論文の要旨
Summary of the Dissertation

論文題目
Dissertation Title

"The Role of Hydrogen and Ammonia in Decarbonizing the Steel and Power Sectors"

"鉄鋼および電力部門の脱炭素化における水素とアンモニアの役割"

氏名　KHUSNIDDIN ALIKULOV ZARIFOVICH
Name

1. Background

Decarbonizing current conventional and fossil fuel-based steel and power sectors is crucial for the sustainable development of the industrial sectors in the future. In the steel sector, several research works, and pilot projects are ongoing to transform the Direct Reduction Iron Ore – Electric Arc Furnace route into the Hydrogen Direct Reduction Iron Ore – Electric Arc Furnace route. On the other hand, there are various research works and projects investigating the stable operation of existing gas turbine units with ammonia and hydrogen fuel blends. The present study focuses on three clusters of research work. Firstly, the optimization of iron ore reduction with hydrogen fuel in a laboratory condition to achieve stoichiometric values for the route. In the second part of the research works, four scenarios with different fuel blending options are applied to existing gas turbine units with an installed capacity of 7.6 MW. In the third part of the current studies, technical and economic comparisons of the steel and power sectors are investigated under the use of 100% hydrogen fuel instead of conventional fuel, and the effect of using each 1 kg of hydrogen in the sectors is analyzed.

2. Objectives

i. Evaluate the energy and mass balance of hydrogen-based steel production.
ii. Optimize the iron ore reduction process for optimal steel production based on the results from the energy and mass balance of the HDRI route.
iii. Develop multi-fuel combustion models for the existing gas turbine at the Fergana Combined Heat and Power (CHP) plant.
iv. Identify and compare the costs associated with steel and electricity production in hydrogen-assisted steel and power plants.

3. Structure of dissertation

Chapter 1. General introduction

Chapter 2. Experimental optimization works on reducing iron ore with hydrogen.

Chapter 3. Development of a multi fuel-fired gas turbine in the existing power unit of Fergana combined heat and power plant.

Chapter 4. Comparative technical and economic analyses of hydrogen-based steel and power sectors.

Chapter 5. General discussion.

4. Materials and methods

Chapter 2

The first part of the research work aims to evaluate the energy and mass balance of the Hydrogen Direct Reduction Iron – Electric Arc Furnace route to identify optimal energy utilization and achieve stoichiometric hydrogen consumption per ton of liquid steel (tls) production under laboratory conditions. The route used 54.00 kg of H_2 and 2.68 MWh to reduce 1,428.00 kg of Fe_2O_3 and produce 1 tls. The experiments were conducted at temperatures of 750, 760, 770, 780, 790, and 800 °C, using 2.3622 g of Fe_2O_3, 1 L/min of H2, 0.001 MPa, and residence times of 1, 2, 3, 3.5, 4, 5, 7, 10, and 15 minutes.

Chapter 3

In the second part of the research, the effects of fuel blends comprising ammonia and hydrogen on the technical, economic, and environmental indicators of an existing 7.6 MW output power gas turbine unit were investigated and analyzed. Four models, each with different fuel-blending options, were designed using Aspen HYSYS and Ansys®Chemkin Pro to analyze the technical and chemical processes. The fuel blends for Scenarios 1, 2, 3, and 4 were 100% natural gas (NG), 30% ammonia (NH_3) and 70% NG, 30% hydrogen (H_2) and 70% NG, and 30% NH_3, 30% H_2, and 40% NG, respectively.

Chapter 4

In the third part, three clusters of research works were conducted. In the first cluster, the mass and energy balance of the existing metallurgical complex based on the Tebinbulak mine were calculated and identified. In the second cluster, an existing gas turbine unit was selected for the complete replacement of natural gas with hydrogen, finding the most optimal mass and energy balance in the cycle through the Aspen HYSYS model. Additionally, chemical kinetics in the hydrogen combustion process were simulated using Ansys®Chemkin Pro to research emissions. In the last cluster, a comparative economic analysis was conducted to identify the levelized cost of production of the route and the levelized cost of electricity of the cycle.

5. Results and discussion

The first part of the research work stated that an experiment using two samples, each containing 2.3622 g of Fe_2O_3, at 770 °C, 0.001 MPa, with a residence time of 7 minutes and 1 L/min of H_2, resulted in reduction yields of 99.7 % and 99.33 %. Another experiment, using a single feedstock and a residence time of 3.5 minutes under the same conditions, yielded an 85.71% reduction. In conclusion, an approach utilizing 4.7244 g of Fe_2O_3 and a residence time of 7 minutes at 770 °C demonstrated a higher reduction yield compared to the one using 2.3622 g of Fe_2O_3 with a residence time of 3.5 minutes.

As for the second part of research work finding and based on the technical and CO_2 emission values of each model developed in Aspen HYSYS, the focus was on Scenario 4 with ammonia and hydrogen co-firing. This scenario exhibited the highest electric efficiency (36.63%) and the lowest CO2 emissions (3,979.00 kg CO_2/h) but had higher costs (0.19 $/kWh) for generated electricity compared to other scenarios. Economic evaluations of all scenarios provided a clear understanding of each fuel cost and Levelized Cost of Electricity (LCOE). Initially, Scenario 2, with ammonia co-firing, appeared to be an attractive option for further implementation. However, detailed analyses of the combustion process in each model dramatically changed the final decision and provided a good reason to focus on hydrogen fuel, which significantly reduced NOx emissions. In conclusion, Scenario 3 with hydrogen co-firing demonstrated attractive performance and favorable combustion kinetics.

In the last part of research works, findings in the economic analysis provided good insight into the details of capital and operational expenditure of each industrial sector, helping understand the impact of consuming each kg of hydrogen in the plants. The outcomes of this study serve as a solid foundation for future research works aimed at reducing the cost of hydrogen-based steel and power sectors. Moreover, the results of this study can also assist ongoing large-scale hydrogen and ammonia projects in Uzbekistan in designing novel hydrogen-based industries with cost-effective solutions.

Considering all the findings, in the case of Uzbekistan, there is limited opportunity to apply hydrogen in the steel manufacturing sector due to the unavailability of a suitable steel plant route at this moment. Most available steel manufacturing can be put into operation by 2027. On the other hand, the power sector in Uzbekistan has several gas turbine units in operation with a capacity ranging from 7.6 MW to 650 MW. An additional and alternative fuel to the gas turbine can be ammonia, but significant NOx emissions are a challenging point to replace natural gas. Therefore, in the short term, hydrogen combustion can be a potential option for replacing natural gas in the power sector. In both cases, the capital and operational expenditure of electrolyzer, compression, and storage units exceed the investment cost of target technologies. Instead of producing, storing, and compressing hydrogen fuel on project sites, it is also feasible to import hydrogen fuel from sellers for the successful implementation of 100% hydrogen-based steel and power plants. On the other hand, water scarcity in the region makes it challenging to produce hydrogen with electrolyzer units on-site. Alternatively, a large-scale hydrogen production project in Kazakhstan can be the optimal solution to meet the hydrogen consumption demand of each project. However, hydrogen transportation for long distances is not feasible at this moment, and ammonia can be a potential hydrogen carrier, which also requires energy for cracking it after transportation to a project site. Taking into consideration all conditions, 30% hydrogen co-firing in the selected gas turbine technology is possible to implement and meet all emission regulations set by the manufacturer. The reason for this ultimate statement is the possibility of meeting the required amount of hydrogen and the operation of all existing parts, including the combustor of the gas turbine. In any case, electrolyzer, compression, and storage units are required for green hydrogen production and supply.