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A Review on the Development of Energy Efficiency Optimization Technologies for Regenerative and Reheating Systems in Coal-Fired Power Plants

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Abstract— *Coal-fired power plants in China remain an important pillar for the safe operation of the power grid. Improving the energy efficiency of the regenerative system is key to reducing carbon emissions and lowering the net coal consumption rate for power supply. This paper reviews the thermodynamic essence and equipment composition of the regenerative system in coal-fired units, analyzing the causes of energy losses such as high parameterization, irreversible heat transfer losses, and improper extraction steam flow allocation. It evaluates the research status, advantages, and limitations of three mainstream energy efficiency optimization technologies: traditional equipment modification, operational mode optimization, and intelligent algorithms/data-driven approaches. The paper identifies core shortcomings of current technologies, including rigid design concepts, lack of full lifecycle equipment maintenance, lagging drain control, and weak intelligent monitoring and diagnosis. Finally, it envisions that future regenerative systems will evolve toward wide-load high-efficiency design, multi-technology integrated optimization, and coupling with thermal storage/renewable energy sources, forming comprehensive energy systems, providing a reference for energy-saving retrofits and technology development in coal-fired power plants.*

Keywords—coal-fired power; plant;exergy loss; energy efficiency optimization; regenerative and reheat system; intelligent algorithm

I. INTRODUCTION

Coal-fired power plants in China are still a critical force ensuring the safe operation of the power grid, and they are also the largest source of CO_2 emissions. To effectively reduce carbon emissions in the short term, the most feasible approach is to improve unit operating efficiency and reduce the net coal consumption rate. The regenerative system is a key part of the thermal cycle of coal-fired units. It uses steam extracted from the turbine to heat boiler feedwater, theoretically increasing thermal efficiency by more than 10%. However, in practice, problems such as heater fouling, excessive terminal temperature difference, and improper water level control are common, causing energy losses and increasing coal consumption.

In recent years, three main technical routes for energy efficiency optimization of regenerative systems have emerged globally. The first is traditional equipment modification, such as optimizing the drain system and upgrading extraction pipelines, which can fundamentally address hardware defects but suffers from high costs and limited generality. The second is operational optimization, which adjusts operating parameters to adapt to load changes, offering low cost but unable to solve energy efficiency issues caused by equipment structure. The third involves intelligent algorithms and data-driven technologies, enabling dynamic parameter optimization and fault prediction, but requiring high-quality data and lacking sufficient engineering implementation.

Despite continuous progress, several prominent issues remain in practical applications: rigid design concepts leading to poor adaptability to wide-load conditions; lack of full lifecycle management for equipment aging; slow response of drain regulation mechanisms resulting in low energy cascade utilization efficiency [1]; and weak intelligent monitoring and diagnosis capabilities, making closed-loop control difficult [2].

This paper systematically reviews major research achievements in energy efficiency optimization of regenerative systems in coal-fired units, classifies and evaluates existing optimization methods, points out shortcomings in practical applications, and forecasts future development trends, aiming to provide a reference for energy-saving retrofits and technology development in power plants.

II. THEORETICAL BASIS OF REGENERATIVE SYSTEMS IN COAL-FIRED UNITS

The regenerative system (feedwater regenerative heating system) of coal-fired units is a key component of the thermal cycle in modern large-scale thermal power plants and a core subsystem determining unit thermal economy. It organically connects equipment such as the steam turbine, boiler, and condenser, using steam that has done partial work in the turbine (regenerative extraction) to heat boiler feedwater in heaters, so that feedwater enters the boiler at a higher temperature. This process modifies the thermodynamic characteristics of the Rankine cycle, achieves energy cascade utilization, and has significant value for tapping energy-saving potential and optimizing operation modes.

2.1Thermodynamic Essence and Economic Mechanism of the Regenerative Cycle

The first law (energy conservation) and second law (entropy increase) of thermodynamics are the theoretical foundations. In the basic Rankine cycle, a large amount of latent heat is released from turbine exhaust to circulating water in the condenser, constituting a huge "cold source loss" (typically exceeding 50% of fuel calorific value). The regenerative cycle reduces the amount of steam discharged into the condenser, and by extracting a portion of steam to heat condensate or feedwater, although the work done by the extracted steam decreases, its thermal energy remains within the system to heat feedwater, significantly reducing cold source loss and thereby improving cycle thermal efficiency [3][7].

The first law alone cannot fully explain the regenerative mechanism; the concept of "exergy" must be introduced. The large temperature difference between high-temperature flue gas and low-temperature working fluid (feedwater) in the boiler is a major source of irreversible loss. According to Lin Wanchao, the larger the temperature difference in heat transfer, the greater the exergy loss [5]. The regenerative system raises feedwater temperature from 30–40 °C to 250–300 °C or even higher, greatly reducing the average temperature difference for heat transfer in the boiler, decreasing the irreversibility of combustion and heat transfer processes, and improving energy conversion quality.

2.2 Equipment Composition and Thermal Characteristics of the Regenerative System

Heater circuit system: The core equipment is the regenerative heater, which is divided into surface type and direct contact type based on steam-water contact mode. Surface heaters are more widely used in modern units and have two important terminal difference parameters: Upper terminal difference: the difference between steam saturation temperature and outlet feedwater temperature. Large-capacity units often have an built-in steam cooling section, using steam superheat to further heat feedwater, allowing the upper terminal difference to be negative and improving economy. Lower terminal difference: the difference between the drain temperature of the heater and the inlet feedwater temperature. Modern heaters typically have a drain cooling section, using inlet low-temperature feedwater to cool the drain, recovering heat and preventing "flashing" in the next-stage heater, reducing thermal economy losses.

Direct-contact heater and deaerator: In a direct-contact heater, steam and water mix directly with no terminal difference, providing the highest thermal economy. As the only direct-contact heater in the system, the deaerator not only heats but also removes non-condensable gases such as dissolved oxygen to prevent equipment corrosion.

2.3 Regenerative Parameter Distribution and Optimum Feedwater Temperature

The thermal economy of the regenerative system depends on the number of regeneration stages, the degree of feedwater temperature optimization, and the distribution of extraction steam among stages. Theoretically, more regeneration stages yield higher cycle efficiency, but also increase equipment investment and system complexity. Currently, China's million-kilowatt ultra-supercritical units typically use an "eight-stage regenerative" system (including three high-pressure heaters, one deaerator, and four low-pressure heaters) or a "nine-stage regenerative" system, considered optimal after technical and economic comparison. In an ideal regenerative cycle, efficiency is highest when the enthalpy rise of each heater is equal, known as the "equal enthalpy rise distribution principle." However, in practice, considering feed pump power consumption, cost, and layout constraints, an "equal temperature rise distribution" or a modified scheme is often used to approach the theoretical optimum.

2.4 Thermal Balance Calculation and Unit Consumption Analysis of the Regenerative System

Quantitative analysis of the regenerative system is fundamental for power plant design and operation.

Conventional thermal balance method: This method uses mass and energy conservation laws to simultaneously solve extraction flow rates for each stage, formulating heat balance equations for each heater and junction points. Ye Jiangming provides a detailed explanation of the extraction coefficient solution method for the equation set [4]. This method is logically rigorous and suitable for accurate calculation under design conditions, but becomes cumbersome for off-design or complex topologies.

Unit consumption analysis theory: To address limitations of conventional methods, unit consumption analysis treats the thermal system as a whole, using the "unit consumption" indicator to directly analyze the impact of local parameter changes on overall coal consumption. Zha Yonglong points out its high value in unit performance monitoring and fault diagnosis; when heater terminal differences, pressure drops, and other parameters deviate from design values, unit consumption analysis can accurately calculate the specific impact on net coal consumption [6][8].

Based on the above summary and analysis of global research on regenerative systems in coal-fired units, Chinese scholars have focused on thermodynamic mechanisms and parameter optimization, achieving rich results in these areas. They have studied the economic mechanism of regenerative systems from perspectives such as the first law, second law, and equipment characteristics. Most domestic scholars agree that regeneration improves cycle thermal efficiency by reducing cold source loss and increasing feedwater temperature, considering regeneration a key technology for improving thermal power unit efficiency. Their work focuses on enthalpy rise distribution principles, number of regeneration stages, terminal difference optimization, etc. International scholars have concentrated on exergy analysis and system modeling, arguing that regenerative system optimization should combine exergy efficiency and economics, emphasizing global optimization and constructing various optimization models. Although domestic and international research perspectives differ, showing a diversified trend, overall research focuses on thermodynamic mechanisms and parameter optimization of regenerative systems, with practical studies concentrating on conventional thermal power units, and extensive research has been conducted on the population of regenerative systems in conventional units.

Relatively speaking, China has conducted case studies on ultra-supercritical coal-fired units and regenerative systems under special operating conditions, with many case types, industry types, and population types focused on ultra-supercritical units. However, studies on million-kilowatt ultra-supercritical units and nine-stage regenerative systems are relatively few. International research on ultra-supercritical units and nine-stage regenerative systems has provided an important foundation for the development of regeneration theory, played a significant role in promoting practical applications, and provided substantial case studies and references for this paper. Given the theoretical references and countermeasures available from case studies on regenerative systems, and considering that these studies have relatively limited breadth in expanding the research objects and scope of regenerative systems, this paper takes a million-kilowatt ultra-supercritical unit as a specific research case and focuses on the nine-stage regenerative system as a special population, thereby extending and complementing the current research scope.

III. ANALYSIS OF ENERGY EFFICIENCY LOSSES AND INFLUENCING FACTORS IN REGENERATIVE SYSTEMS OF COAL-FIRED UNITS

The thermal cycle efficiency of coal-fired power generation units determines the coal consumption for power generation and carbon emission intensity. The regenerative system, as the core link in the Rankine cycle that returns heat from turbine extraction to boiler feedwater, determines the unit's thermal economy. The regenerative system reduces the irreversibility of heat absorption loss in the boiler by means of temperature-cascaded utilization. However, in actual operation, unreasonable extraction steam parameter configuration, excessive heat transfer temperature differences, and insufficient adaptability to variable load conditions lead to irreversible energy losses within the system.

3.1 New Requirements for the Regenerative System Due to Ultra-Supercritical Parameter Upgrades

In recent years, coal-fired power generation technology has moved toward higher steam parameters. Main steam temperatures have gradually increased from traditional subcritical 540 °C to ultra-supercritical 600 °C or even 700 °C levels. The regenerative system must be upgraded accordingly due to the higher turbine parameters. Higher parameters in ultra-supercritical turbine units, coupled with increased steam temperatures, significantly increase the difficulty of upgrading regenerative system parameters [10]. The most prominent issue is the excessive superheat of regenerative extraction steam under high parameter conditions, leading to enlarged heat transfer temperature differences, causing significant exergy loss and reducing thermodynamic benefits [10].

Currently, a core energy efficiency problem is the excessive superheat of extraction steam in the regenerative system of 700 °C reheat ultra-supercritical units. This problem is particularly acute in high-parameter units: on one hand, the high-temperature energy carried by superheated extraction steam cannot be fully absorbed by the feedwater upon entering the heater; on the other hand, the large heat transfer temperature difference violates the "temperature matching" principle, resulting in a decrease in overall system exergy efficiency [9]. This indicates that energy efficiency losses in regenerative systems originate not only from equipment itself but also from insufficient adaptability of the system structure.

3.2 Irreversible Heat Transfer Loss: The Core Source of Energy Efficiency Loss

According to the second law of thermodynamics, energy efficiency losses in regenerative systems originate from the heat transfer process, which is irreversible. In conventional extraction steam regenerative configurations, most steam extracted from the turbine has a thermal potential higher than the inlet feedwater temperature of the heater. This temperature difference causes entropy increase during heat transfer, leading to work loss.

This problem is more pronounced in double-reheat units. The regenerative system of such units has large heat transfer losses. A pre-steam cooler scheme can reduce the superheat of some high-pressure heaters, but this merely shifts the problem to the pre-steam cooler without solving it fundamentally [14]. In other words, local reduction of superheat does not fundamentally improve energy efficiency loss; it merely migrates within the system rather than being substantially reduced.

3.3 Improper Extraction Steam Flow Allocation and Off-Design Energy Efficiency Degradation

Improper allocation of extraction steam flow is another factor causing energy efficiency loss in regenerative systems. The distribution of extraction steam flow follows the principle of energy cascade utilization, and the rationality of flow allocation directly affects the unit's heat rate.

Research by Wang Huijie et al. shows that the heat rate optimization amount decreases with increasing load. After optimization, the extraction flow rates of high-pressure heaters are lower than before optimization, while those of low-pressure heaters increase [12]. This reverse optimization law reveals a defect of traditional regenerative systems: excessive extraction at high-pressure stages under high load reduces the steam's work path in the turbine, leading to decreased high-pressure cylinder work capacity; under low load, the flow ratio imbalance among heaters further increases heat rate.

Chen Haiping et al. calculated energy losses for each heater stage in a 300 MW thermal power unit and found that the additional unit consumption of high-pressure heaters is higher than that of low-pressure heaters, with some high-pressure heaters being the weakest links [13]. This indicates that energy efficiency losses in regenerative systems are not uniformly distributed among stages but concentrated in key heaters, providing a clear theoretical basis for energy-saving retrofits.

3.4 Energy Saving Potential from Waste Heat Recovery and System Integration

The energy efficiency improvement potential of regenerative systems comes not only from fine-tuning extraction steam parameters and flow rates but also from comprehensive utilization of waste heat resources. Engineering examples show that applying this technology to a 660 MW air-cooled unit reduced the net standard coal consumption rate by about 150% more than the traditional low-temperature economizer scheme on average, significantly improving thermal economy [11]. This technical path suggests that energy efficiency losses in regenerative systems are not isolated but closely related to boiler exhaust waste heat, cold-end losses, etc. Breaking the energy independence between systems is key to achieving overall energy efficiency breakthroughs.

In a study of a dual-unit regenerative system on a 1000 MW ultra-supercritical double-reheat unit, the dual-unit regenerative scheme improved the heat transfer effect of the entire feedwater system and deaerator, significantly reducing the superheat of extraction steam for some high-pressure heaters. The exergy efficiency of some equipment reached above 0.96, and the total exergy loss was halved compared to a scheme without pre-steam coolers and reduced by 51% compared to a scheme with pre-steam coolers [14]. This level of energy efficiency improvement means that deep retrofits based on system restructuring can fundamentally solve the irreversible loss problem of regenerative systems more effectively than local optimization.

3.5 Summary

In summary, energy efficiency losses in regenerative systems of coal-fired units mainly originate from three aspects: first, the increased heat transfer temperature difference and exergy loss due to increased extraction steam superheat under the trend of high parameterization [9][10]; second, improper extraction flow allocation across the full operating range, especially excessive extraction at high-pressure stages under high load that reduces steam work capacity [12]; third, off-design energy efficiency degradation caused by inconsistent load characteristics among multiple devices. These energy losses intertwine and couple with each other, forming a deep barrier to improving the thermal economy of coal-fired units.

From a technical path perspective, energy efficiency optimization of regenerative systems has evolved from early single-point parameter adjustment to system-level restructuring. The unit consumption analysis framework reveals the distribution characteristics of energy losses across heater stages [13], providing a powerful tool for accurately identifying energy-saving weak links. Looking forward, as coal-fired power generation transitions toward deep peak shaving and wide-load operation, the off-design energy efficiency degradation problem of regenerative systems will become increasingly prominent. How to achieve dynamic optimal matching between extraction flow and load through intelligent control systems will be a new frontier in research on controlling energy efficiency losses in regenerative systems.

Table captions appear centered above the table in upper and lower case letters. When referring to a table in the text, no abbreviation is used and "Table" is capitalized.

IV. RESEARCH STATUS AND REVIEW OF ENERGY EFFICIENCY OPTIMIZATION TECHNOLOGIES FOR REGENERATIVE SYSTEMS

Against the backdrop of the "dual carbon" goals and the increasing share of new energy, thermal power units are transitioning from base-load operation to deep peak shaving and flexible operation. The turbine regenerative system, which uses extraction steam to heat feedwater, is a core means of improving Rankine cycle thermal efficiency. Guo Xiaolong pointed out that a properly designed regenerative system can increase unit thermal efficiency by 5% to 8% [16]. However, under new conditions such as high parameters, double reheat, and off-design operation, the performance degradation of traditional regenerative systems has become increasingly prominent, necessitating in-depth research from the perspectives of system integration, operation strategies, and optimization algorithms.

In recent years, many domestic scholars have conducted extensive and effective work on regenerative systems. Zhong Ming and Yuan Hongjun focused on the engineering application of dual-unit regenerative systems [15]; Sun Dechuang et al. performed joint optimization of dual-unit regeneration and the regenerative system for ultra-supercritical double-reheat units [17]; Cheng Hui provided a detailed design scheme for the regenerative system of a double-reheat 1000 MW unit [18]; Fan Yangyang et al. explored the coupling relationship between reheat pressure and the regenerative system [22]. In addition, research on novel thermal cycles represented by the S-CO_2 Brayton cycle, ammonia-fueled microturbine chemical recuperation, and organic Rankine cycle regeneration has injected new vitality into regeneration technology [12][14]. The purpose of this paper is to systematically review the above research achievements to clarify current technical progress and future directions.

4.1 Thermal Parameter Optimization in Traditional Regenerative Systems

Optimization of traditional regenerative systems mainly focuses on the number of regeneration stages, extraction parameters, heater terminal differences, and enthalpy rise distribution, with theoretical foundations in the equivalent heat drop method and exergy analysis.

4.1.1 Matching Optimization of Regeneration Stages and Extraction Parameters

A larger number of regeneration stages smoothens the feedwater temperature rise and reduces irreversible losses, but the marginal benefit diminishes with increasing stages, and system complexity increases. Li Fei used particle swarm optimization to optimize the design of a turbine regenerative system, demonstrating that given initial and final parameters, there exists an optimal extraction pressure combination that maximizes cycle exergy efficiency [25]. This study revealed the nonlinear coupling characteristics of extraction parameters, showing that traditional empirical formulas cannot accurately capture the optimal solution, and that intelligent algorithms have significant advantages.

Fan Yangyang et al., in their study of a double-reheat MC unit, pointed out that a strong coupling exists between the choice of reheat pressure and the extraction points of the regenerative system [22]. Too high a reheat pressure reduces the work capacity of low-pressure cylinder extraction steam, while too low a pressure affects the regenerative feedwater temperature rise. Simultaneously solving for reheat pressure and the enthalpy rise distribution of each extraction stage yields the overall optimal thermal efficiency of the unit. This work provides quantitative guidance for the design of regenerative systems in double-reheat units.

4.1.2 Optimization of High-Pressure Heater Terminal Difference

The terminal difference is a critical parameter in high-pressure heater design, directly affecting heat transfer temperature difference and irreversible loss. Lu Jinwen analyzed the impact of high-pressure heater terminal difference variation on the heat rate of a 1050 MW ultra-supercritical unit [20]. The study shows that for every 1 °C increase in terminal difference, the unit heat rate increases by approximately 0.05% to 0.10%. However, a too-small terminal difference requires a significant increase in heat transfer area, sharply increasing investment cost. Therefore, terminal difference optimization is essentially a trade-off of thermal economy, requiring a comprehensive comparison of heater cost and coal price.

Cheng Hui, in his study of a double-reheat ultra-supercritical 1000 MW unit, further pointed out that high-pressure heater terminal difference design faces higher challenges in double-reheat units [18]. Because the superheat of extraction steam after double reheat increases significantly, using conventional terminal difference values would cause serious degradation of high-grade energy. He recommends using a larger heat transfer area in the final high-pressure heater to reduce the terminal difference, while upgrading materials to address high-temperature pressure issues.

4.1.3 Enthalpy Rise Distribution Optimization

The distribution of enthalpy rise of feedwater among heaters directly affects the exergy efficiency of the regenerative system. The traditional "equal enthalpy rise distribution" principle is approximately optimal in simple regenerative systems, but it is no longer applicable in complex systems such as double-reheat or dual-unit regenerative systems. Research by Sun Dechuang et al. shows that double-reheat dual-unit regenerative units should adopt an "unequal enthalpy rise" distribution strategy, i.e., allocating a larger enthalpy rise to stages with higher extraction steam superheat, thereby fully utilizing the heating capacity of high-grade steam [17].

4.2 Integration and Innovation of Novel Regenerative Systems

Traditional regenerative systems use a single heat source (turbine extraction), which has inherent defects such as high superheat and low-grade energy utilization inefficiency. Novel regenerative systems improve these problems by adding auxiliary power equipment and introducing flue gas waste heat.

4.2.1 Dual-Unit Regenerative (BEST/EC-BEST) System

Dual-unit regenerative technology is currently the most concerning regenerative technology in large double-reheat units. Zhong Ming and Yuan Hongjun systematically described the optimization and application methods of dual-unit regenerative systems. The core is to add a back-pressure extraction steam turbine (BEST) in addition to the main turbine. A portion of the high-superheat steam is extracted from the main turbine, first sent to the BEST to do work, driving the feed pump and generating additional electricity, and the exhaust steam from the BEST is then sent to the regenerative heater to heat feedwater [15]. This "work first, then heat" cascade utilization mode significantly reduces the irreversible loss caused by high-superheat extraction steam.

Sun Dechuang et al. performed detailed system simulation and parameter optimization of an ultra-supercritical double-reheat dual-unit regenerative unit [17]. Data show that at 100% load, the dual-unit regenerative system reduces the unit heat rate by approximately 90–120 kJ/(kW·h), equivalent to a reduction in net coal consumption of 3–4 g/(kW·h). They also found that the exhaust pressure of the BEST system is highly sensitive to overall unit performance, and there exists an optimal exhaust pressure range, which should be determined comprehensively based on main turbine parameters and feed pump power requirements.

Cheng Hui's study also pointed out that without dual-unit regeneration, the superheat of extraction steam from the front stages of the high-pressure and intermediate-pressure cylinders in a double-reheat unit can reach 260–325 °C. Directly sending this steam into the heater would cause huge exergy loss [18]. The synergistic application of dual-unit regeneration and double reheat is a key path for deep energy saving in high-parameter units.

4.2.2 Flue Gas-Water Composite Regenerative System

The flue gas-water composite regenerative system proposed by Jiang Xiaofeng et al. breaks the traditional single "steam-water" heat exchange mode [21]. This system adds a flue gas-feedwater heat exchanger in the boiler tail flue, using flue gas waste heat directly to heat feedwater, thereby reducing the usage of high-grade extraction steam. Research shows that this technology can reduce boiler exhaust gas temperature by 15–25 °C, reduce extraction steam volume by 8%–12%, and increase overall thermal efficiency by about 1.0–1.5 percentage points. This technology is particularly suitable for older units with high exhaust gas temperatures and limited air preheater heat transfer area.

4.2.3 Joint Optimization of Double Reheat and Regenerative System

Double-reheat technology itself creates conditions for improving regenerative efficiency. Cheng Hui's study systematically describes the design principles of the regenerative system for a double-reheat 1000 MW unit, including the appropriate selection of extraction points after the first and second reheat, the matching between the heat absorption ratio of the two reheaters and the regenerative enthalpy rise distribution, etc. [18]. The "high-medium-low" three-stage regenerative configuration scheme he proposed has become a reference template for subsequent engineering designs.

Sun Dechuang et al. went further by jointly optimizing double reheat and dual-unit regeneration [17]. They found that after applying dual-unit regeneration to a double-reheat unit, the optimization range for reheat pressure changes, necessitating a re-iteration of the full-system thermal balance. After joint optimization, the thermal efficiency of the unit under rated conditions can exceed 49%.

4.3 Optimization Issues Under Off-Design and Peak Shaving Operation

As deep peak shaving of thermal power units becomes normal, the performance retention capability of regenerative systems under off-design conditions has received widespread attention.

4.3.1 Study of Regenerative Characteristics Under Off-Design Conditions

Fan Zhiyuan systematically studied the optimization of regenerative systems in coal-fired power plants under off-design conditions in his master's thesis [23]. He established an off-design calculation model for the regenerative system based on modular modeling and found that when load decreases from 100% to 50%, the extraction pressure drop of high-pressure heaters is much larger than that of low-pressure heaters, causing the enthalpy rise distribution to seriously deviate from design values. Feedwater temperature decreases by approximately 30–40 °C, and regenerative efficiency attenuates significantly. He recommends reserving off-design adjustment margins during the design phase and considering switching extraction stages under partial load.

4.3.2 Optimization for Peak Shaving Adaptability

Zhang Quanbin focused on peak shaving scenarios and proposed an optimization strategy for turbine regenerative systems based on peak shaving demand [19]. Unlike traditional constant-load optimization, peak shaving conditions require comprehensive consideration of extraction parameter variations under low load, the self-balancing capability of heater drains, and the adaptability of auxiliary systems. He suggests adding a peak shaving bypass on the intermediate-low pressure crossover pipe or extraction pipeline to maintain a higher extraction pressure under low load, thus preventing excessive drop in feedwater temperature. Although this approach sacrifices some efficiency at high load, it significantly improves economic operation indicators at low load. Conversely, Jiang Songtao discussed regenerative system optimization from the perspective of combined heat and power [24]. For heating units, there is a competitive relationship between extraction steam for heating in winter and for regeneration. He proposed a "heat-regeneration" coordinated scheduling strategy that, while satisfying heating demand, prioritizes using low-pressure extraction for heating and reserves high-pressure extraction for regeneration, thereby optimizing the energy efficiency of the entire system.

4.4 Regenerative Systems in Novel Cycles and Working Fluids

The concept of regeneration is not only applicable to steam power cycles but also occupies a core position in supercritical carbon dioxide Brayton cycles, organic Rankine cycles, and ammonia fuel cycles.

4.4.1 Regenerative System in Supercritical CO_2 Brayton Cycle

The S-CO_2 Brayton cycle has advantages such as high density, low compression work, and high thermal efficiency. The design of its regenerative system is fundamentally different from that of steam cycles. Some research using exergy efficiency analysis points out that in a recompression Brayton cycle, the exergy loss proportion of the low-temperature and high-temperature recuperators can reach 30%–40% of the total cycle exergy loss [26]. Optimizing the flow channel layout and material thermal conductivity of the recuperators is key to improving cycle efficiency. This study provides theoretical guidance for the engineering selection of recuperators for S-CO_2 cycles.

4.4.2 Organic Rankine Cycle and Ammonia-Fueled Microturbine

Using the EWM-TOPSIS multi-objective decision-making method, researchers performed thermal-economic analysis and optimization of a regenerative organic Rankine cycle (ORC) system [27]. They found that under low-temperature waste heat conditions of 80–150 °C, a regenerative ORC system increases net power output by 12%–18% compared to a non-regenerative system, but the increased recuperator area extends the payback period. Using the EWM-TOPSIS method, the Pareto front can be found between thermal efficiency and investment cost.

For an ammonia-fueled microturbine, some studies investigated its thermodynamic performance based on the principle of chemical recuperation [28]. Ammonia fuel absorbs waste heat from exhaust gas in the recuperator and undergoes a cracking reaction, generating a hydrogen-nitrogen mixture, thereby increasing the fuel's calorific value and combustion temperature. This "chemical recuperation" concept combines physical recuperation and fuel reforming, providing a new approach for the efficient utilization of carbon-free fuels.

4.4.3 Energy Consumption Characteristics of Regenerative Systems in Large Coal-Fired Units

For large coal-fired units, some studies have systematically analyzed the energy consumption characteristics and optimization directions of regenerative systems [29]. These studies indicate that the regeneration loss of large ultra-supercritical units accounts for about 2%–3% of the boiler heat input, with the exergy loss caused by high-pressure heater extraction superheat being dominant. Adopting advanced technologies such as staged regeneration and flexible regeneration can further tap energy-saving potential.

4.5 Intelligent Optimization Methods and Comprehensive Discussion

How are intelligent algorithms used in regenerative optimization? Traditional regenerative system optimization relies heavily on designer experience and simplified thermal models, struggling to handle multi-variable, strong-coupling, and nonlinear problems. Li Fei pioneered the introduction of particle swarm optimization into the optimal design of turbine regenerative systems, using maximum exergy efficiency as the objective to optimize eight key parameters including extraction pressure and heater terminal difference [25]. Compared to the original design, the optimized system improved exergy efficiency by 1.2 percentage points, validating the effectiveness of intelligent algorithms.

In multi-objective optimization, the EWM-TOPSIS evaluation method was applied to an ORC regenerative system [27]. This method first determines the weights of each indicator using the entropy weight method, then ranks schemes via TOPSIS, avoiding the bias of subjective weighting. Such methods can be extended to steam regenerative systems to balance multiple objectives such as thermal efficiency, investment cost, and carbon emissions.

4.6 Summary

This chapter reviews four categories of mainstream technologies for regenerative system energy efficiency optimization from the perspectives of hardware modification, operational control, intelligent empowerment, and system coupling. Each technology has distinct limitations under different operating conditions, and overall they exhibit a gradient development and complementary application pattern.

The first category is traditional equipment modification and optimization technology. Double-reheat units have extraction steam superheat as high as 260–325 °C and require an "unequal enthalpy rise" distribution strategy. This type of technology eliminates equipment defects at the source, offering stable and durable energy savings, suitable for units with long service lives and conditions allowing shutdown for retrofits. However, it has high implementation thresholds, large investment, long retrofit cycles affecting production, and the solutions are highly case-specific, difficult to generalize.

The second category is operational mode optimization technology. When load decreases from 100% to 50%, feedwater temperature drops by 30–40 °C, and regenerative efficiency significantly attenuates. Adding a peak shaving bypass can maintain extraction pressure under low load. "Heat-regeneration" coordinated scheduling prioritizes using low-pressure extraction for heating and reserves high-pressure extraction for regeneration. This type of technology requires no hardware changes, only controlling parameters such as water level, extraction volume, and load ratio. It has low cost, strong adaptability, and quick results, making it a fundamental means for daily energy-saving management. However, the energy saving gain has an inherent upper limit, cannot compensate for equipment structural defects, and the effect is highly dependent on operational expertise.

The third category is intelligent algorithm and data-driven optimization technology. Particle swarm optimization optimizes eight key parameters with the objective of maximizing exergy efficiency, improving exergy efficiency by 1.2 percentage points. The EWM-TOPSIS method finds the Pareto front between thermal efficiency and investment cost. This type of technology breaks away from empirical control constraints, enabling online dynamic optimization and fault prediction, performing well in low-load peak shaving. However, the optimization models heavily rely on complete, low-noise massive data. Most algorithms are only suitable for a single unit, lacking cross-unit transferability. They also have black-box characteristics, limiting on-site acceptance, and large-scale engineering implementation is rare.

The fourth category is novel structures and multi-system coupling optimization technology. Dual-unit regeneration (BEST) achieves a "work first, then heat" cascade utilization, reducing heat rate by 90–120 kJ/(kW·h) and coal consumption by 3–4 g/(kW·h). The flue gas-water composite regeneration reduces exhaust temperature by 15–25 °C and increases thermal efficiency by 1.0–1.5 percentage points. Joint optimization of double reheat and dual-unit regeneration results in rated thermal efficiency exceeding 49%. The exergy loss proportion of S-CO_2 cycle recuperators is 30%–40%, ORC regeneration increases net power output by 12%–18%, and ammonia-fueled chemical recuperation combines physical recuperation and fuel reforming. This type of technology goes beyond single-system optimization, achieving maximum energy cascade utilization, representing the frontier direction. However, it has complex architecture, high coupling difficulty, high equipment development and maintenance barriers, and is currently mostly at the theoretical simulation stage, unlikely to be widely popularized in the short term.

Looking at the overall technical development trajectory, three major trends emerge: optimization mode from coarse manual regulation to refined control; optimization scope from local retrofits of single units to multi-system coordination across the entire plant; and optimization basis from empirical judgment to data-driven intelligent decision-making. Each of the four technology categories has its own shortcomings; no single mode can simultaneously achieve energy saving effectiveness, economic cost, operational stability, and general adaptability. Future thermal power energy-saving retrofits should be based on traditional equipment modification and daily operation, deeply integrate intelligent algorithms and cross-system coupling technologies, and adopt a multi-technology combination mode to complement each other's strengths and achieve synergistic effects. This is the mainstream path for steadily improving the energy efficiency of regenerative systems in coal-fired units.

V. PROBLEMS AND DEFICIENCIES OF CURRENT OPTIMIZATION TECHNOLOGIES

5.1 Sharp Increase in Exergy Loss Under Off-Design Conditions, Significant Low-Load Energy Efficiency Attenuation

Traditional regenerative systems are designed and optimized based on the rated operating condition of the unit. When the operating condition deviates from rated parameters, the system energy efficiency significantly attenuates, and wide-load adaptability is poor. Fei Tianhao et al. [30] conducted a systematic exergy analysis of the regenerative system of an ultra-supercritical double-reheat unit, confirming that off-design operation disrupts the optimal heat transfer matching state of the regenerative system, and load fluctuations significantly exacerbate irreversible energy losses within the system. The heat transfer performance of heaters at various stages differentiates significantly with changing conditions, becoming an important factor restricting unit energy efficiency improvement. Under low-load peak shaving conditions, the extraction pressure, temperature, and flow rate at various turbine stages deviate significantly from design values, heater terminal differences increase, and the irreversibility of the heat transfer process significantly increases, directly causing a decrease in the overall exergy efficiency of the regenerative system. Research by Duan Liqiang's team [34] on the energy consumption distribution of a 600 MW supercritical unit also confirms this problem: during deep peak shaving, the proportion of energy loss in the regenerative system significantly increases. The traditional design model with fixed extraction stages and points cannot adapt to wide-load peak shaving requirements. Under low-load conditions, insufficient extraction supply and poor feedwater heating not only increase the unit's gross coal consumption rate but also cause low feedwater temperature at the boiler inlet, indirectly affecting boiler combustion stability and furnace outlet flue gas temperature, and adversely affecting the efficient and stable operation of the unit's SCR denitrification system. In summary, the lack of adaptive off-design regulation capability in traditional regenerative systems is one of the core reasons for the significant decrease in energy efficiency of coal-fired units under deep peak shaving conditions.

5.2 Long-Term Equipment Degradation, Lack of Full Lifecycle Operation and Maintenance Technology System

Core equipment such as regenerative heaters, extraction pipelines, and control valves operate long-term under high-temperature, high-pressure, and high-flow-rate severe conditions. Over long-term operation, problems such as tube bundle fouling, internal corrosion, pipeline wear, and valve aging are prone to occur, representing important hardware causes of year-by-year attenuation of regenerative system energy efficiency [31,33]. During long-term service, the heat transfer tube bundle surfaces of heaters continuously deposit scale, rust, and impurities. The thermal conductivity of fouling is much lower than that of metal tubes, significantly increasing the heat transfer resistance of the system and directly weakening equipment heat transfer capacity. The energy efficiency loss caused by equipment degradation has hidden and cumulative characteristics, making it difficult to accurately identify through conventional manual inspection [31]. Existing power plant operation and maintenance systems have long had a wrong orientation of emphasizing equipment operation safety and neglecting system operation energy efficiency. Daily O&M focuses on rigid safety indicators such as equipment leakage, pressure safety, and operational faults, and does not incorporate energy efficiency parameters such as heater terminal difference, actual heat transfer efficiency, exergy loss value, and heat transfer coefficient into normalized O&M assessment [33]. Currently, the industry still lacks mature and complete quantitative analysis models for equipment degradation laws, online real-time energy efficiency warning technologies, and negative energy efficiency problems such as heater tube bundle fouling and heat transfer performance attenuation accumulate over time, causing equipment operating conditions to continuously deteriorate without timely intervention and correction.

At the same time, regenerative systems commonly have hidden faults such as internal valve leakage and abnormal pipeline pressure loss [31]. Aging and internal leakage of extraction and drain valves can cause high-grade extraction steam to short-circuit and be lost, entering downstream equipment or the condenser without participating in feedwater heat exchange. Pressure loss increase caused by pipeline scaling or deformation disrupts the balance of extraction flow distribution among stages, significantly increasing system throttling loss. Such hidden faults have no obvious operational abnormality alarms and cannot be automatically identified and troubleshot by automation equipment. They rely entirely on the experience and judgment of frontline O&M personnel, leading to delayed fault location and corrective action, causing large amounts of ineffective energy loss over long-term operation, and seriously reducing the overall operating energy efficiency of the regenerative system from the hardware side.

5.3 High Coupling Degree of Dual-Unit Regenerative System, Insufficient Stability During Condition Switching

Although the dual-unit regenerative system effectively improves unit energy efficiency, its deep coupling with the main system also brings many operational risks. Zhang Wenxiang et al., in their study of a low-pressure heater cut-off condition in a dual-unit regenerative system, pointed out that under such conditions, problems such as overpressure at the small regenerative turbine extraction port, exceeding limits of reheat steam parameters, and over-power of the small generator are very likely to occur [32]. Current control strategies are still imperfect, lacking effective parameter linkage adjustment mechanisms during condition switching. Once a disturbance condition such as low-pressure heater cut-off occurs, the sudden change in extraction flow and pressure easily triggers protection actions, leading to severe fluctuations in feedwater flow or even unit trip, which has become a major obstacle to the promotion of dual-unit regenerative technology.

5.4 Coarse Operation and Maintenance Management, Unreleased Energy Saving Potential

Ren Baoliang's study mentions that many power plants have obvious shortcomings in the operation and management of regenerative systems, directly leading to the system's energy saving potential not being fully tapped. In actual operation, problems such as improper heater water level control and unreasonable drain valve opening are very common, easily causing steam carry-over or water accumulation in drains, increasing unnecessary heat transfer loss and also increasing the risk of water hammer in pipelines [33]. At the same time, many power plants have not yet established a sound regenerative system efficiency evaluation system, and monitoring of key indicators such as heater terminal difference and extraction parameters is inadequate, making it impossible to timely identify and address energy consumption hazards, wasting significant energy saving opportunities.

5.5 Rigid System Design, Insufficient Flexibility

The design concept of existing regenerative systems is relatively lagging, making it difficult to balance both high-load efficient operation and low-load stable peak shaving. The design mode with fixed stages and extraction points inevitably faces insufficient extraction volume and difficulty achieving the required feedwater temperature under low load. Although double-reheat units can reduce extraction steam superheat to some extent, they have complex systems and high investment costs, and do not fundamentally solve the problem of large exergy loss under low load. Overall, the regenerative system lacks flexible regulation capability and cannot adapt to the current flexible and changeable operation mode of the power system.

VI. FUTURE DEVELOPMENT TRENDS AND RESEARCH DIRECTIONS

6.1 Future Development Trends

The energy efficiency optimization of coal-fired power plants and their regenerative systems is evolving from local improvements to system integration, multi-energy complementarity, and flexible control. The main trends are as follows:

From single thermal system to integrated energy system integration: In the future, coal-fired power plants will not only generate electricity but become comprehensive energy hubs integrating power generation, heat supply, thermal storage, carbon capture, and renewable energy accommodation. The regenerative system will serve as a core link for energy cascade utilization, deeply coupling units such as solar thermal, biomass co-firing, and CO_2 capture and utilization [35]. For example, the IGCC system coupled with photovoltaic hydrogen production can significantly reduce carbon emissions while achieving flexible regulation of power generation output [38]. This trend requires regenerative networks to have multi-energy complementarity and cross-system coordination capabilities.

Design philosophy shifting from steady-state to full-condition flexible control: Traditional regenerative systems based on THA rated conditions experience extraction parameter deviations from optimal distribution under low load, resulting in decreased absolute internal efficiency. Studies show that the absolute internal efficiency at 75% design condition (48.388%) is lower than that at 100% design condition (48.715%) [37]. Therefore, the design philosophy of regenerative systems is shifting from "rated condition optimum" to "wide-load high efficiency."

Coupling of thermal storage systems with regenerative systems: Thermal storage systems are critical for the continuous and stable operation of solar thermal power generation, with energy storage costs approximately one-thirtieth of large-scale battery storage. Dual-tank molten salt sensible heat storage is currently the most mature technology, but high-temperature phase change thermal storage and chemical thermal storage are important development directions due to their higher energy storage density [36]. A future trend is coupling thermal storage systems with regenerative systems of coal-fired units, using thermal storage to smooth load fluctuations while enhancing unit peak shaving capability and thermal economy.

6.2 Key Research Directions

Dynamic modeling and optimization of regenerative systems under off-design conditions: Current off-design calculations using the Flügel formula plus the equivalent heat drop method meet engineering accuracy requirements but have insufficient adaptability to large-range load step changes. Studies have found that under three off-design conditions (25%, 50%, 75%), the absolute internal efficiencies are 47.366%, 47.842%, and 48.388% respectively, all lower than the design condition value of 48.715% [37]. Future development should focus on a dynamic prediction method based on a hybrid thermodynamic and data-driven model to achieve real-time optimization of extraction pressure and feedwater enthalpy rise distribution, supporting flexible unit operation [37].

High-temperature phase change thermal storage materials and their coupling mechanism with regenerative systems: Phase change thermal storage (latent heat storage) has advantages of high storage density and small temperature variation compared to sensible heat storage, but faces bottlenecks such as low thermal diffusivity, phase separation, and medium aging. Suitable high-temperature phase change materials include $NaNO_3$ (melting point 307 °C), KNO_3 (333 °C), NaCl (800 °C), etc. [36]. Future research directions include: (1) developing composite phase change materials with porous media (e.g., silicon carbide foam) for enhanced heat transfer structures; (2) designing a three-tank latent/sensible heat storage structure suitable for direct steam generation parabolic trough systems to solve the two-phase flow issue of water/steam and matching with regenerative parameters [36].

Adaptive optimization method for feedwater enthalpy rise distribution in regenerative systems: Equal enthalpy rise or equal temperature rise distribution is a classic principle in regenerative system design, but deviations often occur in actual operation. For example, the temperature rise of the No. 6 low-pressure heater of a 660 MW unit was as high as 53.3 °C, while that of the next stage was only 16.3 °C. Some optimization studies show that adjusting the feedwater enthalpy rise distribution can increase unit internal efficiency by 0.141% and reduce heat rate by 22.097 kJ/(kW·h) [37]. Future development needs an online monitoring-based adaptive enthalpy rise distribution technology, combined with the equivalent heat drop method to calculate stage extraction efficiencies in real time and dynamically adjust heater operating parameters, keeping the regenerative system close to optimal.

In summary, future coal-fired power plants will gradually become comprehensive energy hubs integrating power generation, heat supply, thermal storage, carbon capture, and renewable energy accommodation, with the regenerative system playing a role as a link for energy cascade utilization. The design philosophy will shift from focusing on rated conditions to wide-load high efficiency, as efficiency drops significantly under low load [37]. Coupling thermal storage systems with regenerative systems will help smooth load fluctuations and enhance peak shaving capability [36]. Key research directions include: (1) dynamic modeling and optimization under off-design conditions; (2) coupling mechanisms between high-temperature phase change thermal storage materials and regenerative systems; and (3) adaptive optimization methods for feedwater enthalpy rise distribution. These directions will fundamentally determine the flexible and efficient operation of regenerative systems in the future.

VII. CONCLUSION

The regenerative system of coal-fired power plants is a core part of the unit's thermal cycle, directly determining power generation efficiency, net coal consumption rate, and carbon emission level. It is a key optimization target for current thermal power energy saving, carbon reduction, and adaptation to deep peak shaving demands. Coal-fired power plants in China still undertake the main power generation task, and energy efficiency losses in the regenerative system (such as heat transfer exergy loss, improper extraction ratio, and equipment degradation losses) have become core bottlenecks restricting unit economy. Therefore, research on its energy efficiency optimization has significant engineering value and practical significance.

Currently, three mainstream technology systems have formed for regenerative system energy efficiency optimization: Traditional equipment modification technology is mature and reliable; upgrading heaters, drains, and extraction pipelines can fundamentally solve hardware defects, but has shortcomings such as high cost, long cycles, and poor generality. Operational mode optimization has low cost and quick results, adapting to variable load conditions, but cannot solve structural energy efficiency problems. Intelligent algorithm and data-driven technology align with the digital transformation trend of thermal power, enabling dynamic parameter optimization and hidden fault prediction, but relies on high-quality data, has weak cross-unit transferability, and lacks large-scale engineering implementation.

Existing optimization technologies still have four core shortcomings: First, rigid design concepts: single-point optimal design for rated conditions cannot adapt to wide-load, deep peak shaving scenarios, and there is a lack of low-cost retrofit solutions for existing units. Second, lack of a full lifecycle equipment operation and maintenance system: degradation problems such as heater fouling and valve internal leakage are hidden and cumulative, and energy efficiency parameters are not included in normalized assessment. Third, lagging drain regulation mechanism: the step-by-step self-flow mode has poor energy level matching and severe flashing loss; local optimization cannot achieve full-system energy cascade utilization. Fourth, weak intelligent monitoring and control: many blind spots in key parameter monitoring, poor adaptability of static models, and insufficient closed-loop automatic control capability. Overall, existing research mostly focuses on single-point local optimization, lacking systematic solutions for the entire system and all operating conditions, and the fit between theory and engineering practice is insufficient.

In the future, coal-fired power plants will transform into comprehensive energy hubs. The regenerative system needs to serve as a link for energy cascade utilization. The optimization direction will shift from single-point improvement to system integration, flexible control, and multi-energy coupling. Core development trends are: design philosophy shifting from "rated condition optimum" to "wide-load high efficiency," balancing peak shaving flexibility and economy; technical paths integrating traditional modification, operational optimization, and intelligent algorithms to form a complementary and synergistic optimization system; system-level coupling with thermal storage, carbon capture, and renewable energy to expand energy efficiency improvement space. Key research directions focus on three areas: First, construct a dynamic model integrating thermodynamics and data-driven methods to achieve real-time adaptive optimization of extraction parameters and feedwater enthalpy rise distribution under off-design conditions. Second, develop high-temperature phase change thermal storage materials, overcome heat transfer enhancement bottlenecks, and establish a thermal storage-regeneration coupling mechanism to smooth load fluctuations and improve peak shaving capability. Third, improve the full lifecycle O&M and intelligent closed-loop control system, build an integrated platform for real-time energy efficiency monitoring, fault warning, and automatic control, to solve the problems of equipment degradation management and lagging intelligent control.

In conclusion, energy efficiency optimization of the regenerative system is a core starting point for the low-carbon transformation of thermal power. Only by breaking through existing technical shortcomings and promoting technological integration and innovation can we achieve efficient, flexible, and low-carbon operation of coal-fired units, providing key support for China's energy structure transformation.

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