A Study of Heat and Material Balances in Direct Reduction Plant with Various Conditions

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ABSTRACT

Global steel companies are actively combating climate change by reducing carbon emissions. Traditional steel production, using the Blast Furnace(BF) – Basic Oxygen Furnace(BOF) process, heavily depends on coal and emits substantial CO_2. To mitigate this, companies are transitioning to the more eco-friendly DRP(Direct Reduction Plant) – EAF(Electric Arc Furnace) process, which lowers CO_2 emissions. This study quantitatively evaluates the impact of increased hydrogen consumption on the Carbon Footprint of Product (CFP) through an analysis of direct reduction process heat and mass balances. The study prioritizes a comprehensive material balance based on mass conservation principles. The heat balance is calculated using differences in enthalpy through state energy properties, avoiding heat consumption. Validation using operational data from Hyundai Steel Dangjin works' blast furnaces shows close alignment between calculated results and actual data, with less than 1% error. This methodology facilitates a detailed analysis of the direct reduction process, offering insights into its feasibility and efficiency. Analysis of the operational impact by increasing the hydrogen ratio demonstrates reduced CO_2 emissions and increased heat requirements due to the endothermic nature of hydrogen reduction, in contrast to the exothermic CO reduction. Possible solutions include raising reducing gas temperature or enhancing flow rate. The study effectively utilizes designed heat and mass balances to assess material quantities and thermal balance under different operational conditions. It lays the foundation for the initial direct reduction process design, aiding in deriving and optimizing operational parameters. Additionally, it provides valuable insights into the challenges of increased hydrogen, contributing to the production of greener steel by addressing these issues.

INTRODUCTION

In response to the global imperative for achieving carbon neutrality by 2050, the steel industry is undergoing a transformative shift from conventional blast furnace and basic oxygen furnace processes to advanced technologies such as DRP coupled with electric arc or Submerged Arc Furnaces(SAF). While the utilization of natural gas-based DRP is already a commercial reality, the exclusive deployment of hydrogen for the entire reducing gas composition necessitates significant modifications to existing facilities. The complexity arises from the fact that hydrogen reduction is an inherently endothermic reaction, demanding intricate design considerations for heat and mass balances within the DRP and the concurrent development of process optimization strategies, with a keen focus on hydrogen consumption.

LITERATURE REVIEW

Review of Literature on Heat and Mass Balances in Blast Furnaces

Historical investigations into the heat and mass balances of blast furnaces trace back to the early 1900s, utilizing diverse methodologies for comprehensive evaluations. A pivotal contribution to this field is the Rist diagram, a graphical representation of blast furnace operations introduced by A. Rist and N. Meysson in the 1960s. This innovative tool aimed at promoting stable operation and enhancing operational performance through mathematical analysis. Concurrently, studies led by Takeo Yatsuzuka in the 1960s delved into carbon consumption based on thermodynamics, marking a departure from traditional experience-based blast furnace operation methods. These studies provided essential insights into evaluating the heat balance of blast furnaces and deriving optimal reductant rates.

Literature Gaps in Heat and Mass Balances in Direct Reduction Plants (DRP)

In stark contrast, a noteworthy gap exists in the literature concerning the heat and mass balances specific to DRP, particularly in the context of hydrogen consumption. Recent contributions have emerged, offering glimpses into the Optimization of the Iron Ore Direct Reduction Process. Notable among these is the work by Rami Béchara and colleagues in 2018, which delves into multiscale process modeling, encompassing single pellet, shaft furnace, and plant models. This research contributes significantly to understanding the intricate dynamics of the DR process, spanning from microscopic grains to the macroscopic scale of the shaft furnace, employing integrated plant simulation tools like Aspen Plus.

Another critical study, conducted by C. Y. Xu and team in 2019, addresses the emerging demand for research on direct reduction-based steelmaking to achieve decarbonization. The study investigates the Effect of H_2/CO Ratio on Gas Consumption and Energy Utilization Rate in Gas-Based DR Processes. By calculating energy and mass balances for typical shaft processes such as MIDREX and HYLⅢ, the researchers shed light on evaluating the heat and mass balance of DRP and identifying trends in balance variations.

OBJECTIVES OF THE CURRENT RESEARCH

Given the imminent transition to hydrogen-rich reducing gases in DRPs, this research seeks to bridge the existing gap in detailed reviews on balances based on hydrogen consumption. The primary objectives are threefold:

1. Development of a Static Tool for Assessing Heat and Mass Balance in DRP:

   The creation of a tool for rapid static assessments of heat and mass balances in DRP.

2. Case Studies on Balance with Hydrogen Increment:

   Conducting comprehensive case studies to understand the dynamic impact of hydrogen increment on the balance.

3. Optimization of DR Process Conditions:

   Identification of methodologies to optimize DR process conditions, particularly focusing on hydrogen consumption.

STATIC MASS AND HEAT BALANCE IN DRP: AN IN-DEPTH EXPLORATION

The foundational principles involve the calculation of static mass balances using the law of mass conservation for various phases, including solids like pellets and Direct Reduced Iron (DRI), and gases. Simultaneously, the heat balance employs the enthalpy difference between reactants and products. In this study, heat and material balances of DRP is designed using Microsoft Excel, with reference to MIDREX process as depicted in Figure 1.

Mass Balance

- Rigorous calculations of mass balance among major raw materials and products based on the law of mass conservation.
- Key results encompass the determination of the amount of raw materials required, the quantity of reducing gas considering efficiency and composition, and the composition and amount of gas after the reaction (top & cooling gas).

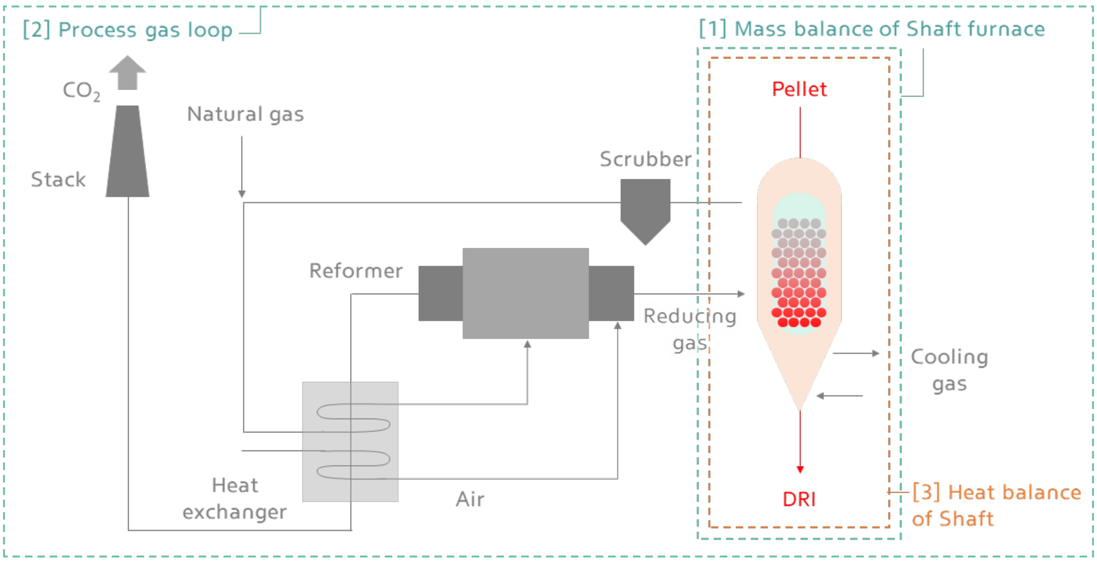

FIG 1. The flowsheet and design scope of DRP heat and material balance.

Heat Balance

- The design of an energy balance using the enthalpy difference between reactants and products.
- Exclusion of considerations related to internal reactions and intermediate products.
- The utility of this approach lies in the comprehensive assessment of heat balance and the calculation of required energy.

APPLICATION OF BALANCE PRINCIPLES TO BLAST FURNACE AND DRP

The practical application of these principles to blast furnaces involves detailed burden calculations, setting blowing conditions, and determining the composition of top gas and slag. This meticulous process ensures stable operation by inputting target production and raw material composition, calculating the burden, setting the efficiency of CO, hydrogen, and oxygen enrichment, and determining the composition and amount of top gas and slag.

Extending this sophisticated methodology to DRP, a robust tool is developed, incorporating shaft mass balance, process gas loop, and shaft heat balance.

Shaft Mass Balance Outputs

1. The quantity of pellet usage based on target DRI production and metallization.
2. Blowing conditions of reducing gas, calculated with the composition of reducing gas and the utilization of hydrogen and CO.
3. Composition and amount of outgoing cooling gas, determined by target DRI carbon content.

Process Gas Loop Calculation

- The quantity of pellet usage based on target DRI production and metallization.
- Blowing conditions of reducing gas, calculated with the composition of reducing gas and the utilization of hydrogen and CO.
- The comprehensive gas mass balance for the DR process is completed.

Shaft Heat Balance:

- Analogous to the approach in a blast furnace, the heat balance of the shaft furnace is calculated using enthalpy values for inputs, outputs, and heat loss.
- The difference between output and input enthalpy facilitates the diagnosis of the heat balance of the direct reduction process.

CASE STUDY – ANALYZING THE IMPACT OF HYDROGEN INCREMENT

Based on the mass balance analysis, as shown in Figure 2, a decreasing trend in the CFP compared to the current commercial MIDREX plant (H_2/CO 64%) was observed with the increase in the hydrogen ratio in the reducing gas. The reason for a 20% CFP occurrence in the case of 100%

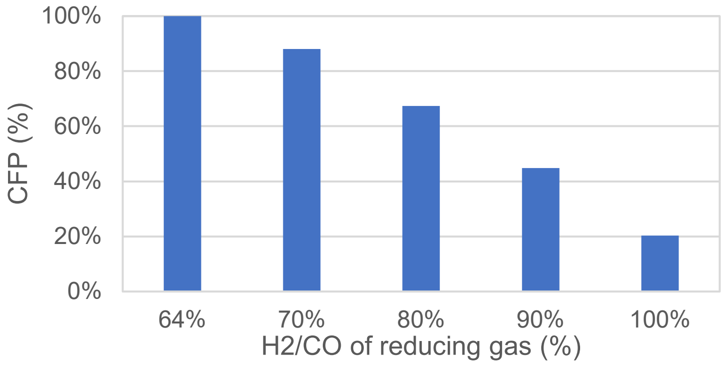

FIG 2. The level of CFP from the DRP varies depending on the H2/CO ratio in the reducing gas.

hydrogen is due to fixing the quantities of gases other than hydrogen and CO (CO_2, H_2O, N_2, CH_4) during the mass balance calculation, and some of the cooling gas being introduced into the reducing gas stream. The amount of CO_2 generated is estimated through the flow of CO2 in the flue gas discharged through the stack.

A meticulous analysis of the heat balance under varying hydrogen ratios reveals a discernible trend – as hydrogen content increases, the required heat also escalates. This phenomenon can be attributed to the endothermic nature of hydrogen reduction. The potential risks associated with insufficient heat in the shaft are multifold, including a decrease in gas utilization, hindrance to reactions such as carburization and internal reforming, and an uptick in operating expenses if more heat is introduced.

Methods for Heat Compensation

Two pragmatic methods for compensating heat in the DRP are proposed:

Heating:

- Preheating pellets before charging.
- Elevating the reduction gas temperature.
- Challenges associated with this approach include issues such as sticking, limitations in temperature elevation using the reformer, and inherent difficulties in increasing the temperature of hydrogen.

Increasing Gas Volume:

- Compensating heat by augmenting the gas volume.
- The challenges encountered revolve around the substantial amount of gas needed for heat compensation, particularly when the reducing gas consists predominantly of hydrogen.

ANTICIPATED ISSUES AND FUTURE CHALLENGES

In summation, the global steel industry's pivotal shift towards hydrogen-rich reducing gases in DRP to achieve carbon neutrality is not merely an ambition but an imminent reality. While the literature on this subject is still in its nascent stage, this study addresses the existing gaps and presents a comprehensive synthesis of the current state of knowledge. The proposed tool for assessing heat and mass balances, coupled with detailed case studies and innovative heat compensation methods, provides a robust foundation for future research endeavors and practical applications. The challenges and anticipated issues underscore the necessity of continuous investigations, not only in understanding hydrogen reduction characteristics but also in the operational implementation of these advancements.

At Hyundai Steel, our commitment to DRP technologies encompasses the diversification of raw materials, enhancement of reduction efficiency, acceleration of carburization, optimization of balance, and stabilization of product quality. By actively developing technologies in these areas, we aim to contribute significantly to the ongoing evolution of DR processes in the steel industry. The holistic understanding and proactive solutions presented in this study lay the groundwork for a sustainable and efficient future in direct reduction processes, aligning with the global imperative of carbon neutrality in steel production.

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