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Current Status and Prospects of Electric Furnace Scrap Steel Preheating Technology

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Abstract

With the transformation of the global steel industry to green and low-carbon, scrap preheating technology has become the core research direction in the field of electric furnace short-process steelmaking as a key means to improve the utilization rate of scrap steel, reduce energy consumption and reduce pollution. This paper systematically reviews the development status of electric arc furnace scrap preheating technology at home and abroad, and focuses on the analysis of the technological process, energy efficiency advantages and limitations of three mainstream technologies: Consteel electric arc furnace, double-shell electric arc furnace and vertical electric arc furnace. The results show that Consteel EAF significantly reduces power consumption and carbon emissions through continuous feeding and reverse heat exchange of high-temperature flue gas, but there are problems such as complex equipment and high investment cost. The double-shell electric arc furnace adopts alternating smelting and waste heat circulation to achieve power consumption of 350~400 kWh/t, but it is necessary to solve the influence of dioxin control and scrap impurities. Shaft EAF is suitable for the production of high value-added steel grades due to its efficient preheating and low emissions, but it faces the challenges of raw material quality and large-scale equipment. The future development direction focuses on intelligent control, clean energy coupling and large-scale equipment, and it is necessary to combine policy support and technological innovation to break through bottlenecks such as scrap recycling system and localization of core equipment. This paper provides a theoretical reference and practical path for the optimization of electric arc furnace scrap preheating technology and the green transformation of the steel industry.

Keywords

Scrap Steel Preheating; Electric Arc Furnace; Consteel; Double-Shell Electric Arc Furnace; Shaft-Type Electric Arc Furnace; Energy Conservation and Emission Reduction.

1. Introduction

With the rapid development of the global steel industry, the effective utilization and efficient treatment of scrap steel, as an important raw material for steel production, has become the focus of attention in the steel industry [1-3]. As an important means to improve the utilization rate of scrap steel, reduce energy consumption, and reduce environmental pollution, scrap preheating technology has been widely studied and applied in the field of steelmaking in recent years [4]. Scrap preheating technology can significantly reduce energy consumption and improve production efficiency in the

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steelmaking process by increasing the temperature of scrap before it enters the furnace. At the same time, preheating scrap also helps to reduce exhaust emissions in the steelmaking process and reduce environmental pollution. Therefore, scrap preheating technology is not only an important direction for the green and sustainable development of the steel industry, but also one of the key factors to enhance the competitiveness of iron and steel enterprises.

As an important raw material in the steel industry, the effective utilization of scrap steel is of great significance for realizing resource recycling, reducing energy consumption, and reducing environmental pollution [5]. In recent years, with the continuous increase of global steel production and the enhancement of environmental awareness, scrap preheating technology has received extensive attention and research as a key link to improve the utilization rate of scrap steel and reduce production energy consumption. At present, scrap preheating technology is mainly divided into two categories: scrap preheating in long-process steelmaking and electric arc furnace scrap preheating. In long-process steelmaking, scrap preheating is usually combined with converter steelmaking, and by preheating the scrap before the converter, the physical heat of the scrap is increased, and the heat in the converter furnace is supplemented, thereby increasing the scrap ratio. The scrap preheating technology of electric arc furnace is more diversified, including gondola scrap preheating, DC double-shell electric arc furnace scrap preheating, shaft furnace scrap preheating and Consteel electric arc furnace scrap preheating. Each of these preheating technologies has its own advantages and disadvantages and is suitable for different production conditions and process needs. This paper systematically reviews the research progress of scrap preheating technology at home and abroad, analyzes the development trend of its key technologies, and then provides theoretical support and process optimization path for the green and low-carbon transformation of the steel industry.

Since the invention of the first industrial steelmaking electric furnace in 1905 by the German R. Linberg, its equipment system has continued to iterate. At present, a multi-dimensional technical architecture with ultra-high power, DC and high impedance electric arc furnace as the core has been formed, and the supporting process deeply integrates smelting technologies such as dynamic compensation of reactive power, intelligent bottom blowing stirring and near-zero carbon, so that the smelting cycle is compressed to less than 40 minutes, the power consumption per ton of steel is reduced to less than 280 kWh, and the control accuracy of nitrogen and oxygen content of molten steel is ±5 ppm, highlighting the advantages of short process and low carbon. For the field of scrap preheating, the early flue gas direct heating method was eliminated due to dioxin pollution and waste heat recovery rate of less than 30%; At present, the mainstream technology adopts gas-solid radiation heat exchange and ultra-high temperature exhaust gas recirculation, combined with oxygen-rich combustion and carbon capture. At present, the electric arc furnaces that use scrap preheating at home and abroad can be divided into three categories according to their technical characteristics: Consteel electric arc furnaces, double-shell electric arc furnaces, and vertical shaft electric arc furnaces, among which Consteel technology is the mainstream in Europe and the United States, accounting for more than 50%, emphasizing continuous and low-carbon; Japan and South Korea focus on vertical shaft electric arc furnaces and pursue high preheating efficiency; China is diversifying, with three types of technologies in parallel. In this paper, the development trend of three types of EAF scrap preheating technologies at home and abroad is reviewed, and the advantages and disadvantages of each technology are analyzed.

2. Consteel Electric Arc Furnaces

In the mid-80s of the 20th century, the Italian company Dexing developed the Consteel electric arc furnace, and its workflow diagram is shown in Figure 1. Consteel's scrap preheating technology enables efficient scrap preheating and clean production by integrating a continuous feeding system and a sealed preheating system. At the heart of the technology is the synergy of the dynamic sealing device, the preheating section feeder, the sealing top cover and the charging trolley. The dynamic sealing device is located between the feeding mechanism and the waste heat combustion chamber, which effectively prevents the leakage of harmful gases such as smoke and dust, dioxins, and ensures

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that the preheating process is carried out in a closed environment [6]. The preheating section feeder has a total length of about 25 meters and adopts a steel structure sealing hood design, and the scrap and slag agent are transported in this section through the high-temperature flue gas discharged from the electric arc furnace for reverse heat exchange, which can preheat the scrap to 500-800℃, significantly reducing the energy consumption of subsequent melting. The sealing top cover is covered above the preheating section and is divided into two configurations: refractory lined and water-cooled pipe, the former is welded with steel plate and insulated with insulating material to insulate, and the latter relies on water-cooled pipe to dissipate heat, both of which can effectively improve thermal efficiency and extend the life of the equipment. As the connection device between the preheating section and the electric arc furnace, the feeding trolley adopts a water-cooled structure and a hydraulic feeding tray to accurately push the preheated scrap steel into the furnace, and its half-year work cycle and automatic operation further ensure the stability of continuous production.

In the preheating process, the system promotes the secondary combustion of CO in the flue gas by automatically adjusting the air volume, which not only reduces pollutant emissions, but also recovers waste heat for power generation or steam production. At the same time, part of the dust in the flue gas is deposited on the surface of the scrap steel when it flows through the preheating section, and melts with the scrap steel back to the furnace, which reduces the load and treatment cost of the bag filter. The dust removal system combines waste heat combustion chamber, rapid cooling technology and bag filter to ensure that the flue gas stays at high temperatures to decompose dioxins, and through rapid cooling to avoid low-temperature regeneration, ultimately achieving near-zero pollution emissions. The electric arc furnace is operated in a closed manner, and the flue gas is discharged after centralized treatment, which greatly reduces the interference to the environment.

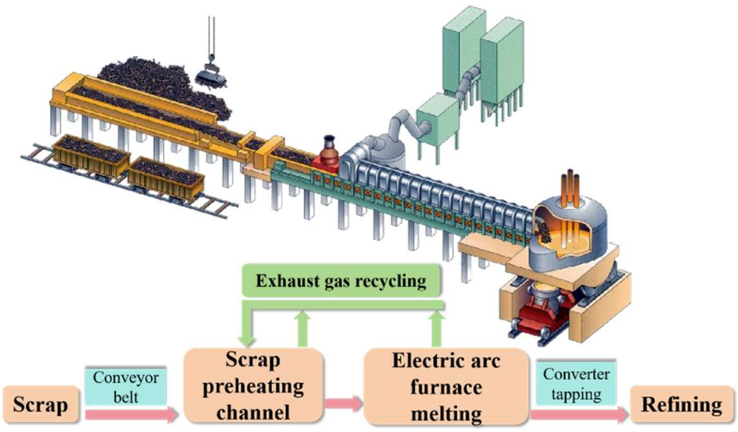

Figure 1. Consteel EAF workflow

At present, Consteel technology is widely used in the world, but the development is uneven in the region. European and American countries account for more than 50% of electric furnace steel, while China has introduced this technology, the proportion of electric furnace steel is still less than 15%. Li Jin [7] systematically analyzed the key technologies and methods of Consteel electric arc furnace steelmaking process, such as continuous feeding, carbon injection and oxygen blowing to produce high-efficiency foam slag and scrap steel preheating, and deeply discussed its mechanism of action in energy saving, consumption reduction and environmental protection benefits. The results show that the continuous feeding process significantly reduces the power unit consumption from 473 kWh/t in the traditional process to 340~380 kWh/t through the continuous transportation and dynamic sealing preheating of scrap steel, and at the same time reduces the impact of smelting cycle fluctuations on the power grid, and reduces the comprehensive energy consumption by 25%~40%. Combined with the submerged arc operation, the carbon injection and oxygen slag making technology optimizes the reaction conditions in the furnace, increases the arc thermal efficiency to 90%~91%, and promotes

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the secondary combustion rate of CO to exceed 60%, effectively reducing electrode consumption and carbon emissions. In the scrap preheating process, the high-temperature flue gas of the electric arc furnace is used to reverse preheat the scrap to 500~800℃, which reduces the electric energy consumption per ton of steel by about 50 kWh, and at the same time, the dust is recycled and melted to the furnace to reduce the load and treatment cost of the bag filter. In industrial production, Zhao Ruimin et al. [8] conducted a study on the optimization of energy efficiency of 60t Consteel electric arc furnace scrap smelting in a steel company, established a phased material, energy balance and energy efficiency evaluation technology, and put forward optimization suggestions. The results show that the efficiency of each stage is improved after optimization, the smelting cycle, feeding and energizing time are shortened, and the power consumption per ton of steel is reduced by 59.5kW·h. Kang Xu et al. [9] took the 40Cr steel smelted in the Consteel electric arc furnace of Zhang Xuan Technology as the research object, and analyzed the effects of the Consteel electric arc furnace with different sizes of DRI on the smelting process, steel material consumption, power consumption and final slag composition of the electric arc furnace by carrying out the test of adding 30 t of direct reduced iron of different sizes. The results show that the addition of small-sized DRI can easily lead to the increase of slag spillage in the smelting process, the high FeO content in the slag spill, the increase of steel material consumption and power consumption, the decrease of alkalinity of the final slag, the increase of FeO content, and the formation of "iron thallium" at the bottom of the slag tank by the discharged slag. When the proportion of DRI size ≤6.3 mm is less than 8.5%, the smelting effect is better, and it is recommended to screen the DRI to screen out the small DRI, and avoid emptying the silo feeding, and try to load in the half bin or higher than the half silo to prevent the proportion of small size from increasing due to DRI crushing.

Consteel EAFs are in a unique position in the field of steel production [10]. Its advantages are significant, in terms of arc characteristics, it has good arc stability, can achieve long-term stable operation, and the arc voltage is high, the current is low, the arc noise level is low, and the flicker voltage is low; From the point of view of energy efficiency and economy, the power fluctuation is small, the active power fluctuation is small, the electrode loss is low, the power consumption is low, and it also has certain environmental protection advantages, and can strongly stir the molten pool. However, it also has some disadvantages, such as high requirements for the power grid, high investment costs due to complex equipment, and limited preheating efficiency; In practice, the quality of scrap steel is high, and it is difficult to control the slag layer. As shown in Figure 2, the advantages and disadvantages of the Consteel EAF are presented in more detail.

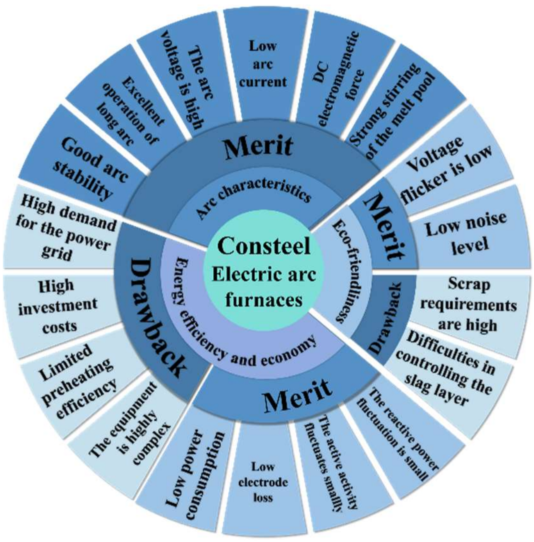

Figure 2. Comparison of the Advantages and Disadvantages of Consteel Electric Arc FurnaceConsteel

3. Twin shel EAF

The dual-shell electric arc furnace (EAF) scrap steel preheating technology is an efficient steelmaking process that achieves scrap steel preheating and continuous smelting through alternating operations of two furnace bodies. Its core lies in utilizing the residual heat from the smelting process to enhance energy efficiency and optimize production rhythm. The dual-shell EAF adopts a 'one power supply for two furnaces' model, where a single power system feeds two furnace bodies, using high-temperature waste gas to preheat the scrap steel. This can increase the transformer utilization time to over 80%, reduce smelting time, enhance productivity by 10%-15%, and save approximately 40-50 kWh of electricity per ton of steel; however, there are shortcomings in dioxin treatment. This technology employs two independent furnace bodies sharing a power supply and electrode system, forming an alternating cycle operation mode: when Furnace A is in the melting smelting phase, the high-temperature flue gas generated by it is diverted to Furnace B through a dedicated channel to preheat the scrap steel, raising its temperature to 600-800℃, as shown in Figure 3. Once the preheating is completed, Furnace B switches to melting mode while Furnace A enters the loading and preheating stage, thus optimizing the traditional intermittent production of electric arc furnaces into a semi-continuous process, shortening the smelting cycle to 50-60 minutes. Furthermore, the dual-shell design enhances arc stability by balancing the three-phase electric arc blowout phenomenon, and combined with the carbon injection foaming slag technology and secondary waste heat recovery, the thermal efficiency can exceed 85%, while also reducing electrode consumption and thermal stress on the furnace lining. The introduction of an intelligent control system further optimizes the power supply curve, oxygen and carbon injection rates, and flue gas distribution, achieving precise control over the temperature and composition of the molten pool.

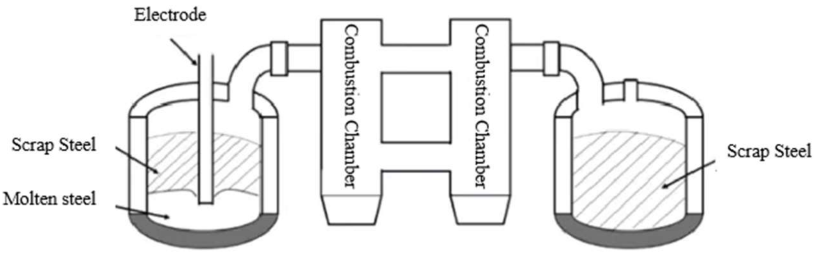

Figure 3. Schematic Diagram of Twin shel EAF

The manufacturing process revolves around the preheating of scrap steel, alternating smelting, and energy management. Initially, after being crushed and sorted, scrap steel is loaded into Furnace B, where it is preheated using the residual heat from the flue gas of Furnace A. Once Furnace A completes the melting process, it enters the refining stage, while Furnace B begins electric melting, and Furnace A prepares for the next charge, reducing non-production time by approximately 30% and lowering electricity consumption to 350–400 kWh/t. The melting stage primarily employs electric arc heating through electrodes, supplemented by oxygen lancing to enhance decarbonization and foaming slag technology, thereby controlling the reaction efficiency of the molten pool. During the refining stage, the composition uniformity of the molten steel is optimized through bottom-blown argon or electromagnetic stirring, with the final phosphorus content controllable below 0.015%. In the steel tapping process, eccentric bottom tapping technology is utilized to achieve slag-free tapping, thereby reducing the risk of phosphorus recontamination. The system integrates an intelligent control module that adjusts power supply parameters and gas distribution paths in real-time, ensuring maximum energy utilization and supporting predictions of terminal carbon content along with dynamic optimization of process parameters.Currently, dual-shell electric arc furnace technology is widely applied in Europe and the United States, with electric furnace steel accounting for over 50% in the U.S. Short-process steel mills leverage this technology to produce high value-added plates at

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scale. Although introduced domestically, the proportion of electric furnace steel remains below 15% due to the limited supply of scrap steel, high equipment investment, and technical bottlenecks. Research indicates that this technology faces challenges such as the preheating efficiency being affected by scrap steel dimensions and impurities, large equipment footprint, and high precision requirements for control systems. Future development directions focus on three aspects: firstly, intelligent upgrades through digital twin models and AI algorithms to optimize preheating parameters and smelting sequences; secondly, coupling with clean energy by exploring hydrogen as a substitute for electricity or in conjunction with hydrogen-based vertical furnaces to promote near-zero carbon emissions; and thirdly, scaling up equipment size to enhance furnace capacity to over 200 tons to meet mass production demands. On the policy front, while domestic documents such as the "Special Action Plan for Energy Saving and Carbon Reduction in the Steel Industry" support the development of short-process technologies, it is essential to overcome bottlenecks in the scrap steel resource recovery system and optimize preheating system design to achieve the efficient promotion of dual-shell electric arc furnace technology, facilitating the green transformation of the steel industry.

4. Vertical Electric Arc Furnac

The vertical shaft electric arc furnace scrap preheating technology is a highly efficient steelmaking process that achieves scrap preheating and continuous melting through a vertical shaft structure. Its core principle lies in utilizing the residual heat from high-temperature flue gas to enhance energy efficiency and reduce energy consumption. This technology is based on the collaborative design of the vertical shaft and melting chamber: after the scrap is introduced from the top of the shaft, the high-temperature flue gases generated during the electric furnace smelting process flow in reverse through the shaft to preheat the scrap, raising its temperature to 600–850℃, thus reducing the electrical energy required for subsequent melting. The preheated scrap continuously enters the melting chamber through a movable support or a chute system, forming a dynamic molten pool, which, together with technologies such as oxygen lance blowing and carbon injection for foamy slag, enhances the decarbonization reaction and covers the electric arc, achieving a thermal efficiency of over 85%. Furthermore, the sealed design of the shaft reduces the oxidation of the scrap and suppresses the generation of harmful gases like dioxins, with emission control achieved through flue gas quenching and activated carbon adsorption technology.

The technological process consists of four stages: pretreatment of scrap steel, preheating, melting, and emission control. First, the scrap steel is crushed and sorted before entering a vertical shaft, where it is preheated to the target temperature using high-temperature flue gas. Subsequently, the preheated scrap steel is batch-fed into the melting chamber via a support or automatic chute system, where electric arc heating and oxygen lance blowing work together to accelerate melting. At the same time, carbon is sprayed to create a foamy slag that covers the arc, reducing heat loss. In the refining stage, bottom-blown argon or electromagnetic stirring optimizes the liquid steel composition, controlling the phosphorus content to below 0.015%. The tapping of steel employs eccentric bottom tapping (EBT) technology to minimize slag contamination. In terms of flue gas treatment, the preheated waste gas undergoes secondary combustion in a combustion chamber to decompose dioxins and is then rapidly cooled to below 250℃, complemented by bag filtration and activated carbon adsorption to ensure emissions comply with standards. An intelligent system continuously monitors flue gas composition and molten pool temperature, optimizing the power supply curve and oxygen-carbon blowing amounts to achieve efficient and stable production.

Currently, shaft-type electric arc furnace technology is widely applied in European and American countries. The Fuchs shaft furnace developed by German company Fuchs and the Ecoarc ecological electric arc furnace by Japan's Nippon Steel have been commercialized, achieving electricity consumption as low as 150 kWh/t, with dioxin emissions below 0.2 ng-TEQ/m^3. In China, the promotion process has been slow due to a shortage of scrap steel resources and technical bottlenecks. However, the new type of shaft furnace addresses the problem of scrap steel bonding through a trapezoidal shaft design and introduces an intelligent control system, gradually being piloted in enterprises such as Shagang. Research indicates that this technology still faces challenges such as the impact of raw material impurities on preheating efficiency and high equipment investment. Future development directions include: (1) intelligent upgrades, utilizing digital twin models to optimize preheating parameters; (2) coupling clean energy sources such as hydrogen, exploring hydrogen-based integrated processes; (3) equipment large-scale (increasing single furnace capacity to over 200 tons) and modular design to enhance capacity and adaptability. On the policy level, the domestic 'Special Action Plan for Energy Conservation and Carbon Reduction in the Steel Industry' promotes the development of short-flow technology, but it is necessary to overcome the bottlenecks of scrap steel recycling systems and the localization of core equipment, in order to achieve large-scale application and green transformation goals for shaft-type electric arc furnaces.

5. Conclusion

The waste steel preheating technology is the core direction for the green and low-carbon transformation of short-flow steelmaking in electric furnaces. Currently, the mainstream technologies such as Consteel Electric Arc Furnace, Double Shell Electric Arc Furnace, and Shaft Electric Arc Furnace each have their own characteristics: the Consteel furnace preheats waste steel to 500-800°C through continuous heat exchange, resulting in low electricity consumption but complex equipment and high investment; the Double Shell Furnace alternately preheats waste steel to 600-800°C, improving production efficiency by 10%-15%, but facing issues with dioxin management and impurities; the Shaft Furnace has high preheating efficiency and low emissions, making it suitable for high value-added steel grades, yet it faces challenges regarding raw material quality and scaling up. Future technologies will move towards intelligent control, clean energy coupling, and equipment scaling, necessitating a combination of policies to break through the recycling system of waste steel and the localization of core equipment to promote the green transformation of the steel industry.

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