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Effect of raw materials on the production process of the silicon furnace

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ABSTRACT

The silicon industry is an energy-intensive industry with high energy operating costs and is currently facing new challenges to improve sustainability and become more competitive. Petroleum coke, coal, and charcoal are typically utilized as carbonaceous reductants for silicon production, and the mixture of different carbonaceous materials plays a very important role in the specific power consumption and the exergy efficiency of the process. Of these materials, in particular, charcoal preparation requires large amounts of wood, and continued and extensive deforestation contributes to ecological damage. Thus, it is urgent to study carbonaceous reductants that can be alternatives to charcoal or to find strategies that do not require the application of charcoal in the silicon production process. Exergy efficiency was used as an overall indicator to evaluate the effect of different carbon materials on the process of silicon production in this study. An exergetic efficiency of 0.39 was obtained for silicon produced with a mixture of woodchips and no charcoal. The overall exergy efficiency and the silicon yield exergy indicator results indicated that the addition of woodchips to a mixture of carbonaceous materials improved the performance of the silicon furnace, even if the fixed carbon contribution was lower. There was no change in exergetic efficiency (0.33) for the mixture of petroleum coke and coal as carbonaceous materials with or without charcoal and woodchips. Therefore, a mixture of petroleum coke and coal without charcoal can be used as carbonaceous reductants while maintaining the exergetic efficiency of the process of silicon production.

1. Introduction

Currently, more than 80% of conventional commercial solar cells are produced using silicon as the starting material, particularly muti-crystalline silicon (MÖller et al., 2005; Flamant et al., 2006; Saffar et al., 2014). However, silicon is produced by the reduction of silicon dioxide (silica or quartz) with carbonaceous reductants (petroleum coke, coal and charcoal) in a submerged furnace, and silicon production requires high temperatures provided by electric power. From both an economic and environmental perspective, the silicon industry, like the stainless steel industry, is an energy-intensive industry with high energy operating costs (Bisio et al., 2000).

Overall, manufacturing companies are facing various economic and environmental challenges, and this is especially true for energy-intensive industries. Exergy efficiency in various industries is extensively considered as a necessary component of sustainable development and effective management (Jovanovic et al., 2014; Shrouf et al., 2014). Currently, the exergy analysis method has been applied to a wide range of industrial processes (Klaasen et al., 2010; Balomenos et al., 2011; Mateos-Espejel et al., 2011; Voldsund et al., 2013; Nguyen et al., 2014; Barrera et al., 2015; Lin and Zheng, 2017), and body metabolism (Rodriguez-Illera et al., 2017), with many studies focused on the steel industry (Marcus et al., 2009, 2011; Gioacchino et al., 2014; Ferreira et al., 2015; Galán-Arboledas et al., 2017; Yasipourtehrani et al., 2017). This analysis has also been applied to the process of electric power generation, principally in electric arc furnaces (EAF). For example, Suetens et al., 2014 performed exergy analysis of two different processes of dust treatment in the production of EAF streams and suggested strategies to increase efficiency. Çmdali et al (Çmdali et al., 2003; Çmdali and Tunc, 2003) studied chemical exergy reactions and determined the exergy values of gases, liquids, and solids to investigate exergy

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efficiency behavior during the melting process of EAF applied to the steel production industry in Turkey. Morris et al. (1983) identified the main sources of exergy losses in the operation of a lead smelter. Balomenos et al. (2011) performed an analysis of energy and exergy to evaluate alternative and sustainable processes for the production of aluminum.

The smelting process of EAF is the most energy-intensive step in the production of silicon. Many studies have been performed focusing on the smelting process to understand the specific exergy dynamics of different parts of the process. The first exergy analysis of the silicon production process was presented in a study by Hjartarson (2009). Takla et al. (2013) extended preliminary reports on exergy (Takla et al., 2012) and energy analyses (Kamfjord et al., 2010; Kamfjord, 2012), and reported that for silicon production using a silicon furnace, only 30% of the total energy input was obtained and 70% of the total energy was lost as thermal energy to cooling water, hot off-gassing by radiation and convection from the furnace, and from cooling of the liquid silicon (Schei et al., 1998). Of these losses, there is a large potential for additional power production from the thermal energy from the released gas. The overall exergetic efficiency of a silicon furnace increased from 0.33 to 0.71 when additional power was recovered by the utilization of thermal exergy from an off-gas of 800 °C (Takla et al., 2013). The analysis revealed that lower exergy was applied in the product and nearly half of the total exergy input was lost in the furnace, with 20% lost as off-gas, the largest exergy output of the process other than the product. The recovery of this untapped energy resource hidden by thermal energy is a key to improve the overall resource utilization in the silicon production process.

Many studies have started to examine the smelting process to determine the influence of various process parameters to increase exergy efficiency and decrease specific power consumption. Børset et al. (2015) evaluated the silicon furnace for two operation periods with and without charcoal for a mixture of carbonaceous reductants using a new silicon yield exergy indicator, and found exergy efficiencies of 0.30, suggesting there is significant room for efficiency improvement. We investigated the correlation coefficients between the exergetic efficiency and the actual raw material consumption (including petroleum coke and coal) in silicon production via linear regression (Chen et al., 2016). We also studied the effect of metal oxide content on the specific power consumption by evaluation of the correlation coefficient (Chen et al., 2017). Petroleum coke, coal, and charcoal are usually used as carbonaceous reductants applied in the production process of silicon. Of these materials, charcoal is tree-derived, and it would be ideal to reduce use of materials that deplete forest resources. However, charcoal is still used in silicon production to ensure higher silicon yield. Petroleum coke and coal are also sometimes used in mixtures of carbonaceous materials. Thus, the use of different carbonaceous materials significantly affects the production process in a silicon furnace. However, there are few reports studying the effect of charcoal and woodchips on energy consumption and exergy efficiency for production. A new silicon yield exergy indicator was established to evaluate exergy efficiency, and the results from that analysis combined with the specific power consumption data reported in Ref (Børset et al., 2015) indicated an exergy value of 0.41 for the mixture without coal. Thus, our findings extend our understanding of the influence of different carbonaceous reductants mixtures based on actual data. In this study, we apply the same methodology as reported previously (Takla et al., 2013) to evaluate the energy and exergy for operation of a 12.5 MVA furnace with three different mixtures of carbon materials: charcoal and woodchips, woodchips without charcoal or in the absence of both charcoal and woodchips. This study is intended to serves as the basis for additional strategies to study the use of carbonaceous reductants as additives or alternatives to charcoal in silicon production to increase exergy efficiency and decrease specific power consumption.

2. Overall methodology designed

2.1. The process of production silicon

A description of the silicon production process is provided in Ref. (Børset et al., 2015), and the main chemical reaction for silicon production can be written in a simplified form as follows:

$$SiO_2 + (1+\eta)C = \eta Si + (1-\eta)SiO\ (g) + (1+\eta)CO(g) \quad (1)$$

where the η ($0<\eta<1$) is the silicon yield as the mole number of Si produced per mole of silicon dioxide (SiO_2). The reduction reaction occurred in a submerged arc furnace (SAF), and electric power is required to achieve and sustain the necessary high temperatures (above 1800 °C). In the left side of equation (1), the SiO_2 represents silicon sources from silica or quartz and C is from carbonaceous materials (petroleum coke, coal and charcoal/woodchips). This reaction includes the consumption of carbon electrodes as carbon materials. In the right side of equation (1), the monatomic Si is the major product and the silicon (MG-Si) purity can reach 99% or higher. The SiO and CO are by-products that are captured by the gas-cleaning system and after filtering, are burned with excess air from the furnace hood. In the actual production process, liquid silicon at a temperature of 1600 °C at tapping is poured into molds and then cooled to 25 °C, before being crushed into the desired particle sizes. The off-gas particles consist mainly of SiO_2 (also called "condensed silica fumes") since the mixtures of SiO and CO were burned before release.

2.1.1. Energy balance of the production silicon

The main energy inputs are electrical energy and energy generated from the oxidation-reaction of carbon materials during the carbothermic reduction process of production silicon. The energy balance of the process can be expressed as follows:

$$E_{Total} = \int_{Charging}^{Tapping} P_{Electric}dt + \Delta H_{Carbon} + \Delta H_{Oxidation} + \Delta H_{Volatiles}$$
$$= \Delta H_{Silicon} + \Delta H_{Slag} + E_{off-gas} + \int \Delta\dot{Q}_{Cooling}dt + \int \Delta\dot{Q}_{Radiation,\ other\ losses}dt \quad (2)$$

The electric power is supplied via three electrodes, and most plants use 11–13 kWh of electrical energy per kilogram of silicon produced. The electrical energy represents about 45% of the total