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The effect of the carbonaceous materials properties on the energy consumption of silicon production in the submerged arc furnace

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The objective of this study was to use a statistical approach to determine the correlation of fixed carbon, volatile matters and moisture with the specific electrical consumption and exergy efficiency by collecting and analyzing an abundance of actual production data generated in silicon plants during the melting process of silicon produced in the submerged arc furnace (SAF). A high positive correlation (the *r* maximum value of 0.82) between the fixed carbon composition and the specific electrical consumption, as well as the perfect negative correlation (the *r* maximum value of −0.92) between the fixed carbon and the exergy efficiency were found, especially when the carbon materials contained a very high amount of graphitized carbon. Compared with the carbon materials without woodchips, the high correlation among the volatile matters, the specific electrical consumption and exergy efficiency was observed when using the carbon materials with woodchips. The influence of the proximate composition on the electrical consumption and exergy efficiency becomes stronger with the increase of the graphitized carbon content in the carbon materials. The analysis results can be used to support decisions when optimizing the proximate composition of the carbonaceous reductants in order to increase exergy efficiency and decrease electrical consumption costs, which is one of the biggest operating costs in the silicon furnace.

1. Introduction

Compared with sustainable energy, conventional fossil fuels are no longer satisfying the criteria of a "sustainable energy" and are among the major causes of the greenhouse effect. Recently, many researchers are focusing on sustainable energy and many world economies are also planning and investing in them. In particular, solar energy is one with remarkably high potential for development among all sustainable energy sources because it is clean and can be harvested and supplied without any considerable environmental pollution (Kalogirou, 2004), relative to other forms of sustainable energy, such as wind, ocean, hydro, geothermal and biomass. Generally, solar energy can be converted into useful form of energy by solar cells, solar thermal collectors, concentrated solar power and concentrated photovoltaic/thermal systems (Hassani et al., 2016). Among them, more than 80% of the conventional commercial solar cells are made with silicon as the initial material (Saffar et al., 2014), and particularly multi-crystalline silicon (MÖller et al., 2005; Flamant et al., 2006).

Silicon is produced by carbothermic reduction of silicon dioxide with carbon materials (such as petroleum coke, coal and charcoal/woodchips) in a SAF, whose specific actual process for silicon production requires high temperatures (1800 °C or more) provided by electrical energy and carbon materials. In terms of energy input, the electrical power needed for this process ranges from 11 to 13 kW h per one ton of silicon produced, which represents about 45% of the total energy supplied to the process, while the chemical energy of raw materials accounts for the rest (Takla et al., 2013). The silicon industry is also an energy-intensive industry whose electrical energy consumption accounts for a large share of the operating costs, which is similar to the stainless steel industry (Bisio et al., 2000). Regarding energy output, roughly 30% of the total energy input is applied to the silicon product by the energy balance analysis method, which means that 70% of the total energy in the process of

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silicon production is lost (Schei et al., 1998). Therefore, the energy-saving and cost-reducing initiatives play a very important role to lower the operational costs in the process of silicon production to a minimum.

The melting process during silicon production in the SAF has been investigated by a number of studies using various approaches with the goal to better understand the effect of various process parameters and thus further decrease the specific electrical consumption and increase the exergy efficiency. Accordingly, the exergy analysis method is well established and has been applied to a wide range of industrial processes: solar thermal collection (Kalogirou et al., 2016), chlor-alkali processes (Morris, 1991), oil platform (Barrera et al., 2015), oil and gas (Voldsund et al., 2013), hydro-char and bio-oil (Mahmood et al., 2016), mature field (Nguyen et al., 2014), economy (Schaeffer and Wirtshafter, 1992), machinery engine (Li et al., 2016), sociology (Ertesvåg and Mielnik, 2000), environmental science (Dewulf et al., 2008), and even human body (Mady et al., 2013), for example. This method can be used to quantify and localize a potential for process improvements, especially to the metallurgical processes involves lead smelter (Morris et al., 1983), chemical metallurgical process (Morris and Steward, 1984), steel industry (Kirschen et al., 2009; Kirschen et al., 2011) and energy recovery of electric arc furnaces (Nardin et al., 2014). In addition, many researchers have applied the exergy analysis method in the silicon industrial process. For instance, Takla et al. (2013) found an exergetic efficiency of 0.33 ± 0.02 for the process of silicon furnace operation, and the value increased to 0.41 ± 0.03 when waste heat (refers mainly to the exergy of the off-gas) was utilized. Børset et al. (2015) studied the overall exergy efficiency and the silicon yield exergy indicator in the silicon furnace; they also found an exergetic efficiency of 0.30 in their study. We have investigated the exergetic efficiency and thermal energy source of the off-gas system of a SAF observed through multiple periods of a real-world furnace (12.5 MV A) (Chen et al., 2016), and it exhibited an additional power capacity up to 2.7 MW, which amounted to 10% of the total energy supplied to the process.

The proximate composition of the raw materials and the diverse raw material play a very important role in the process of industrial production using SAF. Singh et al. (2007) optimized the combination of different raw materials to improve the performance of the furnace and minimize the power consumption using an artificial neural network. We have predicted the relationship between varying materials and the specific electrical consumption as well as the exergy efficiency used by an artificial neural network method (Chen et al., 2018). We have also evaluated the relationship between metal oxide contents and the power consumption of silicon production in the SAF used by the same method as above (Chen et al., 2017a). Additionally, Gajic et al. (2015) estimated the extent and effect of the fluctuations in the chemical composition of stainless steel at the tapping of an electric arc furnace using a state-of-the-art artificial neural network approach. Raw materials (refers mainly to carbon materials) were impact the two main parts of the process of silicon production, namely the energy input provided by combustion and the carbonaceous reductants involved in the carbothermic reduction of silicon dioxide. The main proximate composition of all carbon materials used in the silicon production is fixed carbon, volatile matters, ash and moisture. Among them, the fixed carbon is not only considered as a reductant that participates in the carbothermic reduction of silicon dioxide, but also a provider of energy input by combustion. The volatile matters are mainly considered for energy input by combustion, while the moisture of the raw materials will consume a large amount of energy by evaporation. Additionally, the ash of the raw materials could mainly be considered to affect the quality of metric silicon. However, there have been no research reports about the effect of the proximate composition of raw materials on the specific electrical consumption and exergy efficiency. Thus, to further decrease the specific electrical consumption and increase exergy efficiency, it is crucial to study and understand the influence that the proximate composition of raw materials has on the electrical consumption and exergy efficiency, with the ultimate goal of achieving the minimum operational cost for the process of silicon production.

The main objective of this study is to investigate the effect of proximate composition, including mainly fixed carbon, volatile matters and moisture, on the specific electrical consumption and exergy efficiency of the silicon production process by using a copious amount of actual production data from a silicon plant. A statistical approach was used for confirm the correlation of proximate composition with both the specific electrical consumption and exergy efficiency. In addition, to be certain, three different raw material combinations: Case 1, petcoke, charcoal and coal; Case 2, petcoke, charcoal and woodchips; Case 3, petcoke, charcoal, coal and woodchips were also investigated in this study. It is very important that this study can be used to low cost and high efficiency production according to support decisions when optimizing the properties of the carbonaceous reductants.

2. Overall design

Silicon is produced commercially by the carbothermic reduction of silicon dioxide (silica or quartz) with carbon materials in a SAF. The study mainly focuses on the energy flows, and repeats central aspects of the process of silicon production previously reported (Takla et al., 2013).

The charging ratio of silicon dioxide and carbon in the actual process of silicon production should be based on the following reaction equation:

$$SiO_2 + 2C = Si + 2CO \tag{1}$$

Then, the actual production process of silicon industrial can be written in a simplified form, as follows (Børset et al., 2015):

$$SiO_2 + (\eta+1)\,C = \eta\,Si + (1\text{-}\eta)\,SiO\,(g) + (\eta+1)\,CO\,(g) \tag{2}$$

Where, η is the silicon yield indicator, $0<\eta<1$, generally. The high temperature (1800 °C+) was maintained by the electrical energy input to a three-phase electrode. Silica (or quartz) was considered the main silicon source, which consisted of 100% SiO_2 (but the actual SiO_2>99%) in the process of charging ratio. Carbon referred mainly to the fixed carbon in the carbonaceous reductants.

2.1. Case choice

Silicon is largely produced by Nujiang Hongsheng Kam Silicon Limited, NHKSL in China, using a 12.5 MV A which stands for the power unit of the SAF and was supplied by the Sinosteel Corporation. An overview of the three cases included evaluating the relationship between the chemical composition, the specific electrical consumption and the exergy efficiency is given in Table 1.

2.2. Data collection

Silicon (Si>99%) is produced by the carbothermic reduction of silica (SiO_2>99% from Nujing, China) with carbonaceous reductants in a 12.5 MV A furnace. Petcoke (from Taiwan), charcoal (from Nujing, China), coal (from Xinjiang, China) and woodchips (from Burma) were used as the carbonaceous reductants in this process. The carbon electrode was used as the three-phase electrode for the