for a 1000 MW ultra-supercritical coal-fired power plant demonstrate that this design generates an additional net power output of 13.3 MW while reducing exergy loss by 10.3 MW. Separately, Ma *et al.* [8] installed high pressure and low pressure low temperature economizers in a bypass flue parallel to the air preheater. These units heat high pressure and low pressure feedwater sequentially. They also integrated a closed water circuit into the primary and secondary air waste heat systems to create a front-mounted liquid-medium air preheater. Performance tests under 100% and 75% turbine heat acceptance conditions on a 1000 MW double-reheat power generation unit showed that this system achieves a maximum coal-saving rate of 1.5% compared to traditional waste heat recovery schemes.

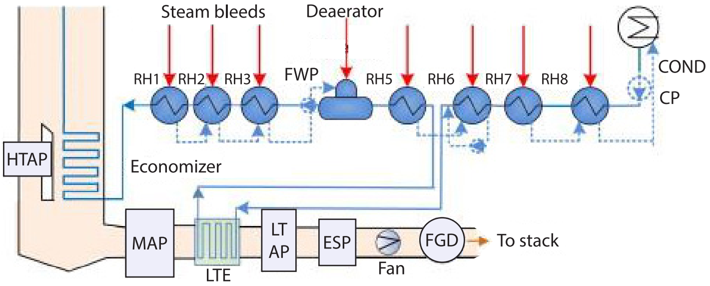

Figure 1. The novel cold-end design for flue gas heat recovery integrated with the steam cycle [7]

A case study [9] conducted a comparative thermo-economic analysis of three flue gas waste heat recovery configurations (low temperature economizer, staged air heating, and bypass flue) using a 600 MW ultra-supercritical coal-fired power plant. Results indicated reductions of 1.51 g/kWh, 1.71 g/kWh, and 2.81 g/kWh in coal consumption for the three configurations, respectively. The corresponding dynamic pay-back periods are 4.42 yeares, 8.66 years, and 3.29 years. Among them, the bypass flue configuration demonstrated the best techno-economic performance. Jiang and Hu [10] performed quantitative thermodynamic assessments of four typical waste heat recovery schemes for a representative Chinese 1000 MW power plant, evaluating the net power output increase, standard coal consumption rate reduction, heat transfer area of recovery exchangers, and fan power increment induced by the flue gas pressure drop. Their findings revealed that the high stage steam extraction replacement scheme outperformed low stage alternatives in both energy savings and waste heat recovery efficiency. Subsequent economic analysis incorporating fuel costs and equipment investments further identified an optimal performance point for the high stage replacement scheme, where marginal benefits peak with increasing recovered heat. Zhao *et al.* [11] designed a high efficiency cascade utilization system for waste heat recovery in the tail-end flue gas of power plant boilers. Theoretical analysis demonstrated an approximately 22% improvement in overall system efficiency, confirming the operational superiority of the proposed integrated system.

Latent heat recovery technology

Compared to sensible heat recovery from boiler flue gas, latent heat recovery technologies primarily focus on the phase change heat released during the condensation of water vapor in flue gas. Key implementation approaches include condensing heat exchangers, spray tower direct-contact heat exchange systems, and heat pump technologies encompassing both absorption and compression types.

Condensing heat exchangers

The basic structure of a shell-and-tube condensing heat exchanger [12] is illustrated in fig. 2. Cooling water flows through the tubes, while flue gas passes through the shell side, with the two fluids arranged in a counter-flow configuration. The cooling water reduces the flue gas temperature below its dew point, causing water vapor to condense and releasing latent heat. They developed a theoretical model for the coupled heat and mass transfer processes in this system. Their calculations established relationships between the quantity of heat transfer and the flue gas outlet temperature, the cooling water outlet temperature, the water vapor fraction, and the rate of water vapor condensation. Experimental validation using a pilot-scale prototype confirmed the model's accuracy. Poškas *et al.* [13] further found that the cooling water flow rate has a significant impact on the condensate flow rate and the local Nusselt number. Additionally, the cooling water temperature and vapor mass fraction have a substantial impact on the average Nusselt number. Rastegarpour *et al.* [14] highlighted that accurately predicting condensation heat release is essential for both exchanger operation and boiler thermal efficiency. Their use of a non-linear model predictive controller resulted in a 6% reduction in fuel consumption compared to conventional proportional-integral-derivative controllers.

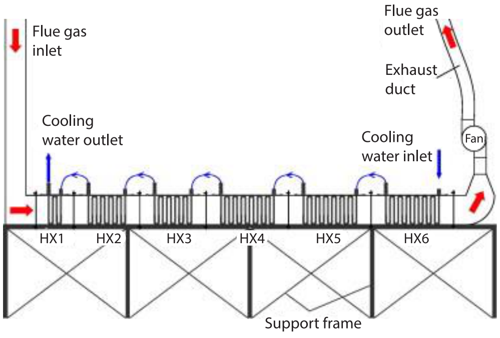

Figure 2. Recuperative condensing heat exchanger of the boiler flue gas [12]

In practical flue gas waste heat recovery, obtaining a cold heat sink at a sufficiently low temperature is often difficult. While the boiler or heat network return water is commonly used as the low temperature heat source, its temperature nears the flue gas dew point. Combined with the terminal temperature difference inherent in shell-and-tube condensers, these factors limit the effectiveness of latent heat recovery. Unlike the heating of the return water, Men *et al.* [15] developed a novel integrated system that couples a condensing heat exchanger with an enthalpy wheel to heat the air additionally. The process works flue gas first passes through the condensing heat exchanger to preheat the boiler return water. Then, the partially cooled gas enters the enthalpy wheel, where a desiccant-coated honeycomb structure enables simultaneous heat and moisture transfer between the flue gas and the incoming air. The heated, humidified air is supplied to the boiler as combustion air. This system achieves approximately a 5 °C increase in flue gas dew point temperature, an average waste heat recovery efficiency of 88%, and a boiler thermal efficiency of up to 106%.

Spray tower direct-contact heat exchange systems

Spray tower latent heat recovery technology utilizes a direct-contact heat exchange mechanism [16]. In this process, cooling water is atomized through nozzles and comes into direct contact with high temperature flue gas, resulting in a heat transfer that lowers flue gas temperature, thereby achieving the goal of latent heat recovery. Zhang *et al.* [17] constructed a direct-contact flue gas waste heat recovery prototype to analyze the effects of spray water temperature, liquid-to-gas ratio, and spray height on performance. They found that lowering spray water temperature and increasing spray height enhance heat transfer efficiency, and the efficiency improvement diminishes progressively with higher liquid-to-gas ratios. Experimental results showed a reduction in exhaust gas temperature from 102-33 °C, achieving a 14% waste heat recovery efficiency. Li *et al.* [18] numerically investigated the impact of flue gas velocity, concluding that excessive gas velocity compromises heat transfer performance.

Zhang *et al.* [19] proposed a falling-film plate direct-contact heat recovery device. In this design, cooling water enters through distribution holes to form liquid films on vertical falling-film plates, which directly contact upward-flowing flue gas from the spray tower bottom, allowing for the simultaneous recovery of sensible and latent heat. Prototype tests demonstrated approximately 20% higher efficiency than conventional spray towers. To further increase the gas-liquid contact area, Min *et al.* [20] developed enhanced configurations: falling-film plates with installed baffles (efficiency: 36.6%) and spray towers with staggered conical baffles (peak efficiency: 41%), as illustrated in fig. 3. Both designs significantly outperformed an empty spray tower. The highest improvement in heat transfer effectiveness was achieved at 41.0% for the optimal case compared to the empty tower case.

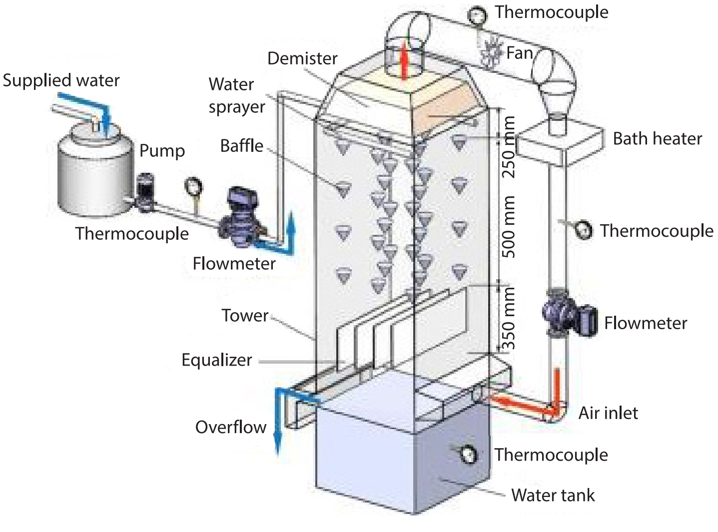

Figure 3. Direct contact waste heat recovery configuration using a falling film of flue gas [20]

Considering the characteristic of large bypass flue gas-flow in hydrogen-rich fuel boilers, Wang *et al.* [21] proposed arranging a spray tower before and after the economizer, featuring a closed water circuit that transfers heat between the two spray towers. In the front spray tower, flue gas exchanges heat with water, while in the rear spray tower, the heated water exchanges heat with air. The heated and humidified air is then sent to the boiler as combustion-supporting air. Thermodynamic calculations for a 4.2 MW gas-fired boiler showed that using a double-spray heat exchanger to recover flue gas latent heat increases system efficiency by 5%, which significantly surpasses the improvement from an economizer, at 0.4%-0.7%.

Based on spray-type direct contact heat exchange technology, Wei *et al.* [22] constructed a steam-pump system with flue gas condensers and air humidifiers at its core for latent heat recovery, as illustrated in fig. 4. Both the flue gas condenser and air humidifier utilize direct contact heat exchangers, employing spray cooling water to facilitate the process. The cooling water spray condenses water vapor in the flue gas, and the condensed water is pumped to the air humidifier as spray water to heat and humidify the combustion air. Experimental results demonstrated that this system can reduce the boiler exhaust temperature to below 30 °C and improve the system efficiency by more than 10%. Wang *et al.* [23, 24] further conducted a theoretical analysis and optimized system configuration for latent heat recovery via the steam-pump system, proposing a dual-spray tower subsystem to achieve full thermal waste heat recovery. This approach increases both the latent heat exchange efficiency and total waste heat recovery efficiency by 14%.

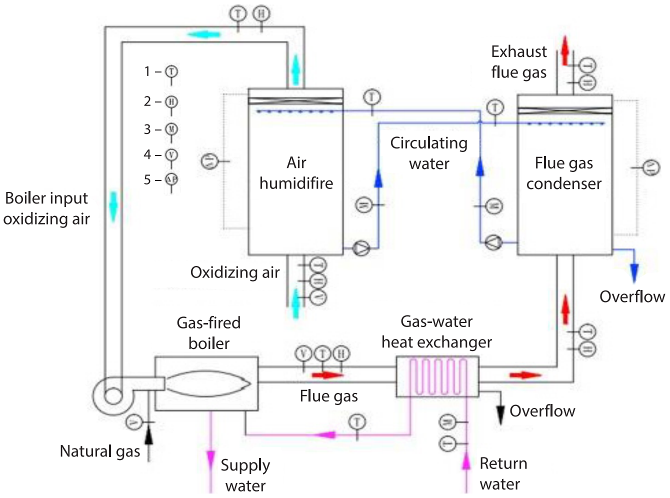

Figure 4. Vapor-pump system for waste heat recovery of flue gas [22]: *1 – temperature sensor, 2 – humidity sensor, 3 – electromagnetic flow meter, 4 – vortex flow meter, and 5 – differential pressure transmitter*

Heat pump systems

Heat pump technology drives the reverse Carnot cycle by consuming a small amount of high grade thermal or electrical energy, thereby pumping low grade waste heat in flue gas to a high grade thermal energy output, thereby improving the energy grade. Utilizing heat pump technology for flue gas waste heat recovery can overcome the limitations of cold source temperature, further reduce flue gas temperature, and achieve deep recovery. The deep recovery of boiler flue gas waste heat using heat pump technology mainly falls into two categories: absorption heat pump (AHP) technology and compression heat pump technology.

Absorption heat pump

The AHP primarily consists of a generator, condenser, evaporator, absorber, and heat exchanger. It utilizes waste heat from flue gas to change the concentration of the internal solution. Meanwhile, the phase change of the refrigerant supports heat transfer, increases the return water temperature, and boosts energy efficiency. Zhang *et al.* [25] observed that concentration differences limit the performance of traditional closed-loop AHP during solution circulation, preventing them from reducing exhaust gas temperatures to an optimal level. Therefore, enhancing the traditional closed-loop AHP system to make better use of waste heat from flue gases is essential.

Wei *et al.* [26] proposed an open absorption heat pump (OAHP) system for flue gas waste heat recovery, which reduces the evaporator and features a non-closed solution flow path. The heat pump interacts with the external flue gas through mass transfer processes. They calculated the thermal efficiency of compression-type, closed-loop absorption, and OAHP systems for flue gas waste heat recovery in gas-fired boilers. The results showed that the OAHP system performed the best, with its thermal efficiency improving by 1.5% compared to the closed-loop AHP system. Furthermore, Wei *et al.* [27] combined OAHP with direct contact heat exchangers to recover waste heat from flue gas after wet desulfurization in coal-fired boilers, and conducted an experimental verification at Jinan Beijiao Power Plant. It was found that the flue gas temperature could be reduced to 25 °C, resulting in an 8% increase in boiler efficiency. Yang *et al.* [28] examined the waste heat recovery system of OAHP with different solutions and found that using a lithium bromide-water solution and a calcium chloride-water solution could increase the efficiency of natural gas boilers by 16.3% and 15.3%, respectively. To reduce heat dissipation during solution regeneration, Zhang *et al.* [29] combined flash evaporation with OAHP and proposed a two-stage and partial regeneration OAHP system for recovering flue gas waste heat from coal-fired boilers, as shown in fig. 5. Compared to the original OAHP system, the heating coefficient of performance of the regenerative OAHP system combined with flash evaporation increased by 4.2% and 17.3%, respectively, after parameter optimization.

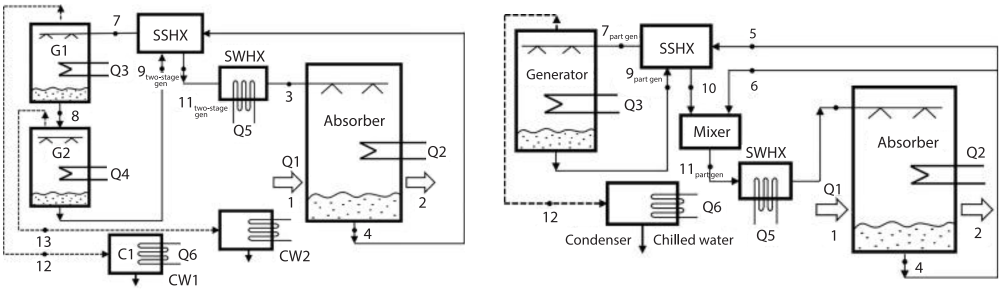

Figure 5. Modified OAHP system [29]

Cui *et al.* [30] proposed a two-stage flue gas waste heat recovery system integrated with an AHP. As the return water temperature approaches the flue gas dew point temperature, the flue gas first passes through the first-stage heat exchanger to heat the air, and then moves to the second-stage heat exchanger, where the low grade thermal energy is enhanced and transferred to the return water via the AHP. Compared to the basic return water heating system, this set-up can increase boiler efficiency by 8.81%. Ma *et al.* [31, 32] introduced a novel flue gas waste heat recovery system based on intelligent control and phase change heat transfer theory. Utilizing a lithium bromide-water solution as the intermediate heat transfer medium, the system enables heat transfer between boiler flue gas and air, thereby reducing corrosion of the heat exchanger before the FGD device and enhancing the efficiency of flue gas waste heat recovery. Zhang *et al.* [33] introduced a self-driven total heat recovery system for humid hot flue gas by combining an AHP with a three-stage flue gas heat exchanger. The key innovation is the segmented design of the heat exchanger, where the high temperature section, intermediate section, and condensation section are arranged separately. Heat from the high temperature flue gas powers the AHP. The intermediate section heats secondary water exiting the condenser for temperature control. The condensation section uses cooling water generated by the heat pump to lower the flue gas temperature below the dew point. This system demonstrates notable energy savings, reducing the flue gas outlet temperature to 41.39 °C and humidity to 31.39 g/kg, with the maximum heat recovery rate reaching 11.6%.

Compression heat pump

The compression heat pump operates the refrigeration cycle by using a small amount of external mechanical or electrical energy. It absorbs low temperature waste heat from flue gases through the evaporator and releases high temperature thermal energy in the condenser after being pressurized and heated by the compressor. Compared to the AHP, the compression heat pump provides benefits such as a high coefficient of performance, greater temperature reduction, and easier installation. These features make it a promising option for recovering latent heat from flue gas and waste heat. Since this technology utilizes external energy, current research primarily focuses on waste heat recovery from gas-fired boilers, with no reported applications in waste heat recovery for coal-fired power plants.

Sun *et al.* [34] developed an experimental test rig for recovering deep waste heat from flue gas by integrating an indirect-contact heat exchanger with a compression heat pump for a gas-fired boiler. The heat exchanger was installed after the economizer to cool further the flue gas, which exchanged heat with the cooling water generated by the compression heat pump. The heat recovered by the heat pump was used to heat the return water. To enhance the heating performance of the compression heat pump, a mixed refrigerant was employed in the heat pump cycle, allowing for temperature glide during phase change in the evaporator and condenser, thereby minimizing irreversible losses. Experimental results showed that the average heating COP of the heat pump was 5.42, the average exhaust gas temperature was reduced to 33.1 °C, the average temperature of the heating network return water increased from 42.9-60 °C, and the actual average waste heat recovery power accounted for 8.7% of the boiler's average value. Sun *et al.* [35] conducted a further theoretical analysis on the pairing and mass ratio of mixed refrigerants, finding that R134a/R245fa (with a mass ratio of 0.41:0.59) was the optimal refrigerant combination.

Jamil *et al.* [36] improved the traditional compression heat pump system by installing an air preheater at the tail of the evaporator and after the condenser, respectively. The preheated air is used for supplying boiler air and building heating. This system can reduce the flue gas temperature of the boiler from 120-30.32 °C, increase the boiler efficiency to 92.27%, and achieve a pay-back period of 5.44 years. Wu *et al.* [37] proposed a flue gas waste heat recovery system for condensing gas boilers driven by a gas engine-driven compression heat pump based on the concept of reducing the cold source temperature, as shown in fig. 6. The low temperature cooling water generated by the heat pump is used to recover the flue gas waste heat from the gas boiler and the gas engine, reducing the flue gas temperature from 50-60 °C to as low as 25 °C, and improving the primary energy utilization rate of the boiler by 10%-20%. Zhang *et al.* [38] proposed combining spray cooling with a compression heat pump to address the issues of poor heat transfer performance in surface heat exchangers and the need for low temperature spray water. After entering the spray tower, the flue gas exchanges heat with the spray water. The heated spray water is sent to the evaporator of the heat pump system, where it exchanges heat with the working fluid to cool it below the flue gas dew point temperature, and then re-enters the spray tower. Under the condition of a 50 °C inlet water temperature at the heat pump's condensation end, the COP of the heat pump can reach a value of 4.48. The exhaust gas temperature can be reduced to as low as 26.9 °C, and the maximum efficiency of the gas-fired boiler can reach 102.3%.

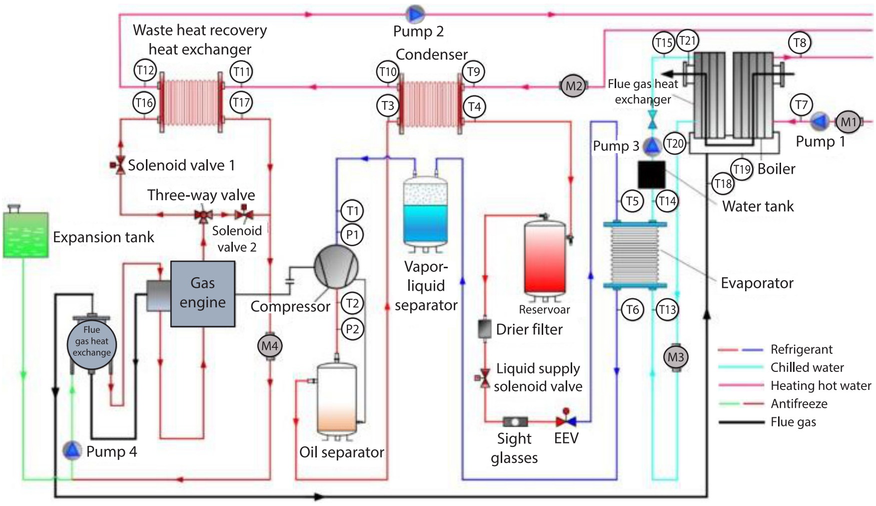

Figure 6. The schematic diagram of gas engine-driven compression heat pump and gas condensing boiler [37]

Jin *et al.* [39] proposed a technical route for waste heat recovery from boiler flue gas by combining the organic Rankine cycle (ORC) with a high temperature compression heat pump. The ORC working fluid and heat pump refrigerant absorb heat in an evaporator located after the air preheater. The ORC expander work is used to drive the heat pump compressor, while the condenser in the ORC heats the condensate water sent to the No. 1 low pressure heater. The condenser in the heat pump cycle heats the return water of the No. 3 low pressure heater. The uniqueness of this system lies in its ability to provide a self-sufficient power supply for the compression heat pump through the ORC system. Theoretical analysis for a 660 MW coal-fired unit shows that the maximum efficiency of boiler flue gas waste heat utilization reaches 17.35%.

Synergistic recovery technology

Coal-fired power plants consume a large amount of water during operation, so reducing water use in unit processes is essential for energy savings and emission reductions. For boilers with high lignite content, as well as natural gas and hydrogenated fuel boilers, the water vapor in flue gas is relatively high. As a result, the combined recovery of flue gas waste heat and water has become an effective way to cut energy and water consumption. Additionally, technologies like wet FGD, selective catalytic reduction for denitrification, and CO_2 capture consume significant energy. If recovering flue gas waste heat and controlling pollutants can work together to produce a synergistic effect, it could become the main solution the challenges of high energy use, pollution, and carbon emissions in power generation and industrial sectors.

Synergistic recovery of waste heat and water

Li *et al.* [40] proposed a system based on flue gas spray technology, adding a flash evaporator and a heat pump system after the desulfurization spray tower to recover water resources simultaneously. In this system, the washing water is pumped into the flash evaporator to generate water vapor, which is cooled by the cooling water supplied from the heat pump system in the condenser to produce condensate water. The condensate can be used to supplement the water for the wet FGD spray tower, and the remaining part can be used to supplement boiler water. Analytical calculations for a 300 MW coal-fired generating unit show that the amount of condensate water produced is positively correlated with the water vapor content in the flue gas. The authors also discussed the possibility of achieving zero water consumption in the wet FGD system of lignite-fired power plants.

Zhang *et al.* [41] improved the closed-loop AHP system, where flue gas passes through a regenerator, a flue gas-water heat exchanger, and an absorber in sequence for waste heat recovery, as illustrated in fig. 7. The evaporated water vapor then enters a closed condenser to obtain condensate water. The key feature of this system is the introduction of a vacuum environment, which reduces the boiling point of the solution, thereby reducing the dependence on high temperature heat sources during solution regeneration. A thermodynamic analysis of a 2.8 MW gas-fired boiler reveals that the flue gas temperature and moisture content are reduced from 200 °C and 120 g/kg to 53 °C and 46 g/kg, respectively. Compared with the traditional condensation system and the open-loop absorption system, the performance is improved by 28.3% and 23.1%, and the recovered condensate water can reach 0.36 tonne per hour. Hou *et al.* [42] proposed a system for synergistic recovery of flue gas waste heat and condensate water from gas-fired boilers by combining a compression heat pump with a LTAP. Theoretical calculations for a 29 MW gas-fired hot water boiler indicate that the flue gas temperature is reduced from 90-20 °C, resulting in a flue gas waste heat recovery rate of 14.8%. Additionally, the amount of condensate water recovered from the flue gas accounts for 54.1% of the boiler's make-up water.

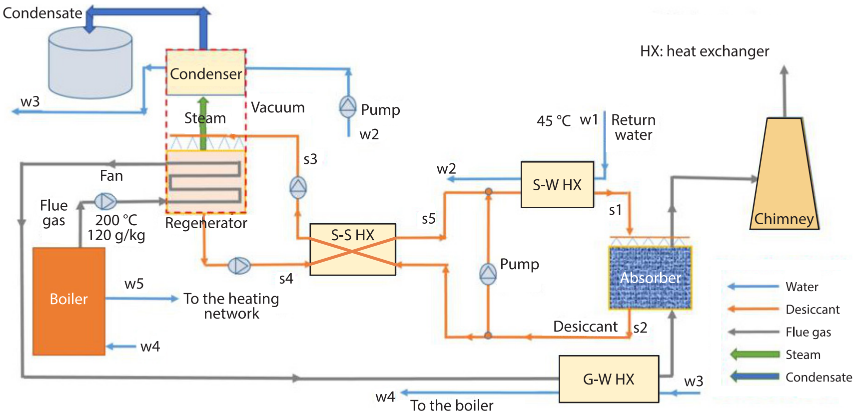

Figure 7. Flue gas waste heat and condensing water recovery based on closed-loop AHP system [41]

Yang *et al.* [43] conducted an optimization analysis of the operating parameters for a flue gas waste heat and water recovery system on a 330 MW coal-fired unit. Under the design conditions, the overall coal savings rate and water savings rate can reach 4.12 g/(kWh) and 15.34 kg/s, respectively. They also discussed the regulation strategy for system parameters under variable operating conditions. To ensure system safety, the maximum energy-saving potential is achieved by adjusting the flow rates of condensate water in the low temperature economizer and circulating water in the low temperature flue gas cooler, as well as adaptively modifying the operating parameters of the air preheater system.

Because the condensate water from return water is of high quality and can be used as boiler make-up water without additional treatment, a new technology [44] for recovering flue gas waste heat and condensate water based on porous ceramic separation membranes has gradually gained attention. The working principle of the porous ceramic membrane [45] is illustrated in fig. 8. High temperature flue gas and cooling water flow in a countercurrent manner outside and inside the tube, respectively. Water vapor in the flue gas condenses within the pores outside the tube, releasing heat. The condensate water is transported to the cooling side through the pore channels by capillary action or a pressure difference, facilitating heat and mass transfer. Meanwhile, non-condensable gases in the flue gas are trapped and cannot pass through the pore channels, ensuring that the condensate water remains of good quality. Several researchers systematically investigated the influence factors on water and heat recovery. Xiao *et al.* [46] analyzed the heat and mass transfer mechanism of a macroporous ceramic membrane condenser with an average pore diameter of 3 μm, highlighting that the condensation rate is a key factor affecting water recovery performance. The thermal resistance mainly exists on the flue gas side, and the thermal conduction resistance of the membrane accounts for only 1% of the total thermal resistance. Experimental tests have shown that the macroporous ceramic condenser exhibits excellent performance in recovering waste heat and water from flue gas, with the flue gas-flow rate, temperature, and cooling water temperature significantly influencing the recovered water flux and heat flux. Huang *et al.* [47] investigated the effects of permeability, materials (coal ash and alumina powder), and ceramic particle size on water and heat recovery in membrane condensers. Experimental results indicate that increasing membrane permeability enhances the efficiency of water and heat recovery. The alumina membrane, with its high thermal conductivity, achieves a 3%-10% higher water recovery rate than the coal ash membrane. Increasing ceramic particle size can improve permeability to promote recovery efficiency. However, it also reduces thermal conductivity, weakening recovery performance, and indicating an optimal ceramic particle size.

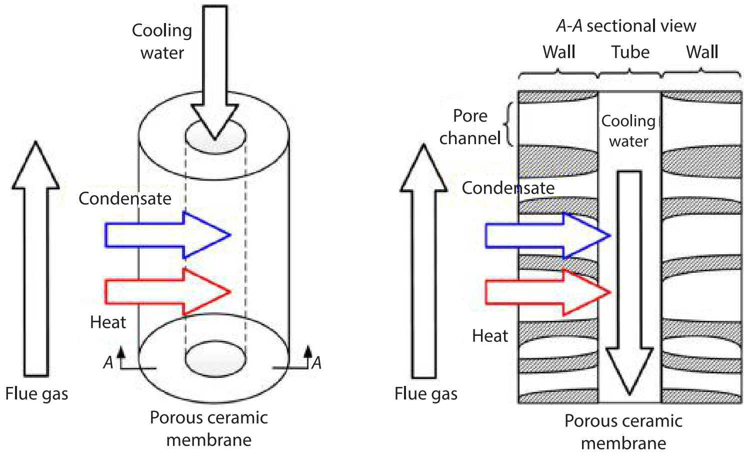

Figure 8. Heat and mass transfer progress of the porous ceramic membrane [45]

Wang *et al.* [48] performed pioneering research work and developed a second-generation ceramic membrane condenser with an improved tube bundle design, altered flow directions of flue gas and cooling water, and a modular set-up. The test results showed that this technology can boost boiler efficiency by over 5% and recover 40% of the water vapor in the boiler flue gas. Yang and Yuan [49] proposed a two-stage ceramic membrane condenser system to address the limitation of single-stage membrane condensers in recovering waste heat due to the restriction of cooling water temperature. Flue gas passes through a shell-and-tube membrane condenser to heat return water and a plate-type membrane condenser to heat and humidify air in sequence. Compared to the single-stage membrane condenser system, the total waste heat recovery efficiency of this system increases from 45.3%-77.0%, and the boiler thermal efficiency reaches 105.4%. Luo *et al.* [50] arranged ceramic membrane condensers after the ESP and before the chimney in a coal-fired power plant to recover boiler flue gas waste heat and water. Their thermodynamic analysis of a 660 MW coal-fired unit shows that the flue gas waste heat recovery power can reach 45.95 MW, the condensate water recovery can reach 26.62 kg/h, and up to 60% of the evaporated water in the FGD can be supplemented.

Synergistic recovery of waste heat and pollutant emission reduction

For the reduction of fine solid particles, Westerlund *et al.* [51] enhanced the OAHP system for flue gas waste heat recovery in small biomass boilers by installing a filter at the solution outlet of the absorber to remove solid particles during heat exchange with the flue gas, thereby realizing synergistic recovery of flue gas waste heat and solid particles. Experimental results show that the system can increase the boiler heat output by 40% and effectively filter 33%-44% of solid particles in the flue gas. Li *et al.* [52] applied a microporous ceramic membrane condenser for flue gas waste heat recovery and fine particle capture. Cooling water flows inside the ceramic membrane tubes, while high temperature flue gas passes through the outer surface of the ceramic membrane tubes. They predicted the application prospects of ceramic membrane tube condensers in coal-fired power plants. Taking a 330 MW coal-fired unit as an example, with an annual operating time of 5500 hours, the payback period is 2.1 years.

To reduce nitrogen oxides, NO_x, Zhao *et al.* [53] designed a flue gas waste heat recovery system combined with denitrification for gas-fired boilers, aiming to boost energy efficiency and reduce pollutant emissions. Considering the high latent heat of flue gas and NO_x as the main pollutants, the flue gas first undergoes low temperature intensive oxidation with ozone, which converts some nitric oxide into higher-valent NO_x, before being directed into a spray tower for absorption by cooling water. The cooling water becomes acidic after absorbing NO_x and needs neutralization with alkaline solutions. Meanwhile, after spraying in the tower, the cooling water exchanges heat with the boiler flue gases and is further heated by an AHP for distribution the heating network. Experimental results show that the flue gas temperature drops from 62-23.4 °C, and the return water temperature reaches 43.9 °C. When the ozone dosage is 8 kg/h and the pH of the spray cooling water is between 7.5 and 8, the NO_x content in the tail flue gas falls below 30 mg/Nm^3. Zhang *et al.* [54] proposed a novel flue gas waste heat recovery system that integrates spray-type condensation waste heat recovery with combustion air humidification, as shown in fig. 9. The system divides the spray tower into two sections: a flue gas heat exchange section and an air humidification section. In the flue gas heat exchange section, spray water undergoes direct contact heat exchange with the boiler flue gas. In the air humidification section, combustion air performs heat and mass transfer with the heated spray water, and is then sent to the boiler burner inlet after heating and humidification. The humidified combustion air can increase the dew point temperature of the flue gas after combustion, which, on the one hand, facilitates the recovery of flue gas latent heat and, on the other hand, enables low nitrogen combustion in gas-fired boilers. Laboratory test results show that when the moisture content of combustion air increases to 49.0 g/kg, the waste heat recovery efficiency of gas increases by 12.2%, and the NO_x emission is reduced to 50.0 mg/m³. Guo [55] combined a compression heat pump with combustion air humidification achieve synergistic treatment of flue gas waste heat recovery and low nitrogen emission systems, analyzing the main influencing factors on waste heat recovery and nitrogen reduction effects. Experimental test results show that when the humidification water volume is 200 Lph, the moisture content of the combustion air is 32.5 g/kg, the nitrogen reduction rate is 35.2%, the flue gas waste heat recovery rate is 21.3%, and the boiler efficiency reaches 103.5%.

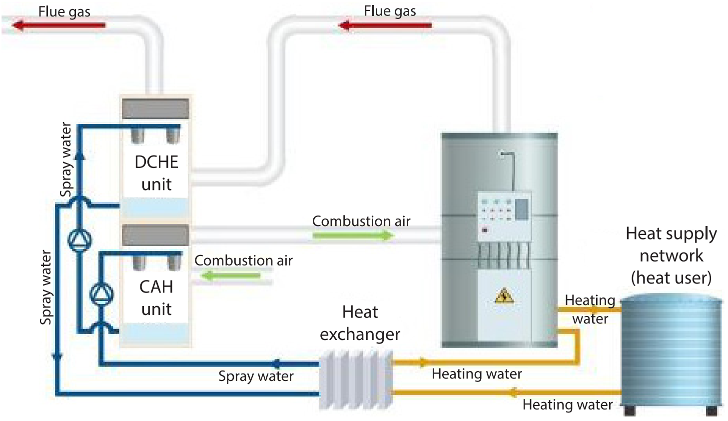

Figure 9. Spray tower type flue gas waste heat recovery coupled low nitrogen emission system [54]

Synergistic recovery of waste heat and carbon emission reduction

For post-combustion CO_2 capture systems, the heat needed for CO_2 desorption and regeneration in the stripping tower usually comes from the extraction steam of low pressure turbines. Therefore, utilizing low grade thermal energy from flue gas waste heat for CO_2 capture to reduce or replace turbine extraction steam has become a research focus.

Dai *et al.* [56] coupled the boiler flue gas waste heat with the CO_2 capture scheme, that is, using a double-absorption temperature-raising heat pump to improve the grade of the low pressure turbine exhaust steam to match the CO_2 regeneration temperature, while recovering the flue gas heat to increase the circulating water temperature entering the heat pump. The process simulation results show that this scheme reduces irreversible losses in the CO_2 regeneration process, resulting in an efficiency increase of 2.06% compared to the conventional capture scheme. Garlapalli *et al.* [57] proposed a process flow for coal-fired power plants integrating direct heat exchangers and carbon dioxide capture, shown in fig. 10. Using silicone oil as the heat transfer medium, the direct heat exchanger recovers the flue gas heat for heating, and then achieves thermal and phase equilibrium with the amine-rich solvent through a flash tank and a separation tank, to transfer the recovered flue gas heat to the amine-rich solvent to reduce the heat load of the stripping tower. The research results indicate that the integrated scheme can reduce the heat load of the stripping tower by 15.1%-31.2%, resulting in an approximately 0.5% increase in the power plant's net efficiency. Chen *et al.* [58] focused on the efficient utilization of CO_2 after capture in coal-fired power plants, and further coupled the CO_2 refrigeration cycle with a hot water heating module. They conducted a thermodynamic system analysis on a 300 MW coal-fired unit, and the results showed that when the CO_2 capture rate is 13.1%-72.9%, the energy utilization efficiency of the new system is increased by 1.2%-5.6%, the exergy efficiency is increased by 7.7%-5.8%, and the comprehensive energy consumption for CO_2 capture is reduced by 79%.

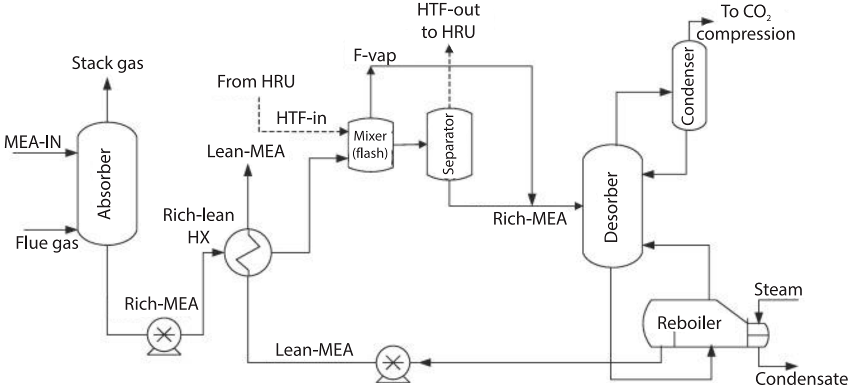

Figure 10. Schematic of CO_2 capture process with heat recovery unit (HRU) integration [57]

Based on the ionic liquid-based CO_2 capture technology scheme, Wang [59] utilized ionic liquids as the medium for flue gas waste heat recovery and tested the thermal and chemical stability of these ionic liquids throughout the cycle in the laboratory. The ionic liquids can effectively reduce the flue gas temperature, achieving a heat recovery efficiency of 41.9%, which preliminarily demonstrates the feasibility of the flue gas waste heat recovery and CO_2 capture technology scheme based on ionic liquids. Gao *et al.* [60] conducted an experimental test using a prototype built by combining a ceramic membrane with waste recovery. In the test, the absorption solution was a double-cationic ionic liquid. The maximum CO_2 absorption amount reached approximately 1.605 mol CO_2 per mol amine at ambient temperature conditions.

Challenges and future directions

Challenges

Sensible heat recovery technology focuses on capturing high temperature sensible heat by lowering flue gas temperatures. Its core objective is to integrate with the production processes of boilers and steam turbines in coal-fired power plants. Through efficient cascade utilization, original processes are enhanced or optimized to achieve increased power generation and reduced heat consumption. The primary implementation methods of this technology include adding air preheaters, low temperature economizers, and bypass flues, achieving a heat recovery efficiency of 41.9%, which is demonstrated at the tail end of the boiler flue. However, sensible heat recovery faces limitations due to the lower flue gas temperature threshold. If the exhaust gas temperature is too low, acidic substances in the flue gas may condense, leading to acid dew point corrosion of thermal equipment and pipe-lines, which significantly restricts the extent of sensible heat recovery. For existing technologies, such as low temperature economizers, which recover sensible heat from flue gas, a low inlet flue gas temperature allows only the heating of condensate water in low pressure heaters. This creates a substantial bottleneck in energy-saving efficiency, hindering further significant improvements. Integrating sensible heat recovery technology with thermal systems such as boilers and steam turbines is relatively complex. In practical settings, coordinating multiple components increases the difficulty of system optimization and may impact the overall safety and stability of the unit.

The latent heat recovery technology is primarily designed to recover the phase change latent heat released during the condensation of water vapor in flue gas. Its main technical paths include condensing heat exchangers, spray tower direct contact heat exchange, and heat pump technology. During latent heat recovery, the condensation of water vapor in flue gas forms acidic liquids, which can cause severe corrosion equipment materials. The corrosion resistance of commonly used materials is insufficient, resulting in increased equipment maintenance costs and a higher frequency of replacements. Latent heat recovery requires low temperature cold sources, however, in practical applications, it is challenging to obtain suitable low temperature cold sources. If boiler or heat network return water is used as the cold source, its temperature is close to the flue gas dew point temperature, resulting in unsatisfactory latent heat recovery efficiency. In this sense, the heat pump technology drives the reverse Carnot cycle by consuming a small amount of high grade thermal energy or electric energy, thereby pumping the low grade waste heat in the flue gas to a high grade thermal energy output, thereby breaking through the limitation of the cold source temperature and enabling deep recovery. However, the equipment investment cost of heat pump technology is high, while the economic benefits from recovered heat are relatively limited. Under the current energy price system, such economic contradictions are prominent, restricting the large-scale promotion and application of this technology.

The synergistic recovery technology enables the enhanced recovery of waste heat, the recovery of water resources, the reduction of pollutant emissions, carbon capture, and other processes through system integration and process innovation, showcasing the technical potential to shift from single energy saving to multi-objective governance. However, the synergistic recovery technology focuses on the following challenges. The synergistic recovery technology must achieve multiple objectives simultaneously, including waste heat recovery, water resource recovery, reduction of pollutant emissions, and reduction of carbon emissions. There may be mutual constraints among these objectives, making the realization of synergistic optimization in system design and operation a significant challenge. The synergistic recovery technology involves the integration of multiple processes and equipment, including heat pumps, ceramic membrane condensers, and ozone generators. The complexity of process integration leads to great difficulties in system debugging and operation, making the system prone to failures. Most importantly, there is a lack of a comprehensive and scientific performance evaluation system to measure the overall benefits of synergistic recovery technologies, which makes it difficult to accurately compare and optimize different technical schemes.

Future directions

For sensible and latent heat recovery, it is advisable to conduct comprehensive research on the synergistic effects of ORC power generation, heat pump heating, low temperature membrane condensation, and other technologies to develop a cascade utilization system that encompasses the entire temperature range of flue gas. This approach will facilitate more efficient recovery of heat. Additionally, the innovative design of cold source systems explores the use of low grade cold sources such as industrial wastewater and groundwater or creates efficient refrigeration systems to provide low temperature cold sources. This can enhance the temperature matching between the cold source and flue gas, thereby improving the efficiency of latent heat recovery. It is also suggested that the optimized design be enhanced to integrate heat pump recovery technology with thermal systems. By utilizing advanced simulation calculations and control technologies, achieve precise co-ordination of each system link while maximizing recovery efficiency and ensuring equipment safety. Moreover, concentrating on the research and development of corrosion-resistant materials, such as innovative ceramic materials and high performance alloys, aims to enhance the corrosion resistance of equipment, reduce maintenance and replacement costs, and prolong the service life of equipment.

For the synergistic recovery technology, it is advisable to develop advanced multi-objective collaborative optimization algorithms that leverage technologies such as artificial intelligence to enhance the design parameters and operational strategies of synergistic recovery systems, thereby achieving an optimal balance among various objectives. Additionally, an innovative research study on the integration of synergistic recovery processes should be conducted to simplify process flows through technological innovation, improve equipment performance, and enhance the reliability and operability of the system. Furthermore, it is crucial to develop a comprehensive performance evaluation system that encompasses various dimensions, including energy efficiency, environmental benefits, economic advantages, and technical feasibility, to provide a scientific basis for the research and development, application, and promotion of synergistic recovery technologies.

Conclusions

By reviewing the research status of the deep utilization technology of boiler flue gas waste heat, the characteristics and impacts of various flue gas waste heat utilization technologies are systematically examined from three aspects: sensible heat recovery technology, latent heat recovery technology, and synergistic recovery technology. The main conclusions are as follows.

- The sensible heat recovery technology of boiler flue gas has significantly reduced unit coal consumption by coupling thermal systems and process reconstruction, however, its potential is limited by the minimum flue gas temperature and the risk of acid dew point corrosion. The latent heat recovery technology surpasses the limitation of dew point temperature, lowering exhaust gas temperature to below 30 °C, which can increase boiler efficiency by 10%-15%. However, it faces challenges such as material corrosion, inadequate matching of cold sources, and economic contradictions. It is recommended to conduct research on a full-temperature-range cascade utilization system for boiler flue gas and to develop energy level matching technology for organic Rankine cycle power generation, heat pump heating, and low temperature membrane condensation, further to enhance the flue gas waste heat utilization efficiency.
- The synergistic recovery technology of boiler flue gas, including waste heat/water, waste heat/pollutant emission reduction, waste heat/carbon emission reduction, achieves a synergistic enhancement of waste heat recovery and environmental benefits through system integration and process innovation, demonstrating the technical potential to transition from single energy saving to multi-objective governance. It is recommended to conduct further optimization of system integration and research on improving the performance of thermal equipment (such as ceramic membrane condensers).

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