Chemical Engineering Science 129 (2015) 208–222

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Sustainable development of primary steelmaking under novel blast furnace operation and injection of different reducing agents

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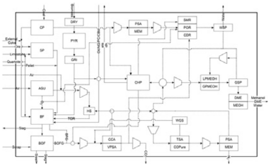
HIGHLIGHTS

- Steelmaking is integrated with a polygeneration system using the residual gases.
- The polygeneration plant is optimally designed for different steel plant states.
- Novel steelmaking scenarios and different reducing agents are compared.
- A torrefaction process for bio-reducers provides a potential sustainable solution.
- Enhanced flexibility and sustainability can be achieved by process integration.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form
12 January 2015
Accepted 29 January 2015
Available online 10 March 2015

Keywords:
Blast furnace
Reducing agents
Carbon dioxide emission
Sustainable development
Torrefaction

ABSTRACT

This paper presents a numerical study of economics and environmental impact of an integrated steelmaking plant, using surrogate, empirical and shortcut models based on mass and energy balance equations for the unit operations. In addition to the steelmaking processes, chemical processes such as pressure/temperature swing adsorption, membrane, chemical absorption technologies are included for gas treatment. A methanol plant integrated with a combined heat and power plant forms a polygeneration system that utilizes energy and gases of the site. The overall model has been applied using mathematical programming to find an optimal design and operation of the integrated plant for an economic objective under several development stages of the technology. New concepts studied are blast furnace operation with different degrees of top gas recycling and oxygen enrichment of the blast to full oxygen blast furnace. Coke in the process may be partially replaced with other carbon carriers. The system is optimized by maximizing the net present value, which includes investment costs for the new unit processes as well as costs of feed materials, CO_2 emission and sequestration, operation costs and credit for products produced. The effect of using different fuels such as oil, natural gas, pulverized coal, coke oven gas, charcoal and biomass is studied, particularly focusing on biomass torrefaction and the effect of integration on arising reductant in steelmaking to reduce emissions from the system. The effects of steel plant capacity on the optimal choice of carbon carriers are also studied. It is demonstrated that it is possible to decrease the specific CO_2 emissions of primary steelmaking from fossil fuels from 1.6 t of CO_2 to a level of 0.75–1.0 t and further by more than 50% through the integration of biofuels in considered scenarios.

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http://dx.doi.org/10.1016/j.ces.2015.01.069
0009-2509/

1. Introduction

Concerns about global warming and climate change have increased during the last decades and in many countries they have led to policies aimed at reducing emissions, particularly from the power and industrial sectors. Industry should improve its energy efficiency and gradually convert its processes towards considerably more sustainable operation. The steelmaking sector is one of the largest industrial carbon dioxide emitters worldwide, and recently many efforts have been made to reduce the emissions and many research projects with this target have been undertaken. Investigation on available energy efficiency technologies at Chinese steel industries, as the largest crude steel producers worldwide, has shown a potential for CO_2 emission reduction (Hasanbeigi et al., 2013). Analyzing steel demand, energy consumption and CO_2 emissions in China predicts a rise to a peak value of 772 Mt in steel production from 627 Mt in 2010 and then a gradual decrease to 527 Mt in 2050. With the deployment of energy conservation technologies, energy and CO_2 intensity of steelmaking are estimated to decrease during the time (Chen et al., 2014). Li and Zhu (2014) estimated the cost effectiveness of technologies for energy saving and CO_2 reduction based on fuel and emission price in Chinese steelmaking. Some of these technologies have already been implemented within the steel sector in developed countries, including the EU, due to economic benefits. Hence, finding the optimal state of operation becomes very important (Brunke and Blesl, 2014).

Porzio et al. (2014,2013) developed a management tool considering the stringent environmental policies as well as rising energy costs and the always-present drive for profit to help plant decision makers in their daily choices, giving advice on the best practices on how to operate a plant in order to reduce the energy consumption and the CO_2 emissions simultaneously keeping costs under control. Arens and Worrell (2014) investigated diffusion of energy efficient technologies in German steel industry and their impact on energy consumption. Other options investigated include the development of new routes of iron production or modifying present technology in combination with carbon dioxide capturing and utilization. In Europe, the ULCOS (Ultra Low Carbon dioxide – CO_2 – Steelmaking) project (Birat et al., 2009) has proposed and studied ways for steelmaking industry to suppress emissions, e.g., by combining a modified operation of the blast furnace with stripping and geological storage of carbon dioxide. Tanaka (2012) provided a comparison study of methods to assess CO_2 emission reduction and energy saving in the iron and steel industry in EU and in Japan within the COURSE50 (CO_2 Ultimate Reduction in Steelmaking process by innovative technology for cool Earth 50) program (Tonomura, 2013). Joint Research Center scientific and policy reports have also presented prospective scenarios for improved energy efficiency and reduced carbon dioxide emission in Europe's iron and steel industry (Moya and Pardo, 2013; Pardo and Moya, 2013), listing best available technologies (BATs) within this area and investigating the effect of applying the selected technologies on energy consumption and carbon dioxide emissions. The studies conclude that there is a large potential in saving energy from power plants on site integrated steelmaking, and by optimizing the operational conditions of the unit processes.

Another way to suppress harmful emissions from the steelmaking sector is by replacing coke with other carbon and hydrogen carriers, such as pulverized coal, oil, natural gas, biomass and hot reducing gases available in the plant (Johansson, 2013; Suopajärvi et al., 2013). Depending on the amount of auxiliary injectants, a conventional blast furnace consumes 350–400 kg coke per ton hot metal (kg/t_{hm}) as reducing agent, energy source and as supporting medium for the process, and coke is therefore the main source of carbon dioxide. The highest amount of pulverized coal injection reported is about 250 kg/t_{hm} while the amount of coke was is similar. The chemical properties of the coal have a significant impact and may cause problems for complete combustion within raceway, gas permeability in the shaft, dirtying of deadman zone and, as a consequence, irregular furnace operation and decrease in productivity (Babich et al., 2002; Luengen et al., 2012). Heavy oil injection up to 150 kg/t_{hm} have been reported, but the benefits of injection of oil as an effective reducing agent depend on price and availability. Natural gas has been used up to 155 kg/t_{hm} with a coke rate of 310 kg/t_{hm}. Higher natural gas injection rates lead to local supercooling of the hearth, an increment of slag viscosity, incompleteness combustion with char generation and worsening of melting products drainage. In summary, compared to all-coke operation, 200–250 kg/t_{hm} coke can be replaced by injected reductants, which may result in lower emissions. The main incentive to use other reducing agents has, however, been the price advantage and the potential it provides to increase productivity, but today the suppression of emission from the plant already plays an important role. The use of biomass and hot reducing gases are among the more interesting alternatives (Johansson, 2013; Suopajärvi et al., 2013).

Both of these reductants need pre-treatment which implies additional cost, but they have a potential to reduce the carbon dioxide emission from the blast furnace dramatically. Suopajärvi et al. (2014) estimated the mitigation costs for using three different biomass reducers for the same Finnish steel sector as considered in the present work, replacing coke by bio-reducer in the blast furnace. Biomass may be considered as an almost carbon-neutral carrier. Furthermore, by recycling carbon monoxide and hydrogen from the blast furnace top gases, it is possible to additionally reduce the total emissions. Literature reviews highlight advantages and challenges in the use of biomass-based reducing agents in steelmaking (Norgate et al., 2012; Suopajärvi et al., 2013). Moisture content, heating value and bulk density of biomass are noted as key factors for the use, and therefore charcoal has been the main focus area for researchers (Babich et al., 2010; de Castro et al., 2013). The results of the analyses show that the replacement ratio of using charcoal could be comparable to or better than that of pulverized coal, but the operational conditions may be site dependent. On the other hand, for biomass to be considered as a potential future reductant in the blast furnace, fuel availability, transportation and cost issues must be resolved (Helle et al., 2009). Therefore, there has been a need to investigate this integration by a holistic approach to find optimal operation and design for integrated steelmaking system (Grip et al., 2013; Karlsson, 2011). The present paper addresses this by presenting a process integration approach implemented for creation of constraints of the whole modelled system. Recently, among biomass pre-treatment technologies torrefaction has been studied as a way of producing a denser energy carrier, which has a significant influence on the supply chain costs and logistics (Uslu et al., 2008). The torrefaction process may be a feasible route to transform biomass into a solid fuel with properties approaching coal used in the blast furnace process (Chen et al., 2012; Helle et al., 2009).

Utilizing available residual gases in the steel sector such as coke oven gas, blast furnace gas and basic oxygen furnace gas to replace coke in the blast furnace has also been studied as short- or medium-term approaches to reduce carbon dioxide emissions. The injection of coke oven gas has been reported up to 130 kg/t_{hm} which makes the coke/COG replacement ratio up to 0.45 kg/m^3 compared to 0.85 kg/m^3 for natural gas (Babich et al., 2002). Using heated recycling gas after carbon dioxide stripping could result in a 25% increase in production rate and a 20% decrease in fuel rate. This concept requires higher degree of oxygen enrichment in blast furnace operation. An estimated coke consumption is around 200 kg/t_{hm} with pulverized coal injection of 180 kg/t_{hm} and hot reducing gases of 600 m^3n/t_{hm} (Babich et al., 2002; Suopajärvi et al., 2013).