Life Cycle Assessment of a New Steel-making Process for Sustainable Steel Industrial Development in China

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Abstract. With the increasing emphasis on sustainable development, the development of green industry has become particularly important. The steel industry, as a key industry with high pollution and high emission, is bearing a huge environmental pressure. In China, the traditional steelmaking industry of blast furnace-converter has the problems of huge energy consumption and carbon emission, which is contrary to the requirements of sustainable industrial development. Therefore, based on the resource characteristics and technical basis of China, the theory of replacing the traditional steel-making process with coal-to-gas-gas-based shaft furnace-electric furnace steel making process is proposed in this paper. At the same time, this paper will establish an LCA model for the new process, objectively evaluate its relationship with the environment, and deeply analyse the relationships between each unit process in coal-to-gas-based shaft furnace-electric furnace process and environmental protection, energy consumption, pollution emission. Through the simulation of steelmaking process and life cycle assessment, the impact of new process on environment and energy is analysed quantitatively. It provides a new research direction and a reliable theoretical support for optimizing steel refining process and developing sustainable steel refining industry.

1. Introduction

1.1 Research Background

The short process steel-making process generally refers to the direct reduction iron-electric furnace steel-making process. Compared with the traditional long process steel-making process, the process is simplified, and it has a significant effect in reducing energy consumption, carbon emissions, and coke consumption. With the gradual emphasis on environmental protection and the continuous accumulation of scrap steel worldwide, the short process steel-making process is bound to become the future development direction of the steel industry.

At present, steel industry of China is still dominated by traditional blast furnace-converter long process technology. In 2018, China's carbon emissions accounted for 28.7% of the world's carbon emissions. Most of the carbon emissions were generated by the long process steel-making process. Quantitative analysis of the proportion of carbon emissions in the traditional long steel-making process, in which the blast furnace steel-making accounted for 53%. This shows that the blast furnace steel-making process has the greatest impact on the environment and should be replaced by a more environment friendly process.

Compared with the blast furnace iron-making in the traditional long process, the direct reduced iron in the short process has higher purity and less harmful impurities, making it the more ideal raw material for electric furnace steel-making. The development of direct reduced iron technology is conducive to improving the final quality of steel products.
Life cycle assessment is an environmental analysis method from cradle to grave. By analysing the impact of energy, material utilization and waste emissions on the environment to quantify and evaluate the impact of energy and resource consumption on the environment throughout the steel production, people can analyse the results and optimize the production process, which is an opportunity and method to improve its environmental performance.

1.2 Proposal of research topics
According to the investigation, the gas-based shaft furnace method is currently the most mature and widely used direct reduction iron process recognized internationally. At present, the main raw material of foreign gas-based shaft furnace method is natural gas, but China's natural gas resources are characterized by small total reserves and extremely uneven distribution. Therefore, China is not suitable for the application of natural gas-based shaft furnace reduced iron technology. In comparison, China's coal resources are relatively abundant, and the coal-to-gas process can also meet production needs. In addition, the literature research shows that the domestic coal-to-gas process is gradually improving. Therefore, the use of coal-to-gas to replace natural gas, coupled with direct reduction and electric furnace steel-making processes, will be the key development direction of China’s steel production industry. This paper will focus on this research direction.

At present, for the coupling process of coal-to-gas and gas-based shaft furnace reduction methods around the world, neither large-scale industrial production nor life cycle assessment has been carried out. Therefore, based on the above considerations and the current situation of domestic raw materials, it is of great significance to evaluate the life cycle of the coal-to-gas and gas-based shaft furnace coupled process.

This paper will try to establish LCA model for short steel-making process so as to carry out environmental assessment for the whole life cycle of coal to gas, direct reduction iron-making and electric furnace steel-making, in order to quantitatively analyse the impact of different processes on the environment, find out the key links, and lay a theoretical foundation for optimizing the process and improving the scheme.

1.3 Research significance
Through the LCA method, objectively evaluate the new steel-making process of coal-to-gas, direct reduction and electric furnace short process. Explore the interaction between the new process and the environment. At the same time, provide theoretical support for the domestic short process steel-making industry.

Based on the above background, this paper puts forward the research topic of life cycle assessment for the whole process of coal to gas, direct reduction iron-making and electric furnace steel-making.

2. Review of the Steel smelting process
2.1. Non-blast furnace ironmaking process
Direct reduction ironmaking refers to the process of reducing iron-containing raw materials into direct reduced iron in the solid state [1]. Direct reduction ironmaking is divided into coal-based method and gas-based method. Compared with coal-based method, gas-based method has the advantages of low energy consumption, high production efficiency and stable product quality. It can be applied to mass production in industry. At present, the domestic direct reduction ironmaking is mainly based on the coal-based method, which has significant disadvantages of causing more pollution and greater environmental load. China should widely promote gas-based shaft furnace ironmaking process with large production capacity, high degree of automation, and low environmental load. It is an effective way for development of Chinese steel industry to expand the production of direct reduced iron, improve the energy conservation and reduce the overall economic cost.
2.2 MIDREX method (gas-based direct reduction process)
The MIDREX method is the largest gas-based shaft furnace process around the world for producing direct reduced iron. In 2018, the proportion of direct reduced iron produced by the MIDREX method accounted for more than 79% of the total output of direct reduced iron. The specific process is shown in the Figure 1.

![Figure 1. MIDREX method (gas-based direct reduction process)](image)

2.3 Review of the coal-to-gas technology
Coal-to-gas process refers to the process of coal gasification under certain conditions to produce syngas. At present, coal to gas technology is divided into fixed bed coal-to-gas technology, fluidized bed coal-to-gas technology, air flow bed coal-to-gas technology and some new coal-to-gas technology [4]. Fixed bed coal-to-gas technology is the first coal-to-gas technology developed and applied in the world. Generally, bulk coal or coking coal is used as raw material, and the bed is required to have uniformity and permeability. It is difficult to operate other technologies which is difficult to be widely used in industry. [5]

Coal-to-gas technology has many advantages. First of all, China is rich in lignite and low-quality bituminous coal, accounting for about 55% of the total coal reserves, which is the main raw material of China's coal-to-gas industry. Second, the domestic cost of coal-to-gas is low. Thirdly, the direct use of coal will cause great environmental pollution. The coal-to-gas process is a way of efficient and clean utilization of coal resources, and also an important direction of green development of coal chemical industry in China. In addition, coal-to-gas technology can also effectively supplement natural gas resources, improve the energy structure of our country, and meet the growing demand for natural gas in our country. [6]

3. Application of LCA in the steel industry

3.1 Overview of life cycle assessment

3.1.1 Definition
Life cycle assessment is to analyse the impact of energy and material utilization and waste discharge on the environment, quantitatively evaluate the consumption of resources and energy as well as the impact on the environment in the whole production process, by analysing the results and seeking opportunities and methods to optimize the production process and improve its environmental performance.

3.2. LCA application in the steel industry

3.2.1. Research status abroad
The research on LCA in foreign countries can be traced back to the quantitative research on resource utilization and environmental emissions of packaging products conducted by Coca Cola company in 1969 [7]. In the early 1990s, under the background of vigorous development of environmental protection movement, LCA attracted much attention. At this time, Japan also launched LCA methodology research
and made some contributions [8]. In 1997, the international organization for Standardization (ISO) issued the principles and framework of life cycle assessment, which regulated the definition and principles of LCA and formulated the technical framework [9]. After entering the 21st century, the theory and method of life cycle assessment have been gradually improved. LCA has been widely used in different industries, such as power [10], construction [11], agriculture [12], cement [13], etc. Since 1996, the world Steel Association has collected the life cycle inventory data of steel all over the world, and made two updates and evaluations. Baogang Group of China participated in the third inventory preparation and impact assessment [14]. Since 2004, with the purpose of developing new steel-making technologies to meet stricter environmental protection standards, the European steel industry has launched the ultra cooperation project, in which LCA assessment plays a crucial role [15]. Burchart [16] conducted a life cycle assessment study on the integrated steel production and EAF route in Poland. Bieda [17] collected and sorted the data of continuous casting production process of Arcelor Mittal Steel Poland branch and studied the application of LCA. Now the main life cycle assessment software is ‘Simpro’ software in the Netherlands, ‘Team’ software in France and ‘Gabi’ software in Germany. The software not only includes the detailed industry list database and the corresponding product characterization and normalization functions, but also has the data consistency test and other ancillary functions.

3.2.2 Environmental benefits of introducing LCA into new process
LCA quantifies the environmental impact of each production unit, which can not only help to analyse the high pollution and high emission links, but also analyse the resource consumption of each production unit, comprehensively and intuitively reflect the optimization links in the process flow, and put forward suggestions for the optimization of production structure. Therefore, the application of LCA in steel industry is of great significance to steel enterprises in optimizing industrial structure, improving production efficiency, reducing costs, reducing energy consumption and reducing pollution emissions.

4. Establishment of short-cycle process life cycle evaluation model

4.1 Process system and target scope
This paper took the short process of coal-to-gas, gas-based shaft furnace, electric furnace as the research object, established a life cycle assessment model, compiled a life cycle list and analysed the system's material energy flow, resource, energy consumption and waste emissions. Life cycle assessment quantitatively analysed the contribution of each process to different types of impact, found the key links that have the greatest impact on the environment, and made rational suggestions accordingly. According to the characteristics of the process, the full life cycle of coal-to-gas, gas-based shaft furnace, electric furnace process is divided into three stages: upstream stage of raw material acquisition (coal, electricity, natural gas, etc.), transportation stage and product production Stage (coal to gas purification, coal to gas heating, etc.). In this paper, molten steel is used as the final product, 1 ton of electric furnace molten steel is selected as the functional unit (FU), and life cycle inventory analysis is carried out on this benchmark.

The main sources of the research data of this paper are as follows: basic process parameters, national (international) relevant standards, Gabi database, journals and other documents.

4.2 Preparation of life cycle list

4.2.1 Process flow
In this paper, the coal-to-gas, gas-based shaft furnace, electric furnace process with an electric furnace charge structure of 30% DRI and 70% scrap is selected as the analysis case, and the life cycle list is compiled on this basis. Coal-to-gas, gas-based shaft furnace, electric furnace short-flow process can be divided into coal-to-gas, coal gas purification, coal gas heating, pellet production, gas-based shaft
furnace reduction, furnace top gas treatment. Electric furnace steelmaking are the main production links. Coal-to-gas purification includes several steps of coal-to-gas desulfurization, debenzene, and decarbonization.

4.2.2 Energy consumption and emission inventory
Compiled with the main products of each process as the functional unit. The list of each process is given. According to the flow of materials in the process and the inventory data of each process, the energy consumption and emissions of different processes in the whole life cycle are calculated. According to the characteristics of coal-to-gas-gas-based shaft furnace-electric furnace process pollution emissions, this study focuses on the impact of gas emissions.

5. Results and discussion
The life cycle impact assessment of coal-to-gas-gas-based shaft furnace-electric furnace is a process that combines the life cycle inventory data to quantify the contribution of the process to different types of environmental impact and evaluate the process environmental load. Life cycle assessment is generally divided into three steps: impact classification, normalization and weighting.

5.1 Process contribution
Characterization is a quantitative analysis process that selects a specific environmental factor as a reference, unifies other environmental factors of this type into the same unit value with relative
characteristic factors. The results of quantitative analysis are called potential of impact types: resource consumption potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (gwp100), human health toxicity potential (HTP), photochemical ozone synthesis potential (POCP).

In order to obtain the contribution of each process to different impact types more intuitively, define the total potential value of each environmental impact type as 1, and calculate the percentage contribution of each process to the potential value of different environmental impact types. As the figure shows, due to the different environmental factors of consumption and emissions in each process, different processes have different contributions to different types of environmental impact.

![Fig. 2 contribution diagram of coal gasification gas based shaft furnace electric furnace process](image)

It can be seen from the figure that the four processes of pellet, decarbonization, heating and electric furnace are the most discharged processes in the whole life cycle of the short process of coal to gas, gas-based shaft furnace and electric furnace. A lot of SO2 and NOx will be produced in pellet production process, so this process mainly contributes to AP and EP two potential values, accounting for about 14%. For the complete system, the proportion of pelletizing process is small, so its contribution to ADP of the whole process is not outstanding. In the decarbonization process, a part of CO, CH4 and other gases will be removed when CO2 is removed from coal gasification and top gas. Therefore, there are more CO2, Co, CH4 and other gases in the exhaust gas of decarbonization process, so it has a great contribution to gwp100 and POCP, which are 26% and 67% respectively. The heating process includes fuel combustion. The fuel is natural gas. A large amount of CO2 will be emitted during the combustion process, so it is mainly contributed to gwp100. EAF steelmaking is the process that contributes the most to the environment in the whole life cycle. Its contribution to six environmental impact potentials is 97%, 70%, 67%, 40%, 82%, 26%, respectively. In the whole process of coal gasification gas based shaft furnace electric furnace, each link will consume electric energy, and the production of electric energy will bring greater environmental impact, which will lead to indirect contribution of each process to environmental impact. Since all the top gas produced in the reduction process of gas-based shaft furnace enters the decarbonization process, and all the product direct reduction iron enters the electric furnace, the reduction process of gas-based shaft furnace has little contribution to the six potential values. From figure it can also be seen that the contribution of other links such as desulfurization and benzene removal to the potential of environmental impact is also small, because these links have less gas emissions.

5.2 Process energy consumption and emission analysis

According to the energy consumption and emission list, further analyze the comprehensive energy consumption and emission of the process. When producing 1t electric furnace molten steel, the energy consumption of the whole process is shown in Figure 7.
Fig. 3 Energy consumption of coal to gas gas-based shaft furnace electric furnace process

The comprehensive energy consumption per ton steel of coal to gas gas-based shaft furnace electric furnace process is 263.67 kgce.

Among them, coal to gas process has the highest energy consumption, accounting for 42.62% of the total energy consumption, followed by electric furnace process and heating process, accounting for 22.85% and 20.26% of the total energy consumption respectively, and the energy consumption contribution rate of these three links exceeds 85%. It can also be seen from the figure that the main energy consumption of coal to gas is the consumption of coal, oxygen and desalted water; the main energy consumption of heating process is the consumption of natural gas; and the main energy consumption of electric furnace process is the consumption of electric power.

6. Conclusion

Based on the analysis of the life cycle assessment of coal-to-gas-gas-based shaft furnace-electric furnace process, the relationships between each unit process in coal-to-gas-based shaft furnace-electric furnace process and environmental protection, energy consumption, pollution emission are evaluated. The result which the three processes of electric furnace, coal-to-gas and gas heating can be regarded as the key link with the greatest impact on the environment is concluded. Through the simulation of the production process, this paper finds out the improving points of the short process steelmaking process, which provides the future direction and theoretical basis for the development of steel manufacturing industry. At the same time, the coupling method of life cycle assessment and industrial process provides an example for the development of environmental protection and green industry in China and makes a great contribution. However, due to the prevalence of COVID-19, the methods provided in the paper could not be studied in the laboratory. In the future, the author will apply this method to experiments and further study to perfect the theoretical system.

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