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Potential of Nuclear and HyREX Technologies to Replace Blast Furnaces in Steel Production

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1. Introduction

Achieving global Net Zero Carbon by 2050 necessitates decarbonization across all industrial sectors. The steel industry alone accounted for approximately 2.4 Gt of CO_2 emissions globally in 2020, according to the International Energy Agency (IEA) [1]. To meet the target of net-zero emissions by 2050, the steel industry's carbon emissions must be reduced to 200 million tons. In this study, the potential reduction in carbon emissions is investigated by substituting the blast furnace process—the largest contributor to carbon emissions in steel production process—with High-Temperature Gas-cooled Reactor (HTGR) and Hydrogen Reduction by Exothermic Reaction (HyREX).

2. Steel Production Process

The steel production process can be divided into four main stages: (1) raw material preparation, (2) ironmaking process (Blast Furnace), (3) steelmaking process (Basic Oxygen Furnace), and (4) post-processing. These processes consume a significant amount of coke, which plays a crucial role in the reduction of iron ore during the blast furnace stage.

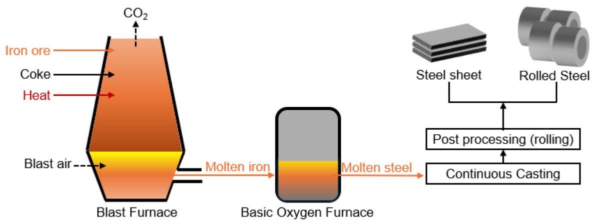

Fig. 1 Overview of the steel production process

$$(1)\ C + \frac{1}{2}O_2 \rightarrow CO$$
$$(2)\ CO + \frac{1}{2}O_2 \rightarrow CO_2$$

Most iron ores, including hematite (Fe_2O_3), magnetite (Fe_3O_4), and goethite (FeOOH), contain approximately 65% iron (Fe) on average. After mining, iron ore is typically found in powdered form; however, introducing it directly into a blast furnace can hinder gas flow and reduce furnace efficiency. To improve this, the ore undergoes a sintering process before being fed into the blast furnace. During sintering, small iron ore particles are fused into larger lumps (sinter), enhancing both particle size and reactivity [2]. The primary reaction in the sintering process is the combustion of coke, which generates the necessary heat for sintering. The raw material preparation stage, encompassing coke production and sintering, accounts for approximately 25% of the total carbon emissions in the steel production process [3].

Sintered iron ore and coke are fed into a blast furnace, where hot air is injected from the bottom to combust the coke. The combustion of coke generates carbon dioxide, which then reacts with additional coke at high temperatures to form carbon monoxide. The carbon monoxide generated during this process reduces the iron ore to produce pure iron. The ironmaking process alone accounts for over 50% of the carbon emissions in steel production. Therefore, it is crucial to reduce carbon emissions at this stage to alleviate the overall environmental impact of the steel industry.

$$(3)\ C + O_2 \rightarrow CO_2$$
$$(4)\ CO_2 + C \rightarrow CO$$

Following the blast furnace process, the molten iron (pig iron) collects at the bottom of the furnace and is transferred to the basic oxygen furnace for the steelmaking process. This stage produces pure steel, which is then transformed into steel products through continuous casting and rolling. The steelmaking process and subsequent post-processing contribute approximately 20% of the total carbon emissions [3].

In the steel production process, the blast furnace is the primary source of carbon emissions due to the reduction of iron ore using coke. To mitigate this, there is increasing interest in using hydrogen (H_2) produced with high-temperature heat from HTGR (High-Temperature Gas-Cooled Reactor) for iron ore reduction. In HTGR, helium gas (He) heated to around 900°C in the reactor transfers heat via a heat exchanger to the hydrogen production system, where hydrogen is produced through either the Sulfur-Iodine Cycle (S-I Cycle) or Solid Oxide Electrolysis Cell (SOEC) process.

3. Blast Furnace Replacement

In this section, the potential reduction in carbon emissions achieved by replacing the blast furnace process—currently responsible for the majority of carbon emissions in steel production—with HyREX and HTGR is analyzed. The energy consumption and carbon emissions associated with the blast furnace process to produce 1ton of pig iron are calculated.

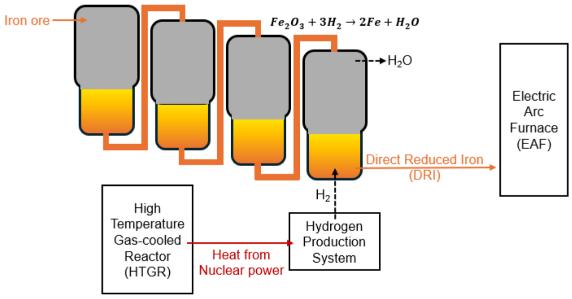

Fig. 2 Overview of the ironmaking process with High-Temperature Gas-cooled Reactors (HTGR) and Hydrogen Reduction (HyREX)

The analysis assumes that the sintered ore, pellets, and other inputs fed into the blast furnace consist of hematite (Fe_2O_3) and magnetite (Fe_3O_4) in a 7:3 ratio, with no other impurities considered. Hematite has an iron content of 69.9%, while magnetite has iron content of 72.4%. To produce 1ton of steel, approximately 1.41 tons of this iron ore mixture are required, consisting of 0.989 tons of hematite and 0.424 tons of magnetite. Given that the molar masses of hematite and magnetite are 159.7g/mol and 231.5g/mol, respectively, this corresponds to 6,196 mol of hematite and 1,831 mol of magnetite.

$$(5)\ 3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$
$$(6)\ Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$
$$(7)\ FeO + CO \rightarrow Fe + CO_2$$

The reduction of iron ore involves several sequential steps: it is converted from hematite to magnetite, then from magnetite to FeO, and finally from FeO to pure iron (Fe). The conditions inside the blast furnace, where this reduction occurs, are around 1,500 degrees Celsius with pressures between 2 and 4 atmospheres, differing from standard conditions. However, when analyzing the chemical reactions within a blast furnace, the difference of enthalpy of formation (ΔH_f) values under standard conditions and actual blast furnace conditions show no significant difference [4]. Therefore, the values of standard enthalpy of formation were used to calculate the heat required for the reduction of iron ore. The values for the reduction of hematite and magnetite, as shown in Equations (5), (6), and (7), are -47.2 kJ/mol, +19.4 kJ/mol, and -11.0 kJ/mol, respectively. Initially, 6,196 mol of hematite reacts with carbon monoxide in an endothermic reaction absorbing 292 MJ of heat to produce 4,130 mol of magnetite. Subsequently, 5,962 mol of magnetite releases 116 MJ of heat, resulting in the production of 17,886 mol of FeO. The FeO then absorbs 197 MJ of heat to produce approximately 1 ton of pig iron. Consequently, the energy required to produce 1 ton of pig iron is 373 MJ, with a total of 25,913 mol of CO_2 produced, resulting in 1.14 tons of CO_2 emissions.

Table. 1 Standard enthalpy of formation of substances in the blast furnace

Substance	Standard enthalpy of formation ($\Delta H_f°$) [kJ/mol]
Fe_2O_3	-824.2
Fe_3O_4	-1118.4
FeO	-272
Fe	0
CO	-110.5
CO_2	-393.5

The annual pig iron production by blast furnaces in Korea is approximately 47 million tons [5]. Based on the carbon emissions calculated for producing 1 ton of pig iron, a complete transition from blast furnaces to HTGR and HyREX could potentially reduce CO_2 emissions by 53.6 million tons per year. It is important to note that the estimates for CO_2 emissions do not account for the presence of impurities, actual temperature and pressure conditions, or heat losses during the process. Consequently, while the actual CO_2 emissions and energy consumption may differ, a similar reduction in carbon emissions is anticipated with the replacement of the blast furnace process.

4. Summary and Conclusions

Converting traditional blast furnace process with High-Temperature Gas-cooled Reactors (HTGR) and Hydrogen Reduction (HyREX) presents a substantial opportunity to reduce carbon emissions in the steel industry. Given that the blast furnace process accounts for the majority of carbon emissions in steel production, the adoption of these technologies is expected to significantly reduce CO_2 emissions by 53.6 million tons per year in South Korea alone (7.9% of South Korea's annual CO_{2eq} emissions [6]). In conclusion, replacing the blast furnace process with HTGR and HyREX technologies provides a promising pathway to dramatically reduce the carbon footprint of the steel industry and aligns with global efforts to achieve carbon neutrality by 2050.

Acknowledgements

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