Substitution of Coal by Renewable Reductants for Green Steelmaking

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by

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Chapter 6 Overall conclusions

Three hardwood biomass species suitable for short rotation forestry were selected and studied for their application in ironmaking. The biomasses were carbonized under different conditions to make charcoals. Charcoals were studied for their potential use in ironmaking. Characterization of the charcoals was performed using various conventional and non-conventional characterization techniques. These charcoals were then utilized as reductant to study the reduction behaviour of iron ore. Reduction behaviour and kinetics were studied by using iron ore and charcoal as composite pellets in a thermogravimetric setup. Parameters for maximum reduction were established. Further, the DRI was produced at larger scale under the optimized conditions. The DRI was melted in an EAF to make steel. The main conclusions of the thesis are as follows:

1. The selected biomass species had different compressive strength, carbon and hydrogen contents. These exhibited a marked difference in pore morphology. The strength and the pore size were found to be highly correlated: smaller the pores stronger was the wood. Thermal stability test on biomasses helped determine charcoal making (i.e., carbonization) temperatures. Among these wood species cellulose and lignin degradation completed over the temperature of 400 to 1100 °C. Degradation of the macromolecules in W3 wood completes earlier (200-800 °C) than W1 and W2 (200-1100 °C) species.

2. Studied wood charcoals demonstrated superior chemical composition than non-coking coal and metallurgical coke in terms of carbon, hydrogen and energy content. However, the compressive strength was inferior as compared with the coal and coke. Half or lesser mechanical strength in charcoals, as compared with a typical coke, make these unsuitable for direct application in blast furnace. However, these can be used in other applications like pulverized injection in blast furnace or in alternative processes of

ironmaking as a substitute to coal, where strength is not a requirement. Among the selected species, *Leucaena* (W3) had the highest amorphous carbon content and CO_2 reactivity, establishing it as the best reductant.

3. Reduction of iron ore with charcoal as composite pellet is rapid and achieves higher reduction levels than with fossil coal. In reduction experiments it was found that reduction of iron ore with *Leucaena* (W3) had resulted in higher degree of reduction (83%) and faster kinetics under different reduction conditions. Among the selected species, activation energy was found to be the lowest (170 kJ/mol) in case of W3. Therefore, among the selected species, W3 is recommended for ironmaking as a replacement to coal in composite pellets. Using the master plot method, the overall reduction reaction was established to be controlled by the diffusion of the reactant gases and at a later stage by the gasification of the charcoal.

4. The melted DRI, i.e., the green steel, had 12% and 10% lower S and P respectively than conventional low carbon steel. Decrease in sulphur and phosphorous content was most probably due to the use of charcoal as reductant in DRI making and, the basic & oxidizing slag during melting respectively.

Despite operating close to its theoretical thermodynamic limit, conventional steelmaking process still consumes one-sixth of global coal production and emits approximately 7% of global greenhouse gases. On the contrary, the future of charcoal based direct reduction of iron ore (charcoal DRI) is looking promising as the technology continues to evolve and become more efficient. Carbon emission from charcoal based direct reduction process can be reduced further with carbon capture and storage technologies to make the process carbon negative. With increasing cost competitiveness of renewable electricity (12 to 29% cheaper than lowest cost fossil fuel), the economic prospect of green steelmaking by proposed route also appears very promising.

Steelmakers around the globe are shifting from conventional steel to green steel in order to boost their sustainability credentials and capitulate to government norms. Conglomerate firms like ArcelorMittal, SSAB, SMS group, Tata Steel etc. are investing heavily and partnering up with manufacturing giants such as Volvo group and Ford Motor Company as consumers of green steel. Along the same lines, Indian steelmakers like Tata steel India, JSW steel and Kalyani steel are pushing hard to decarbonise their steelmaking process and become the first commercial producer of green steel.

Overall, the charcoal based direct reduction of iron ore (charcoal DRI) is a promising alternative to traditional ironmaking and has the potential for a more sustainable and economically viable future for iron and steelmaking.

Chapter 7 Future scope

Solid product of biomass carbonization, i.e., the charcoal, was characterized for its use in ironmaking. Gaseous product evolved during carbonization can also have use in ironmaking. Gases might also find some use as well depending on their composition. Quality and quantity of gaseous and solid products are dependent on parameters during carbonization. Gas emission monitoring and carbonization kinetics of selected species should be studied in details to help with the process optimization and hence, in controlling the quality control of the solid product i.e., charcoal.

Three hardwood biomass species were studied in the present work. Similarly, other hardwood species shortlisted in the beginning of Chapter 2 can be studied. The characterization and reduction results can be compared and a better biomass species may be discovered. Agronomy aspects such as biomass productivity, yield and land availability need to be researched in order to get a complete picture in terms of economics and industrial suitability of the process.

Biomass has several advantages which has been already discussed in chapter 1. Encouraging results of the study and decreasing prices of renewable electricity indicate that this approach has a huge potential to become an industrial process. However, the scale up of the composite pellet reduction with an aim to make the process energy efficient and economically competitive in future will require a multipronged research activity. These activities involve material selection and reactor design, optimization of the operating conditions, process modelling and optimisation in addition to further fundamental studies at lab scale.