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Current status and potential of biomass utilization in ferrous metallurgical industry

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ABSTRACT

This paper provides a critical review on the current status and potential of biomass utilization in ferrous metallurgical processes, i.e., the blast furnace (BF) – basic oxygen furnace (BOF) route, the direct reduction (DR) – electric arc furnace (EAF) route, the scrap – EAF route and the other routes. In the BF-BOF route, biomass can be used as a fuel for iron ore sintering, or as a raw material for the production of bio-coke, and utilized for blast furnace injection. In the DR-EAF route, direct reduction iron can be produced form iron ore and biomass pellet. In the scrap – EAF route, biomass can be utilized in EAF through a cogeneration system. In addition, biomass can be utilized in magnetic separation of refractory low-grade iron ore, in reuse of iron and steel slag, or as an adsorbent for pollutant control, etc. The challenges and outlook of biomass utilization in metallurgical industry are also discussed in this paper.

1. Introduction

Steel production has increased significantly in the past decade, and more than 1.65 billion tonnes of steel were manufactured worldwide in 2013, among which close to 70% was produced in Asia and Oceania with approx. 20% from the European Union and North American countries [1]. In some developing countries, such as countries in Latin America, Asia, Africa and the Indian sub-continent, steel production is still expected to grow [2].

Based on the raw materials utilized and technologies, there are two main routes for steel production [3,4], as shown in Fig. 1. The first route is the primary steel production route using iron ore as main raw material and including the blast furnace (BF) – basic oxygen furnace (BOF) processes [5], the smelting reduction (SR) – direct reduction direct reduction basic oxygen furnace (BOF) processes [6] or the direct reduction (DR) – electric arc furnace (EAF) processes [7]. The second route for steel production uses scrap as the main raw material involving the electric arc furnace (EAF) process [8]. At present, steel production in many countries, such as in China and Japan, mainly uses iron ore as raw materials via the BF – BOF route. Driven by the coupled challenges of the resources availability and the environmental concerns, the SR – BOF and DR – EAF routes have been evolved in recent years, as well as the Scrap – EAF route due to the constant accumulation of scrap.

Currently, the dominant energy sources in these routes are fossil fuels (e.g. coal, coke and natural gas), contributing to a great amount of CO_2 emission. In fact, iron and steel industry is one of the highest energy and emission intensive sectors [9–11]. For instance, iron and steel sector accounts for about 5% of the total CO_2 emissions. In particular, steel production via the BF-BOF route consumes 13–14 GJ/MT tonne of steel produced, accompanied with 1.9 t of CO_2 emitted, which has rendered enormous challenges for the iron and steel industry and increased the pressure in seeking clean and renewable energy sources for the industry [12].

Biomass is clean and renewable energy which can partially substitute fossil energy directly, or can be converted into gas, liquid, solid fuels and other chemicals or materials [13,14]. Thus, biomass research has received growing interest due to the increased concerns over fossil resources depletion and enormous environmental issues associated with the use of fossil fuels [15]. In the 21st century, biomass has found more applications in the iron and steel metallurgical processes, mainly as fuels and reducing agents for various metallurgical processes, as overviewed below.

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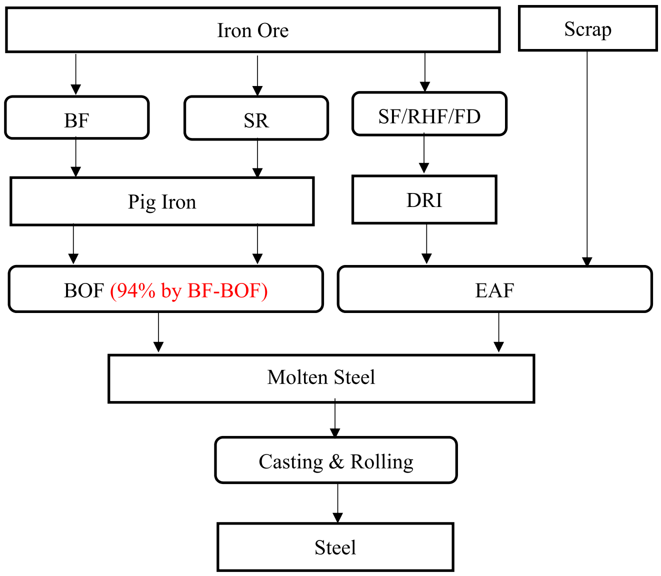

Fig. 1. Overview of iron and steel production processes.

2. Biomass properties and conversion

2.1. Biomass properties

Biomass comprises mainly carbon(C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur(S) as the five organic elements, as well as inorganic elements such as Al, Si, K, Ca, Na, etc. in its ash. The composition of biomass varies depending on the biomass varieties. The ultimate and proximate analyses of different types of biomass are shown in Table 1. Overall, biomass has average C, H, O, N and S contents of 49.3%, 6.0%, 40.5%, 0.8% and 0.2%, respectively, and average volatile matter (VM), fixed carbon (FC) and ash contents (A) of 18.2%, 77.0% and 4.8%, respectively. Irrespective of ultimate analysis or proximate analysis, there are tremendous differences between biomass and the fossil fuels commonly used in iron and steelmaking processes (e.g., coal, coke and heavy oil), as summarized in Table 2. The contents of C, H, and O (on dry basis) can be used for estimating the heating value of fuels via some empirical formula such as the Dulong formula (HHV (MJ/kg) =0.3383 C +1.422 (H-O/8)). A high oxygen content in biomass along with a high water content result in a much lower energy content (usually 14–21 MJ/kg) for biomass compared with that of a fossil fuel (~30 MJ/kg for coal and ~40 MJ/kg for heavy oil) containing generally an oxygen content of less than 5.5 wt% [14]. However, the sulfur content in the biomass (generally $\ll$1 wt%) is lower than that of fossil fuels (up to 3–6 wt%) [16,17], rendering the environmental dividends by replacing fossil energy with biomass and bioenergy in ferrous metallurgical industry. Proximate composition is very important as it affects the combustion and reduction phenomena of the fuels. Compared with fossil fuels, low ash and high volatility characteristics for biomass offer many advantages in utilizing biomass as a fuel or reducing agent in the ferrous metallurgical processes [18], while biomass's low fixed carbon content and low heating value are disadvantageous to be as a reducing agent and fuel for the traditional ironmaking processes, as will be discussed below.

2.2. Biomass conversion

Biomass can be converted into various energy and solid, liquid and gaseous fuel products via three main processes, i.e., physical conversion, chemical or thermochemical conversion, and biochemical conversion. Thermochemical biomass conversion involves direct combustion, gasification, liquefaction and pyrolysis [22].

Physical conversion involves process such as palletization to transform the loose biomass feedstock into pellets of a certain shape and density in order to reduce the transport costs, increase the combustion intensity and thermal efficiency. Chemical conversion includes transesterification (for bio-diesel production from fat, lipids or oils) and thermochemical conversion of lignocellulosic biomass [23]. The latter produces charcoal, tar (bio-oils) and combustible gases and other high-grade energy products [24]. Biochemical conversion proceeds via the activities of microorganisms mainly in hydrolysis, fermentation, enzymatic synthesis and photosynthesis, producing ethanol, methane gas, bio-diesel, hydrogen and other products [22].

Solid fuel produced by physical conversion (e.g., wood pellets) can be injected into the BF as a fuel or reducing agent [25]. The synthesis gas with a high content of reducing gases (H_2 and CO) as well as charcoal and bio-oil (including tar), generated from thermochemical and biochemical conversions, can be directly applied as a fuel or a reducing agent in the BF [4,26,27]. In addition, some new metallurgical technologies using biomass is under development, such as the combined generation technology for co-production of iron and high-heating value gas (CO or H_2)[28].

2.3. Biomass pre-treatment

Biomass pre-treatment aims to make the biomass polymers more accessible for subsequent processes, e.g. pyrolysis, hydrolysis and densification processes.

Torrefaction is a pre-treatment process that removes moisture and some volatile, and improves biomass energy density and grindability. Biomass torrefaction is commonly operated at a low temperature ranging from 250 to 400 °C and medium residence time (15–30 min), producing a solid residue (i.e., torrefied biomass) with a high mass yield up to 87.5%. When the temperature of torrefaction is very high, over 400 °C, the LHV of the produced torrefied wood approaches to 26–27 MJ/kg [29]. Moreover, torrefaction of biomass can also improve the quality of syngas in biomass gasification: torrefied woods was found to produce approximately the same quantities of CO_2, 7% more H_2 and 20% more CO than the parent wood under the same gasification conditions [30]. Syngas with high H_2 and CO content is good for reducing iron oxide and can be used in the DR processes.

Although steam explosion is a commonly used pre-treatment process for cellulosic ethanol production (treating biomass with hot steam (180–240 °C) under pressure (1–3.5 MPa) followed by explosive decompression), studies have shown that steam explosion of a biomass feedstock can improve the rate, the heat value and charcoal yield during pyrolysis. Han et al. [31] reported that pellets of steam explosion pre-treated straw achieved higher metallization than charcoal based pellets for DRI production.

3. Biomass applications in BF – BOF processes

BF – BOF processes is the major route for iron and steel making, produce 64.4% of crude steel, but are associated with high energy consumption and emissions from the sintering, coking and BF processes [1]. In order to reduce BF coke rate and CO_2 emissions, significant amount of effort has been in exploring biomass applications in the BF – BOF processes, as detailed below.

3.1. Injection of charcoal into blast furnaces

BF is one of the major emission sources in steel production, and the use of biomass in this process could reduce 22–32% of carbon dioxide emissions [32]. Biomass can be injected into BF in three forms, i.e., biomass char, bio-oils and biomass-derived synthesis gas (syngas) [25,33,34]. For the economy, operability and other reasons, the previous studies are mainly on injection of charcoal into BF [19,32,35–37]. Charcoal is not suitable for replacing lump coke directly in a blast furnace due to its insufficient strength compared with coke