



Performance Evaluation of the MIDREX Gas Processing System for Reducing Energy Consumption and Carbon Dioxide Emissions in the Steel Industry

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ABSTRACT

The steel industry is one of the largest consumers of energy and one of the major sources of greenhouse gas emissions worldwide. Among ironmaking technologies, the natural gas-based direct reduction process, particularly the MIDREX technology, is recognized as one of the most efficient and low-carbon methods for producing direct reduced iron (DRI). Despite its advantages, the performance of the gas processing system, especially the reformer, recuperator, and recycle gas circuit, has a significant impact on energy consumption, process efficiency, and CO₂ emissions. Therefore, evaluating and optimizing this system is essential for improving operational performance and reducing environmental impacts. This study aims to evaluate the performance of the gas processing system in an industrial MIDREX plant with an annual production capacity of 825,000 tons of DRI. Operational data, including process gas composition, reformer efficiency, recuperator performance, recycle gas quality, and operating conditions, were collected and analyzed. Subsequently, a comprehensive process model was developed using Aspen HYSYS to simulate plant operation and assess various optimization scenarios. The results indicate that reduced reformer efficiency, heat losses in the recuperator, and increased concentrations of CO₂ and H₂O in the recycle gas are the primary factors contributing to higher natural gas consumption and increased CO₂ emissions. Simulation results show that improving recuperator performance can reduce the reformer heat duty by 6–8%. In addition, reducing CO₂ in the recycle gas, replacing the reformer catalyst, and increasing the inlet gas preheating temperature can collectively decrease the reformer energy consumption by approximately 12%. Furthermore, the evaluation of improvement scenarios demonstrates that combining these optimization measures with a 30% hydrogen substitution in the reducing gas can lower CO₂ emissions to approximately 0.5–0.6 tons per ton of DRI produced. These findings highlight that optimizing the gas processing system is an effective strategy for enhancing energy efficiency, reducing fossil fuel consumption, and advancing the steel industry toward sustainable and low-carbon production.

Introduction

The steel industry is one of the largest energy consumers and a major contributor to global greenhouse gas emissions, accounting for approximately 7–9% of worldwide CO₂ emissions. Growing global demand for steel, combined with increasingly stringent environmental regulations and international commitments to climate change mitigation, has accelerated the search for low-carbon ironmaking technologies. Among the available alternatives, the natural gas-based Direct Reduction Iron (DRI) process, particularly the MIDREX technology, has gained considerable attention due to its lower carbon footprint compared with conventional blast furnace routes. In addition, MIDREX technology offers operational flexibility and the potential for future integration with hydrogen-based reduction pathways. Within the MIDREX process, the methane gas processing system plays a critical role in determining overall process efficiency, reformer performance, reducing gas quality, and environmental emissions. This system includes gas cooling, scrubbing, drying, compression, purification, recycling, and reforming units. Any inefficiency within these components can increase natural gas consumption, deteriorate the H₂/CO ratio of the reducing gas, elevate thermal loads on the reformer, and consequently increase CO₂ emissions. Despite its significance, comprehensive assessments of the environmental implications of gas processing performance in industrial MIDREX plants remain limited. Therefore, this study investigates the operational behavior of the methane gas processing system and evaluates its contribution to reducing environmental impacts in a commercial MIDREX direct reduction plant. The primary objective of this research was to evaluate the efficiency of the methane gas processing system in reducing environmental burdens associated with MIDREX-based ironmaking. Specifically, the study aimed to identify major energy bottlenecks, quantify their effects on energy consumption and CO₂ emissions, and assess the effectiveness of various improvement scenarios, including reformer optimization, recuperator enhancement, CO₂ removal from recycle gas, and partial hydrogen substitution.

Method

A combined industrial-process analysis and engineering simulation approach was employed. A MIDREX direct reduction plant in Iran with an annual production capacity of approximately 825,000 tons of DRI was selected as the case study. Operational data were collected from various process units, including the reformer, shaft furnace, recuperator, scrubber, compressors, and Top Gas recycling system. Parameters such as gas composition, pressure, temperature, equipment efficiency, and energy consumption were analyzed. Thermal imaging techniques were used to identify abnormal temperature distributions and heat losses in the reformer and recuperator. Subsequently, a comprehensive process model was developed using Aspen HYSYS V9. The model incorporated major chemical reactions, including steam methane reforming, dry reforming, and methane decomposition. Actual plant operating conditions were implemented to compare real performance with ideal design conditions. Several improvement scenarios were simulated, including increased recuperator efficiency, reduced CO₂ concentration in recycle gas, enhanced reformer performance, implementation of Hot Direct Reduced Iron (HDRI) technology, and hydrogen integration. Environmental impacts were quantified through mass and energy balance calculations. CO₂ emissions from fuel combustion and process operations were estimated for each scenario, allowing a comparative evaluation of their environmental benefits. The simulation results were validated against actual plant data to ensure accuracy and reliability of the model predictions.

Results

The results revealed that the reformer, recuperator, and Top Gas recycling system represent the most significant contributors to energy losses and environmental impacts within the MIDREX process. Analysis of the Top Gas system indicated that elevated concentrations of

CO₂ and water vapor reduce reducing-gas quality and decrease the H₂/CO ratio. Environmental factors such as ambient humidity, temperature fluctuations, dust contamination, atmospheric pressure variations, and the presence of SO_x and NO_x pollutants were found to influence gas quality and reduce Top Gas efficiency by approximately 10–12%, resulting in an additional 0.05–0.10 tons of CO₂ emissions per ton of DRI. The reformer was identified as the largest energy consumer within the plant. Catalyst deactivation, uneven flame distribution, carbon deposition, and inadequate insulation were found to significantly increase fuel consumption. Simulation results demonstrated that reformer optimization could reduce natural gas consumption by up to 12%, corresponding to a reduction of approximately 0.12 tons CO₂ per ton of DRI. The recuperator was found to have a substantial influence on process energy efficiency. Improving heat recovery performance increased inlet gas temperatures and reduced reformer thermal demand by approximately 6–8%, resulting in a further reduction of CO₂ emissions. Additional simulations showed that reducing recycle-gas CO₂ concentration from 15% to 8% increased the H₂/CO ratio from 1.2 to 1.6 while decreasing reformer heat requirements by approximately 5%. Furthermore, replacing 30% of natural gas with hydrogen reduced reformer energy demand by 18–20% and significantly lowered carbon emissions. The combined implementation of all improvement measures yielded the most promising results. Total natural gas consumption decreased by approximately 22–25%, while CO₂ emissions were reduced by 0.5–0.6 tons per ton of DRI produced. These findings demonstrate that systematic optimization of the methane gas processing system can achieve substantial environmental benefits while maintaining operational efficiency.

Conclusions

The findings confirm that methane gas processing performance in the MIDREX direct reduction process has a major impact on energy consumption, reducing gas quality, and CO₂ emissions. The reformer, recuperator, and Top Gas system were identified as the main sources of efficiency losses. Reformer inefficiency caused by carbon deposition, temperature non-uniformity, and inadequate insulation increases natural gas consumption and CO₂ emissions, while recuperator heat losses and poor recycled gas quality increase the reformer's thermal load and reduce the H₂/CO ratio. Simulation results indicate that improving these three sections through better control, heat recovery, and gas drying can significantly enhance system performance. Combined optimization measures have the potential to reduce CO₂ emissions by approximately 0.5–0.6 tons per ton of DRI, with substantial benefits for energy costs and emission intensity. The study also indicates that gradual hydrogen integration, particularly with 30% substitution of natural gas, could provide an effective pathway for further decarbonization. Overall, optimization of the gas processing system is both a technical necessity and an important strategy for sustainable and low-carbon steel production. Future studies should focus on the effects of furnace load variations, economic evaluation of hydrogen substitution scenarios, and real-time optimization of gas processing systems.

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