Effect of Carbonaceous Reducers on Carbon Emission during Silicon Production in SAF of 8.5 MVA and 12.5 MVA

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Research Article

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Posted Date: August 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-813450/v1

Effect of Carbonaceous Reducers on Carbon Emission during Silicon Production in SAF of 8.5 MVA and 12.5 MVA

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Abstract

The silicon manufacturing process produces a large amount of carbon emissions, which is of deep concern to the Chinese government. Previous research has calculated the amount of carbon emissions incurred in silicon production, while research on the factors that affect carbon emissions during the silicon production process has been scarce. The effect of the carbonaceous reducers' consumption on the carbon emission during silicon production was investigated using statistical analysis of the actual production data in order to lower the carbon emissions of silicon production. The effect of different type furnaces (8.5MVA and 12.5MVA) on the carbon emission were also investigated in the study. Based on the results, the soft coal has the greatest impact on carbon emissions when using the 8.5MVA submerged arc furnace. When using the 12.5MVA furnace, petroleum coke has the greatest impact on carbon emission. The use of the 12.5MVA furnace reduces the carbon dioxide emissions of the production of one ton of silicon by approximately 74 kg compared to the 8.5MVA

furnace. To obtained reduced carbon emissions in silicon production, we suggest that the silicon manufacturers should (1) use the 12.5MVA submerged arc furnace as much as possible; (2) and optimize the ratio of carbonaceous reducing agents in raw materials for the different furnace types.

Kay words:

Carbonaceous Reducers, Carbon Emission, Silicon Production, Different type of submerged arc furnaces

1 Introduction

In the last several decades, due to increasing concern about global warming, energy conservation and carbon emission reduction have attracted intense attention worldwide. China is currently the largest carbon dioxide emitter in the world [1-4]. However, over the last decade, China has made great efforts to slow down the growth of its carbon emissions. In November 2009, China announced its first greenhouse gas emission reduction target. In the 2015 Paris agreement, China committed to reach peak CO_2 emission by 2030 and decrease its carbon intensity by 60-65% by 2030 relative to the 2005 [2]. On December 18th, 2017, the National Development and Reform Commission announced the "National Carbon Emissions Trading Market Construction Plan (Power Generation Industry)", setting the threshold for China's power generation industry to be included in the carbon market [3]. This plan provides guidance for the industrial silicon sector.

Solar energy is a green renewable energy that is usually obtained by conversion of light into electricity by solar photovoltaic cell materials made from crystalline silicon [5]. Current photovoltaic power generation relies largely on polycrystalline. Polycrystalline silicon can be used to manufacture different types of optoelectronic and photonic circuit [6,7]. It can realize different types of optoelectronic and photonic circuits by integrating on the same silicon chip [8]. Therefore, it is highly necessary to study the factors that affect the carbon emissions in the production of industrial silicon used as the raw material for polycrystalline silicon.

The smelting process of industrial silicon is an extremely energy-intensive industrial process that mainly consumes carbonaceous reducing agents such as petroleum coke, soft coal and wood block that are used to produce silicon via carbon thermal reduction in a submerged arc furnace [9,10]. These raw materials as well as the silica used as the silicon source are non-renewable resources and their use gives rise to considerable fossil CO_2 emissions. Since the submerged arc furnace consumes the major part of the energy required in the production chain from silica to industrial silicon, it is appropriate to focus on this process. While multiple approaches for reducing the energy requirements and the carbon dioxide emissions of this process have been suggested and investigated, research on the factors that affect carbon emissions during the industrial silicon production process has been scarce.

A variety of methods have been developed for the study of the environmental impact and CO_2 emissions of different technologies by researchers around the world. Heijungs et al. [11] discussed three cases using the Human and Ecological Life cycle tool of Systematic Comprehensive Evaluation (HELIAS), but did not proposed the specific factors affecting carbon emissions. Kirschen et al. [12] showed that in the steel industry, the use of natural gas (NG) can help to reduce the total carbon dioxide emissions produced by electric arc furnaces, but this method does not explicitly calculate the amount of carbon dioxide to be reduced. Kang et al. [13] developed a robust IO-LP model, which suggests that China's coal and hydropower technologies are likely to be significantly developed between 2020 and 2050, but there are significant uncertainties in this approach. O'Ryan et al. [14] analyzed data from the Chilean electricity market based on a Computable General Equilibrium (CGE) model, demonstrating that Chile is on track to reduce the country's overall carbon emissions. Takla et al. [9] analyzed the actual and theoretical production processes of industrial silicon, and used exergy and energy analysis to evaluate the resource utilization of industrial silicon production process.

Since the industrial silicon production process is quite similar to the steel production process, we used the method used in the steel industry for the calculation of carbon emissions. The studies focusing on the major steel industry methods used to calculate carbon emissions and their mitigation strategies are listed below.

Worrell et al. [15] analyzed the baseline for 1994 energy use and carbon dioxide emissions from US steel manufacture and identified as many as 47 energy-efficient practices and technologies. Helle et al. [16] investigated the potential of the use of biomass in iron industry production. The results shed light on using biomass in steelmaking can effectively reduce carbon dioxide emissions and reduce smelting costs. Mitra1 et al. [17] used genetic algorithms to analyzed solutions that can provide guidance in the search for more sustainable production concepts. Zhang et al. [18] evaluated the potential of waste heat recovery and carbon reduction in a steel plant in northern China. This study demonstrated that for a steelmaking plant with an annual output of 10 million tons, 1.65 million tons of coal equivalent and approximately 5 million tons of carbon dioxide emissions could be saved by adopting low-energy heat recovery technology. By establishing China's 2011 Economic Input-output Life Cycle Assessment (EIO-LCA) model, Li et al. [19] proved that coke and coal are the biggest influencing factors of direct carbon dioxide emissions in the steel industry and put forward corresponding suggestions to reduce carbon emissions. By limiting 61 key constraints, Shen et al. [20] obtained the best solution for the batch-up ratio and energy saving and emission reduction of the steel production system. The maximum energy saving rate per ton of steel could reach 20.63 kgce. In view of the high carbon emissions in China's steel industry, other researchers believe that enhancing energy efficiency and the development and application of energy saving/recycling technologies and breakthrough carbon dioxide technologies, as well as the continuous use of renewable energy are important ways to reduce greenhouse gas emissions from the steel industry [21-24].

In previous studies, we determined the correlation coefficients between the different raw material consumption and exergetic efficiency via linear regression on industrial silicon production in the furnace [25,26]. We used several artificial neural network (ANN) models to simulate and evaluate the approximate composition fluctuations of carbon materials and the final power strain and combustion efficiency under different petroleum coke, soft coal, silica and electrode [27-29]. The effects of raw materials, fixed carbon, volatile substances and water contained on the silicon yield and the energy consumption during silicon production were also studied [30-32]. Our recent research has turned up evidence of the correlation between the impurity content in silicon products and the consumption of different carbonaceous reducers [33]. These studies provided different method for studying the impact of raw materials on carbon emissions in the industrial silicon production process.

2 Research method

2.1 Silicon production process

Figure 1 shows the silicon production system that including the feed, electrode, SAF, product, and waste gas and slag treatment systems [9]. The arc formed between the graphite electrode and the production material in the furnace and the resistance of the charge to the current will cause the furnace temperature to exceed 1800°C. At such high temperature, silica is reduced by a mixture of soft coal, petroleum coke and wood block with certain proportions. To facilitate the calculation of carbon emissions, we adopt simplified equations for the following major reactions:

$$SiO_2(s)+C(s)=Si(l)+CO_2(g) \tag{2.1}$$

$$SiO_2(s)+2C(s)=Si(l)+2CO(g) \tag{2.2}$$

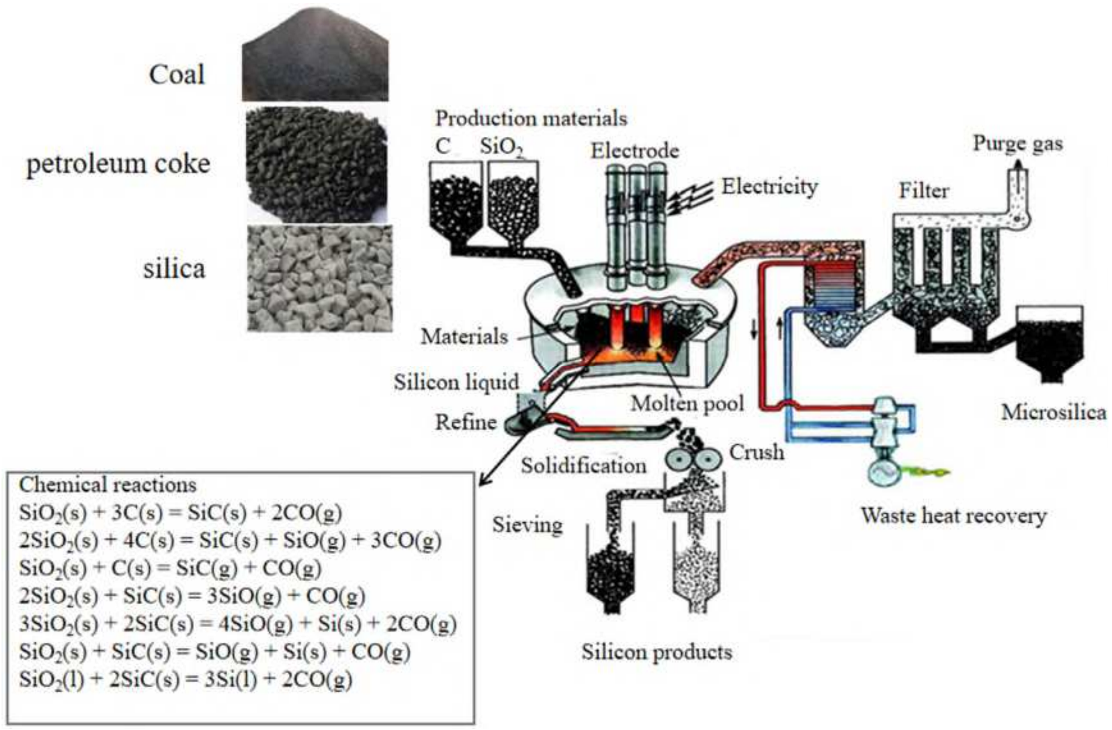

Fig. 1 Industrial silicon production process [9]

2.2 Raw materials

The main carbonaceous reducers for the production of industrial silicon include silica, soft coal, petroleum coke, blue carbon, semi-coke, asphalt coke, coke powder, charcoal, wood block, biomass charcoal and so on. Coal, wood block and petroleum coke were used as the carbonaceous reducers, and graphite with a carbon content of 100% was used as the electrode material. These materials are mainly composed of fixed carbon, volatiles, moisture and ash. Table 1 shows the main components of the carbon-containing feedstock used in the industrial silicon production experiments carried out in this work.

Table 1 Industrial analysis of several carbonaceous reducers (wet basis %)

Raw materials	Fixed carbon (%)	Volatiles (%)	Moisture (%)	Ash (%)
Petroleum coke	84.74	14.68	0.12	0.46
Soft coal	53.37	39.55	4.70	2.38
Wood block	10	32	57	1

Charcoal	52	10	33	5
Electrode material	100	0	0	0

2.3 Experimental data collection

In the course of the experiment, we collected a large amount of actual production data through cooperation with an industrial silicon enterprise in Yunnan province and deleted the abnormal data caused by power failure. Analysis of these data reveals the relationship between the raw material consumption and the carbon emission in the process of industrial silicon production in different furnace types. Understanding the relationship between the data is beneficial for reducing production costs and carbon emissions, achieving a more rational and effective use of resources, improving resource utilization and product quality, and protecting the environment.

The 8.5 MVA furnace type was named as 1# and 2#, and the 12.5 MVA furnace type was named as 3# and 4#. To facilitate comparison and analysis, the data for the consumption of the three kinds of carbonaceous reducers are converted into data for the production of one ton of industrial silicon, and the data unit is ton/ton. We consider that the silicon dioxide content and the electrode material is 100% fixed and the carbonaceous reducers react completely with silica. All data are analyzed using average values.

2.4 Carbon emission calculation method

The carbon emission calculation methods can be divided into three categories: activity level method, mass conservation method and continuous monitoring method. The calculation principle of the activity level method is based on the consumption data and default emission factor. While the calculation method is simple, there is a large uncertainty for the value of the default emission factor. The conservation of mass method is based on the calculation of the carbon difference between the input and output of the enterprise. This method is relatively complex and the calculation results are relatively accurate. However, when a third party uses this method to calculate the information asymmetry, the accuracy of the results will be reduced. The continuous monitoring method is a method for the continuous monitoring of related parameters, but it is often difficult for enterprises to monitor all of the emission parameters, and the cost of monitoring is high.

In view of the characteristics of the three methods, currently the most commonly used method is the activity level method. In this work, the study of carbon emissions also used the activity level method to measure the carbon emissions of enterprises.

2.4.1 Direct emissions

Direct emissions refer to the CO_2 emissions generated by the combustion of fossil fuels, including internal fixed source emissions and mobile source emissions used for production, etc. These emissions can be calculated as follows (the formula is derived from the IPCC Guidelines):

$$E = \sum AD_i \times EF_i \tag{2.3}$$

where E is the value of the total carbon emissions caused by the combustion of all fuels in the production of industrial silicon, i is the type of fossil fuel, AD_i is the total consumption of i, and EF_i is the CO_2 emission coefficient of i. Using the energy recommended carbon emission coefficient formula published in the IPCC guidelines, the carbon emission coefficients of various fuels can be obtained as:

$$C = A \times B \times (\frac{44}{12}) \times 1000 \tag{2.4}$$

$$F = C \times 4186.6 \times 10^{-9} \times 10^{-3} \tag{2.5}$$

$$H = F \times G \tag{2.6}$$

where A is the carbon emission coefficient (kgC/GJ), B is the carbon oxidation factor, and all the raw materials for industrial silicon production have the weight of 1 kg each. C is the CO_2 emission coefficient ($kgCO_2$/TJ), F is the original coefficient ($kgCO_2$/kcal), C is the CO_2 emission coefficient ($kgCO_2$/TJ), G is the calorific value (kcal/kg), and H is the recommended emission coefficient ($kgCO_2$/kg). It is important to note that the CO_2 emission factors used for the calculation are taken from 2006 IPCC Guidelines, because these values are more suitable for the silicon produced in

China. The calorific values of both wood-solid and charcoal are Chinese calorific values. The calorific value of the wood block is approximately 1.2×10^{7} J/kg, which is converted into a common unit of 2866800 calories/kg, or 2866.8 kcal/kg. The calorific value of charcoal is 3.4×10^{7} J/kg, which means that 3.4×10^{7} J is released when 1 kg of charcoal is completely burned and this is converted into a common units to obtain 8122600 calories/kg, or 8122.6 kcal/kg.

Table 2 Calorific value G data at standard condition (25 ℃,1 atmosphere)

Type of fuel	Soft coal	Petroleum coke	Wood block	Charcoal
Calorific value kcal/kg	6400	8200	2866.8	8122.6

Table 3 Carbon emission coefficient data of each fuel

Type of fuel	Soft coal	Petroleum coke	Wood block	Charcoal
Emission coefficient kgCO_2/kg	2.53	3.35	1.35	3.81

Using the data in Equation (2.3) and Tables 2 and 3, the carbon emissions from the combustion of fossil energy in the production of industrial silicon can be obtained.

2.4.2 Emissions from industrial processes

The carbon emission of industrial production process refers to the CO_2 emissions generated by other purchased carbon-containing raw materials such as electrodes in the production process of industrial silicon. The calculation formula is as follows：

$$E_{electrode} = P \times EF_P \tag{2.7}$$

where $E_{electrode}$ is the amount of CO_2 produced by consuming the electrode (kgCO_2/kg), P is the electrode consumption (kg), EF_P is the CO_2 emission factor of the electrode, and its value is 3.6630 tCO_2/t. These values are derived from the IISA Guidelines for the Collection of Carbon Dioxide Emission Data.

2.4.3 Emissions from the use of electricity

The CO_2 emissions are driven by the electricity purchased by industrial silicon manufacturers. The power output consumed by industrial silicon enterprises actually occurs in the power production enterprises and is consumed by industrial silicon enterprises. In accordance with the benefit principle, the carbon dioxide emissions embodied in the output power of industrial silicon enterprises are used to calculate the total emissions. The emissions are calculated as follows：

$$E_e = P \times EF_e \tag{2.8}$$

where E_e is the indirect CO_2 emissions generated by the purchased power ($kgCO_2$), P is the power consumption (kWh), EF_e is the CO_2 emission factor of the power consumption in the emission region, and is equal to 0.7035 $kgCO_2$/kWh. The data is derived from the IISA Guidelines for the Collection of Carbon Dioxide Emission Data.

2.6 Total Carbon Emissions

On the basis of the above classification, the carbon emissions of industrial silicon enterprises can be divided into direct emissions and indirect emissions according to their emission sources. The direct emissions mainly refer to the emissions from the burning of fossil fuels in the production process, while the indirect emissions mainly refer to the net carbon dioxide emissions generated by the consumption of electricity. Therefore, the calculation formula of total carbon emission is as follows:

$$E_{total} = E + E_{electrode} + E_e \tag{2.9}$$

Once the total carbon emission values are obtained, the carbon emissions of the five main raw materials electricity, electrodes, petroleum coke, soft coal and wood bloc can be compared. It was found in Fig. 2 that the purchased power produces the largest contribution to carbon emissions, with the average of 63.45% for the low-rated capacity furnace and 60.85% for the high-rated capacity furnace. Low-rated capacity furnace type has the largest proportion of petroleum coke emissions, averaging 16.4%, while high-rated capacity furnace type has the largest proportion of soft coal emissions, averaging 17.35%.

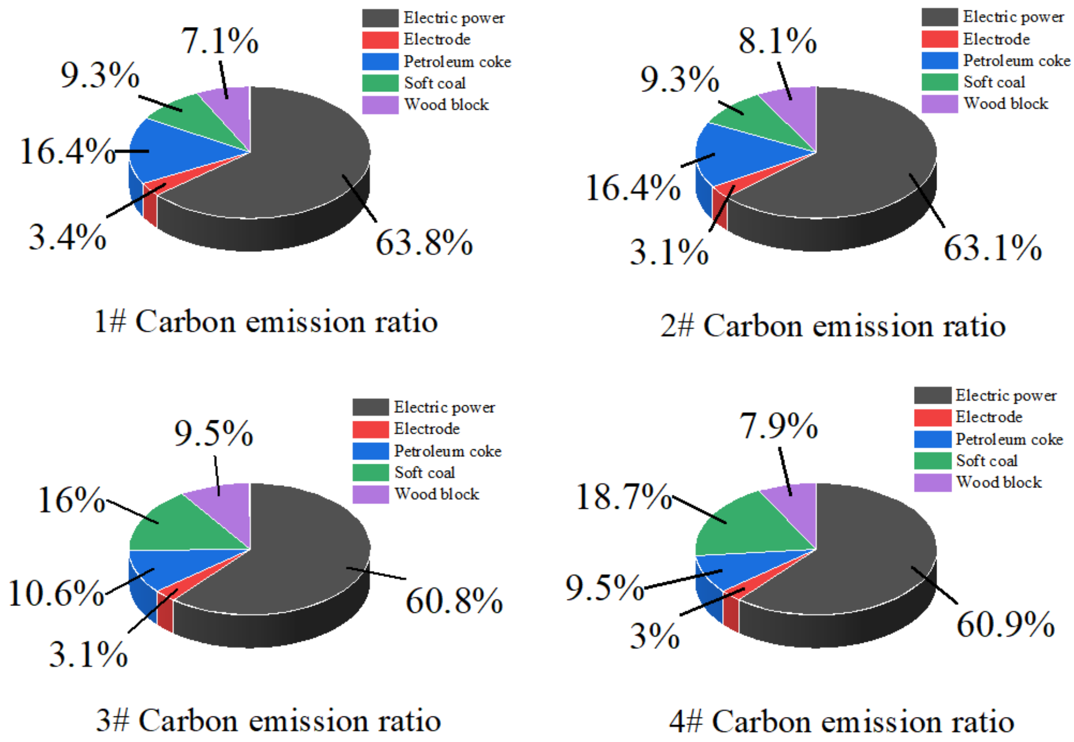

Fig. 2 The proportion of carbon emission from different furnace

3 Experimental results and discussion

3.1 Effect of carbonaceous reducers on direct carbon emissions

In order to study the effect of carbon reducing agent consumption on carbon emissions during silicon production, Pearson's correlation coefficient method, which is widely used to evaluate the correlation of variables, and the trend diagram measuring the linear correlation between variables were used for analysis. The specific relationship is shown as follows [33]:

$$\mathrm{r}=\frac{\sigma_{x_i y_i}{}^{2}}{\sigma_{x_i}\cdot\sigma_{y_i}}=\frac{\frac{\sum(x_i-\bar{x}_i)(y_i-\bar{y}_i)}{n}}{\sqrt{\frac{\sum(x_i-\bar{x}_i)^2}{n}}\times\sqrt{\frac{\sum(y_i-\bar{y}_i)^2}{n}}}=\frac{\sum(x_i-\bar{x}_i)(y_i-\bar{y}_i)}{\sqrt{\sum(x_i-\bar{x}_i)^2}\cdot\sqrt{(y_i-\bar{y}_i)^2}} \tag{3.1}$$

3.1.1 The 8.5 MVA SAF

In this section, we analyze the influence of soft coal, petroleum coke and wood block on the direct carbon emissions. More than 150 groups of experiments were carried out on the three reducing agents containing petroleum coke, soft coal and wood block respectively in 1# and 2# furnaces, and then the available data were compared using linear regression analysis. Fig. 3 shows the trend of the three major reducing chemicals and direct carbon emissions, with strong linear correlation observed for all cases. The absolute r values of 1# furnace soft coal, petroleum coke and wood block are 0.94041, 0.98248 and 0.97656, respectively. The absolute r values of 2# soft coal, petroleum coke and wood were 0.92147, 0.96294 and 0.94735, respectively. The absolute values of the straight slope between soft coal, petroleum coke and wood block and carbon emission of 1# furnace are 8.49575, 6.25631 and 5.8344, respectively, and those of 2# furnace were 7.30551, 6.41443 and 5.44356, respectively. Based on the analysis of 1# and 2# low-rated capacity submerged arc furnaces, it is concluded that soft coal has the greatest impact on the direct carbon emissions generated by the production of single ton of industrial silicon, followed by petroleum coke, and wood block has the least impact.

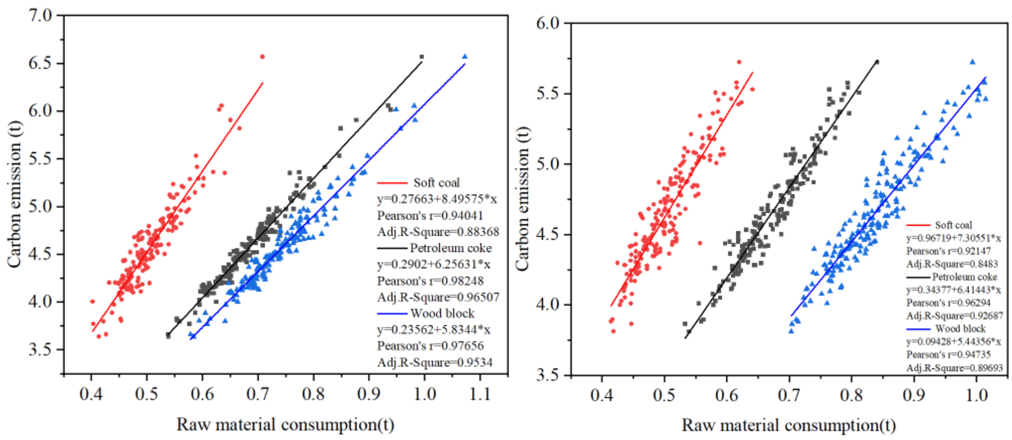

Fig. 3 Relationship between carbonaceous reducers and direct carbon emissions in 1# and 2# furnaces

3.1.2 The 12.5 MVA SAF

In this section, we mainly analyze the impact of the three reducing agents, namely soft coal, petroleum coke and wood block, on the direct carbon emissions. More than 80 groups of experiments were carried out on the three reducing agents containing soft coal, petroleum coke and wood block in 3# and 4# furnaces, respectively, and then the available data were compared using linear regression analysis. Fig. 4 shows the variation trend of the three main reducing agent and direct carbon emissions, and strong linear correlation is observed in all cases. The absolute r values of the 3# furnace soft coal, petroleum coke and wood block are 0.93602, 0.92976 and 0.92912, while the absolute r values of the 4# furnace soft coal, petroleum coke and wood block are 0.83585 and 0.880, respectively. The absolute values of the linear slope between soft coal, petroleum coke and wood block and carbon emission 3# SAF are 5.76843, 8.3217 and 4.33515, respectively, and those of 4# SAF are 5.37373 and 11.28009 and 5.09019, respectively. Based on the analysis of 3# and 4# high-rated capacity submerged arc furnaces, it is concluded that when using 12.5MVA submerged arc furnace, petroleum coke has the greatest impact on the direct carbon emissions generated by the production of a ton of industrial silicon, followed by soft coal, and wood block has the least impact.

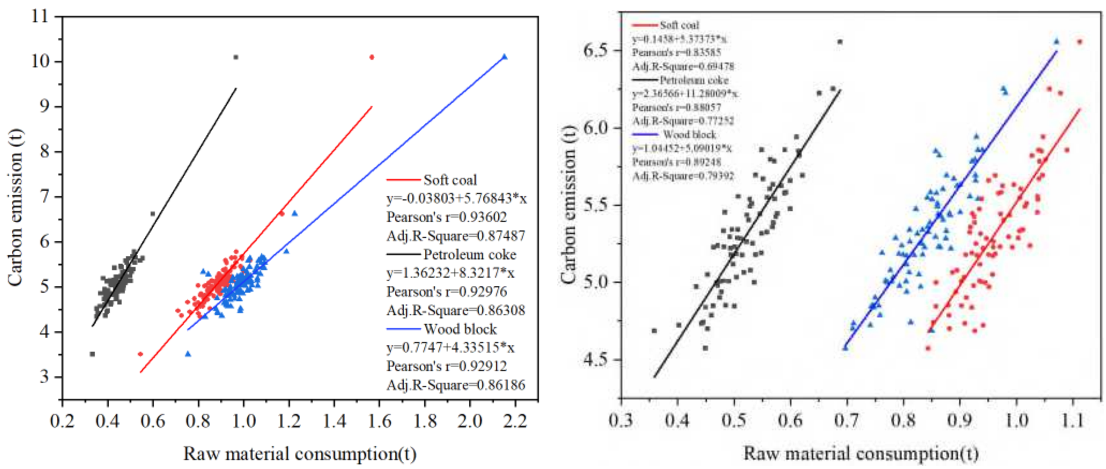

Fig. 4 Relationship between carbonaceous reducers and direct carbon emissions in 3# and 4# furnaces

3.2 Effect of carbonaceous reducers on total carbon emissions

3.2.1 The 8.5 MVA SAF

Similar to 3.1.1, Fig. 5 shows the variation between the three main reducing agents for the total carbon emissions, which also shows a medium linear correlation. The absolute r values of soft coal, petroleum coke and wood block in 3# furnace are 0.8247, 0.72399 and 0.73295 respectively, and the absolute r values of soft coal, petroleum coke and wood block in 4# furnace are 0.87311, 0.87957 and 0.88502, respectively. The linear slope between soft coal, petroleum coke and wood block and carbon emission of 1# submerged arc furnace are 19.29899, 11.79839 and 11.41911, respectively, and those of 2# submerged arc furnace are 18.18864 and 15.39529 and 13.36241, respectively. Based on 3.1.1, it can be concluded that soft coal has the greatest impact on the total carbon emissions generated by the production of single ton of industrial silicon, followed by petroleum coke, and wood block has the least impact when using 8.5MVA submerged arc furnace.

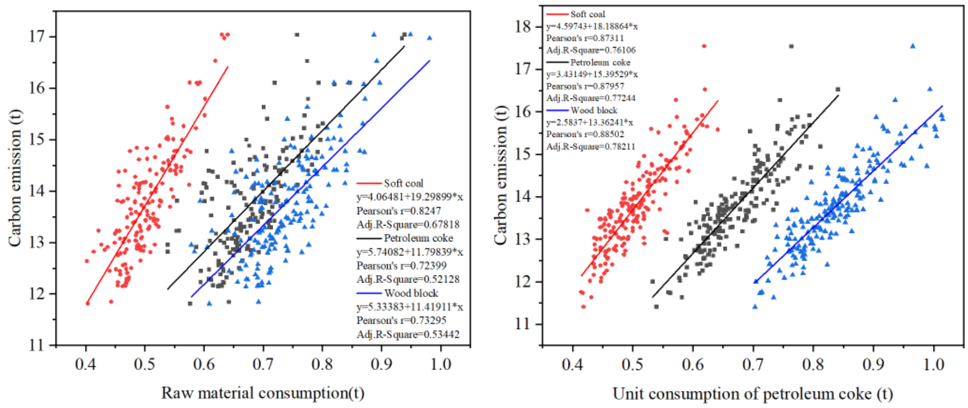

Fig. 5 The relationship between carbonaceous reducers and total carbon emissions in 1# and 2# furnaces

3.2.2 The 12.5 MVA SAF

Similar to 3.1.2, Fig. 6 shows the variation for the three main reducing chemicals and the total carbon emissions, revealing in some linear correlation. The absolute r values of the 3# furnace soft coal, petroleum coke and wood block are 0.7265, 0.81006 and 0.7, respectively. The absolute values of the linear slope between soft coal, petroleum coke and wood block and carbon emission of the 3# submerged arc furnace are 8.28397, 13.39245 and 8.04538, respectively, and those of 4# submerged arc furnace are 11.61836, 13.23908 and 11.49253, respectively. According to 3.1.2, it can be concluded that petroleum coke has the greatest influence on the total carbon emissions generated by the production of a ton of industrial silicon, followed by soft coal, and wood block has the least influence.

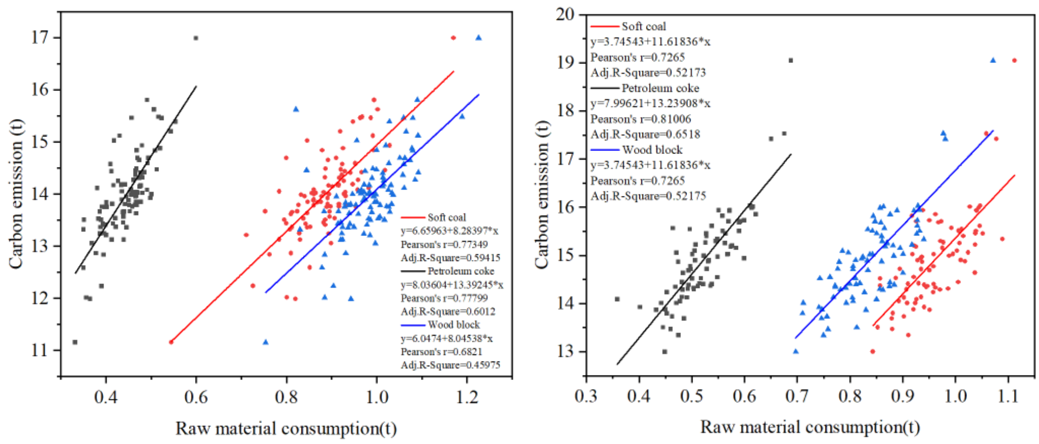

Fig. 6 The relationship between three carbonaceous reducer and total carbon emissions in 3# and 4# furnaces

3.2.3 Change of the slope of the linear equation between raw material consumption and carbon emission under different furnace types

To more intuitively understand the change of the slope of the linear relationship between different raw materials and carbon emissions under the condition of 8.5MVA and 12.5MVA furnace types, it is drawn as a broken line graph, as shown in Fig. 7. The results show that with the increase in the rated capacity, the slopes of the carbon emissions from coal and wood decreases, while the slope of the carbon emissions from petroleum coke increases. Therefore, we can draw the following conclusion: when using 8.5 MVA furnace, to improve the industrial silicon production and reduce carbon emissions, it is necessary to reduce the usage of soft coal, and increase the use of petroleum coke and block. When using the 12.5MVA furnace, to improve the production of industrial silicon and reduce carbon emissions, it is necessary to reduce the usage of petroleum coke and to increase the usage of soft coal and wood block.

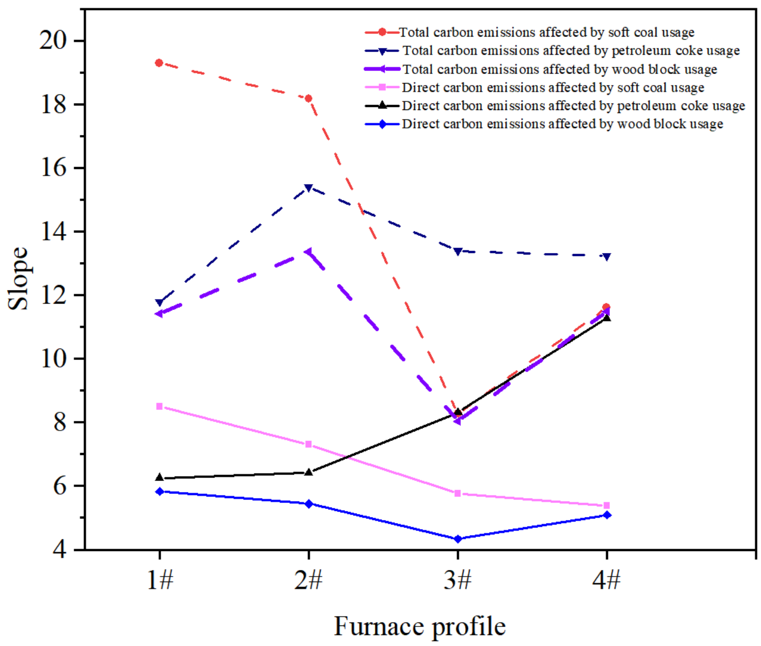

Fig. 7 The slope of a linear equation

3.2.4 Comparison of average raw material consumption and average carbon emission of different furnace types

It is clearly observed from Fig. 8, that the power consumption of a ton of industrial silicon produced by different furnace types is essentially maintained at 12384±215 kWh/t, and the electrode material consumption is essentially maintained at 0.12±0.005 t/t. However, the consumption of raw materials varies greatly. The consumption of petroleum coke, soft coal and wood block of the 8.5MVA furnace is essentially maintained at 0.6791±0.0073 t/t, 0.506±0.0013 t/t and 0.7915±0.0460 t/t. The consumption of petroleum coke, soft coal and wood block of the 12.5MVA furnace is essentially maintained at 0.4839±0.0397 t/t, 0.9234±0.0391 t/t and 0.9131±0.0735 t/t.

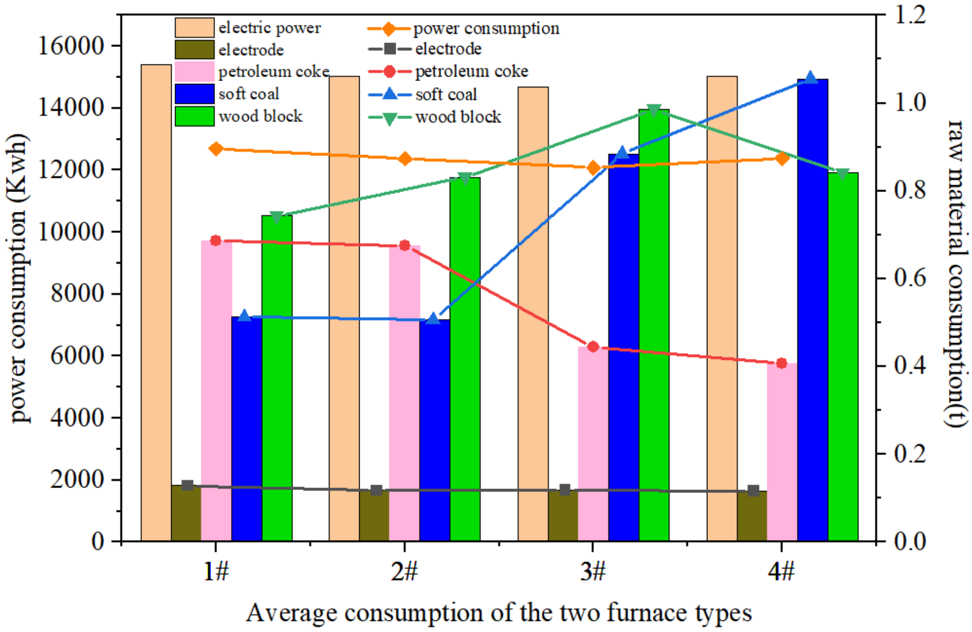

Fig.8 Average consumption of electric power, electrode and carbon reducing agent for both furnace types

According to Fig. 9, the direct carbon emission of one ton of industrial silicon produced by the 1# furnace is 4.5848t±0.4350 t/t and the total carbon emission is 13.9973±1.6327 t/t. The direct carbon emission of one ton of industrial silicon produced by the 2# furnace is 4.6476±0.3683 t/t. The total carbon emission is 14.0241±0.9400 t/t and the direct carbon emission of one ton of industrial silicon produced by the 3# furnace is 5.0520±0.3356 t/t. The total carbon emission is 13.9339±0.7835 t/t and the direct carbon emission of one ton of industrial silicon produced by the 4# furnace is 5.3182±0.3802t/t and its total carbon emission is 13.9404±1.1886 t/t. Although the direct carbon emission of the high-rated capacity furnace is higher than that of the low-rated capacity furnace, the total carbon emission of the high-rated capacity furnace is lower than that of the low-rated capacity furnace. We believe that this is because the raw materials of the high-rated capacity furnace incur a too high carbon cost, resulting in large direct carbon emissions. Next, we calculate the excess carbon coefficient and the reasonable batching amount of the high-rated capacity furnace.

Based on the calculation, we conclude that the high-rated capacity furnace reduces the total carbon emission by 0.0736 t/t on average compared to the low-rated capacity furnace, proving that the use of the 12.5MVA furnace can improve the smelting efficiency of industrial silicon and reduce the energy consumption and carbon emission of industrial silicon production.

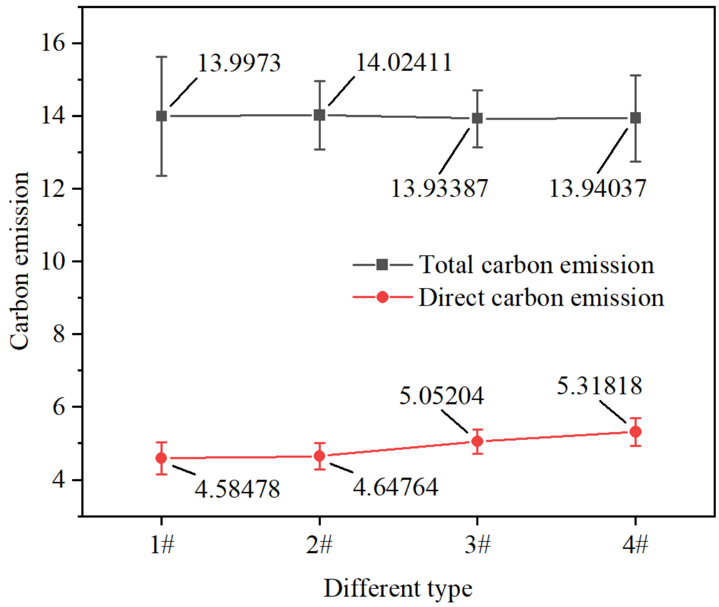

Fig. 9 Comparison of total average carbon emissions and direct carbon emissions of different furnace types

4 Conclusion

In this paper, the origins of carbon emission in industrial silicon production are studied. The results show that when using the 8.5MVA furnace, soft coal has the greatest impact on the carbon emissions generated in the production of one ton of industrial silicon, followed by petroleum coke, and wood block has the least influence; when using the 12.5MVA furnace, petroleum coke has the greatest impact on the carbon emissions generated by producing a ton of industrial silicon, followed by soft coal, and wood block has the least influence. The results show that when 8.5MVA furnace is used to produce a ton of industrial silicon, approximately 4.6162 tons of direct carbon emissions and 14.0107 tons of total carbon emissions are generated. When a 12.5MVA furnace is used to produce a ton of industrial silicon, approximately 5.1851 tons of direct carbon emissions and 13.93715 tons of total carbon emissions are generated. Based on the above analysis, we propose that the 12.5MVA submerged arc furnaces are more conducive to energy saving and carbon emission reduction in the process of industrial silicon production. This research is highly significant for improving the industry's market competitiveness, reducing the energy consumption of industrial silicon production, and achieving energy saving and emissions reduction.

Acknowledgments

The authors are grateful for financial support from the National Natural Science Foundation of China (No. 51804147) and the Yunnan Province Department of Education (No. 2018JS018).

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* Ethics approval and consent to participate

We don't cover ethics approval and consent to participate.

* Consent for publication

Not applicable.

* Availability of data and materials

All data generated or analysed during this study are included in this published article.

* Competing interests

The authors declare that they have no competing interests.

* Funding

The authors are grateful for financial support from the National Natural Science Foundation of China (No. 51804147) and the Yunnan Province Department of Education (No. 2018JS018).

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* Disclosure of potential conflicts of interest

We declare that we have no conflict of interest.

* Research involving Human Participants and/or Animals

Not applicable

* Informed consent

Not applicable