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Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO_2) Steelmaking (ULCOS) program

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ABSTRACT

The iron and steel industry is the largest energy consuming manufacturing sector, consuming 5% of the world's total energy consumption and producing 6% of the total world anthropogenic CO_2 emission. Under the European Ultra Low CO_2 Steelmaking (ULCOS) program, several breakthrough technologies for the drastic reduction of CO_2 emissions from iron and steelmaking industry have been investigated, including (1) blast furnace with top-gas recycling (TGR-BF),(2) a new smelting reduction process (HIsarna), (3) advanced direct reduction (ULCORED) and (4) electrolysis of iron ore (ULCOWIN and ULCOLYSIS). Besides, hydrogen-based steel making and the use of biomass as reducing agent have been evaluated as supporting technology to decrease CO_2 emissions. The aim of the present article is to analyze the technological developments in iron and steel industry and the progress of present experimental works developed inside the ULCOS I and II projects by collating updated information from a wide range of sources. In addition, the breakthrough technologies expected to develop or are currently being demonstrated at pilot/industrial scale for significant reduction of CO_2 emissions in Europe have been identified in this paper. Economic and environmental performance of the ULCOS cutting edge technologies shows that the implementation of CCS technology in coal-based integrated steel plants might reduce 80% of CO_2 emissions. However, hydrogen and biomass-based steelmaking also offers very attractive perspectives, while raising lots of major challenges. Finally, comparative assessment of the ULCOS program with others CO_2 breakthrough programs around the world has also been done.

Contents

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1. Introduction

Global warming is one of the crucial challenges of humanity. In order to combat climate change, several ambitious objectives have been set in Europe such as 20–20–20 target and the 2050 Energy Roadmap [1]. The 20–20–20 target aims to reduce 20% CO_2 emissions compared to 1990 levels, produce 20% renewable energy and reduce 20% primary energy consumption by 2020. The 2050 Energy Roadmap illustrates a European pathway for the reduction of 80-95% greenhouse gas emissions (GHG) by 2050 compared to the 1990 levels [2,3].

In 2008, EU Emission Trading System (EU ETS) launched a series of targets through EU Strategic Energy Technology Plan (SET-Plan) for the development of clean, efficient and low-emission technology in energy-intensive industries [4,5]. Iron and steel production is one of the biggest energy-intensive and CO_2 emission industries worldwide. Due to the dominating iron and steelmaking processes are still mainly coal-based and highly dependent on fossil fuels such as oil, diesel, and substantial amounts of fossil CO_2 emissions are released [6]. Globally, iron and steel production accounts for about 6% of anthropogenic CO_2 emissions each year [7]. In the EU, the sector is accountable for 4.7% of the total CO_2 emission (182 million tonnes of CO_2) and approximately 27% of CO_2 emission from the global manufacturing sector [8,9]. One ton of steel manufacturing emits about 1.8 t of CO_2 [10] and collective energy demand of steel production is 21.0–35.4 GJ/t steel [11].

There are two main methods for producing steel: (1) extracting iron from iron ore through a reduction process, (2) recycling steel scrap through a melting process. Steel production from crude iron ore is preceded by iron production. The main refining process for iron production is through the blast furnace and basic oxygen furnace method (BF+BOF), accounting for 95% of global iron production and about 70% of global steel production [12]. On the other hand, about 5% of global iron is produced via direct reduced iron (DRI) method. Electric arc furnace (EAF) uses Steel scrap and steel recycling, where the steel or solid iron from a direct reduced iron process is melted by electric power [13]. About 30% of global steel is produced via this method [14]. In the ironmaking process, the blast furnace process extracts iron from crude iron ore (Fe_2O_3) by heating the ore and melting the metal fractions to liquid pig iron. An efficient reduction reaction is required, in order to extract the O_2 from the iron ore. This is achieved by adding a reducing agent, usually coke, to the blast furnace. The carbon reacts with the iron oxide and produces carbon monoxide, which again reduces the iron oxides to pure iron during a combustion process. Finally, iron oxides are chemically converted into molten iron (Fe), which produces massive amounts of CO_2 and carbon monoxide (CO) as a by-product gas or blast furnace gas (BFG). The basic chemistry of the iron-making processes is listed as the following equations [15]:

$$C + \tfrac{1}{2}O_2 \rightarrow CO$$

$$C + O_2 \rightarrow CO_2$$

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

$$Fe + O_2 \rightarrow 2FeO$$

$$Si + O_2 \rightarrow SiO_2$$

$$2Mn + O_2 \rightarrow 2MnO$$

$$2P + 5FeO \rightarrow P_2O_5 + 5Fe$$

Thus, large amounts of CO_2 are produced by the reduction reaction in the blast furnace and the combustion reaction of carbonaceous materials (coke breeze, etc.) and carbon-containing gases, such as blast furnace gas (B gas) and coke oven gas (C gas) in the sintering machine, coke ovens, and hot stoves. Therefore, controlling and reducing CO_2 emissions from this industry is now a pressing issue [16]. Over the last decade, a number of researches and development initiatives around the world under the 'CO_2 breakthrough Programs' (ULCOS[1], AISI[2], POSCO[3], COURSE50[4], etc.) have been investigated [17] for carbon-free green and sustainable iron and steel production. The target is to develop CO_2 breakthrough technologies in combination with top gas recycling for the blast furnace (TGR-BF), direct reduction (DR) with electric arc furnace (EAF), iron ore electrolysis also called electrowinning (EW), carbon capture and sequestration (CCS) by using fossil fuels, biomass, hydrogen and electricity as innovative reducing agents for the reduction process [4,18]. Among all of this research programs, the Ultra-low CO_2 Steelmaking (ULCOS) is the most extensive research program with big budget. It is a consortium of 48 European companies and organizations from 15 European countries and is supported by European Commission. ULCOS consists of all major European Union steel plants, engineering partners, research institutes and universities [19]. It is divided into two phases: ULCOS I in 2004 and ULCOS II in 2010. It is proactively looking for solutions to the threat of global warming. The main aim of this massive project is to reduce CO_2 emission by at least 50%, i.e., to reduce CO_2 emission from 2 t CO_2 per ton steel to 1 t CO_2 per ton steel production [20]. In addition, for large scale industrial production it will develop potential and feasible ultra-low CO_2 steel production technologies that must be sustainable, i.e. environmentally-friendly, economically viable and socially acceptable [21,22].

From the beginning of the second phase of the ULCOS proposed CO_2 emission projections for the year of 2010–2050. According to the ULCOS research, prediction, worldwide average CO_2 emissions are 1.8 t for every ton of steel produced in the year of 2010 [16]. In 2050, a trend scenario assumes that CO_2 emissions will be cut by only 15% (1.1 t_{CO2}/$crude_{steel}$), mainly dependent on the extensive deployment of advanced technologies like Best Available Technologies (BATs) [23]. On the other hand, low carbon (LC) scenario assumes that global emissions can be dropped around 0.2 t CO_2/t crude steel in such a way, if CO_2 breakthrough technologies are available and policies have been designed to be applied (Fig. 1) [24–27].

There are a few numbers of studies have been done on worldwide CO_2 breakthrough programs focusing on their current research status and environmental assessment. To the best of our knowledge, there is no study focusing on comprehensive study on ULCOS and comparative assessment of the ULCOS program with

[1] ULCOS = Ultra-Low CO_2 Steelmaking (EU).
[2] AISI = American Iron and Steel Institute with technology roadmap programme.
[3] POSCO = CO_2 Breakthrough Framework (Korea).
[4] COURSE50 = CO_2 Ultimate Reduction in Steelmaking process by innovative technology for cool Earth 2050.