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Operability Analysis of Direct Reduction of Iron Ore by Coal in an Industrial Rotary Kiln

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Abstract: Operability analysis enables process designers to evaluate the control aspects of a given process design early in the design cycle. One of the major obstacles to such an evaluation was lack of a metric that quantitatively measures the inherent operability of a given process design. Operabilty Index (OI) framework developed by Vinson and Georgakis (2000) addressed this important limitation. Subsequent work reported by Georgakis and coworkers developed the framework further for dynamic and nonlinear systems (Georgakis et al., 2003). In this communication, OI methodology is used to study the operability characteristics of direct reduction of iron ore by coal in a rotary kiln using a rigorous process model. Though the objective is not to quantify OI, but to develop deeper understanding of the process, the methodology is adopted here for its systematic approach to exploring the operating spaces. The predictions are based on a rigorous phenomenological model developed by Runkana et al. (2010) and made available in the steady-state simulator called DRIKS^{TM}. Guided by the OI methodology, input-output relationship of the process were explored using DRIKS^{TM}. Key inputs investigated are coal and primary air flow rates. Their impact on selected outputs, especially % metallization are observed and analysed in an effort to identify optimum or robust operating regions. This methodology can help one to locate better operating conditions as well as unsafe and infeasible operating regions.

Keywords: Operability, Flexibility, Rotary Kiln, Direct Reduced Iron, Coal.

1. INTRODUCTION

With increasing emphasis on tight quality control and stricter regulations on emissions, process industry is under constant pressure to keep processes under economical operation. Operability analysis can help the process engineers to design and sustain processes by effectively exploiting the mathematical models. Operability can be viewed as the ability of a process to provide acceptable steady-state and dynamic operational performance over the desired range of operating points. Operability Index (OI) framework developed by Vinson and Georgakis (2000) and Georgakis et al. (2003) is applicable for linear and nonlinear process models. It aids in the understanding of inherent steady-state and dynamic operability of the processes. This framework has been proven to be effective for both linear and nonlinear processes (Vega et al., 2014).

The OI framework had been applied to study the operability of idealized nonlinear reacting systems (Subramanian and Georgakis, 2001) and plant-wide systems including Tennessee Eastman process (Subramanian and Georgakis, 2005). In this study, the goal is to apply the methodology to production of direct reduced iron (DRI) or sponge iron using the model developed by Runkana et al. (2010). Direct reduction is an alternative route of iron making. India is the largest producer of DRI in the world. DRI is used as the raw material for making steel through the electric arc furnace (EAF) route. The specific investment and operating costs of the direct reduction plants are low compared to the integrated steel plants. The important step in the manufacture of DRI is direct reduction of iron ore by coal in a rotary kiln or using reducing gases such as carbon monoxide and hydrogen in a moving bed reactor (Chatterjee, 2010). Reader may find the comparison of alternative technologies for DRI useful (DRI, 2015). The focus here is limited to direct reduction of iron ore by coal in a rotary kiln. Inferior quality coal could be effectively used in the DRI process. In fact, non-coking coal, which is not suitable for preparing metallurgical coke for blast furnaces is the main reducing agent used in majority of the DRI plants in India. India has large reserves of non-coking coal and the ash content in coal could be as high as 30%. It forms low melting complexes consisting of ash, gangue and metallic iron and deposit (accretion) inside rotary

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kiln. Accretion causes frequent shut-down of the plant. A comprehensive mathematical model for direct reduction of iron ore by a mixture of coals in a rotary kiln is used here to study the operability behavior of DRI process.

The outline of the article is as follows. First, in Section 2 the concept of operability and the OI methodology is briefly introduced. Then in Section 3 salient features of DRI process and model used in DRIKS^{TM} are outlined. Observations from several systematic simulations are shared in Section 4. Section 5 concludes the article by summarizing the key results, and possible future work.

2. OPERABILITY ANALYSIS

Operability analysis can be viewed as one of the bridges that links process design with process control. A process can be said to be operable if the available set of inputs is sufficient to achieve the desired steady-state and dynamic performance requirements defined at the design stage, and can take the process to all the set points of interest, in the presence of anticipated disturbances without violating any of the process constraints. The OI framework attempts to capture the inherent ability of the process. As process design has the greatest impact on its operability, a plant should be designed keeping its (steady-state and dynamic) control requirements in perspective. The broader objective is to help the designer to design processes with good operability qualities. A necessary component to effectively perform this task, is that we have a measure/yardstick for operability of a given process design. Then it can help to rank competing designs from the operability point of view.

In this study, our focus is limited to steady-state operability behavior of a process. The OI framework of Vinson and Georgakis (2000) laid a good starting point for this purpose. Some of the key ideas as relevant to the objective of the article is emphasized here. A schematic representation of OI calculation in the input and output spaces is shown in Fig. 1. The available set of inputs for controlling the process is called Available Input Space (AIS). The set of outputs that can be achieved using AIS is called Achievable Output Space (AOS). This can be calculated using the simulation model of a process. By comparing the AOS with Desired Output Space (DOS), the set of outputs that are desired, one can calculate the OI in output space. It is defined as a fraction of DOS that is achievable. Design calculations (using the inverse model) can performed to compute the set of inputs required to meet the requirements in DOS, and it is called Desired Input Space (DIS). The fraction of DIS that is covered by AIS yields the OI in the input space. For a more comprehensive, overall OI, one should certainly consider the impact of disturbances and uncertain parameters in such an evaluation. Interested reader is referred to Georgakis et al. (2003) and references therein for a detailed discussion on the subject.

The OI methodology encourages a systematic exploration of input, output and disturbance variable spaces onto each other through a use of steady-state model. The focus of the current work is to perform a systematic set of simulations to map a given input space to the corresponding output space of interest to help one understand the DRI process characteristics better. It is worth noting that when the process models are computationally intensive, one could use a reduced order model to study the systems behavior in a region of interest. Such an approach is demonstrated by Georgakis and Li (2010).

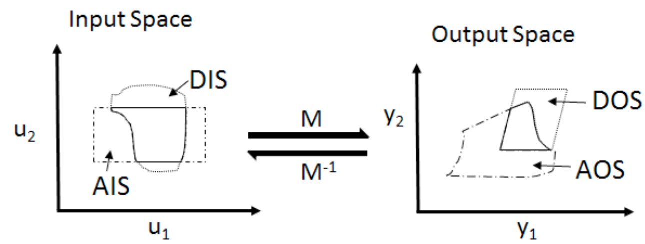

Fig. 1. Schematic of different spaces used in Operability Index definition

3. DIRECT REDUCTION OF IRON ORE BY COAL IN A ROTARY KILN

In the direct reduction process, iron ore is fed along with coal into a rotary kiln. The kiln is mounted at a slight inclination to the horizontal and is rotated at a slow speed ($\approx$ 0.5 rpm). The rotation and inclination aid in good mixing and movement of solids towards the discharge end. It also faciliates efficient mass and heat transfer with the gases that flow counter-currently. The combustion of coal heats up the feed stock and coal is also the source of the main reducing gas, carbon monoxide (CO). Fresh air, called Primary Air (PA) is blown from the discharge end of the kiln. Fine coal is injected from the discharge end of the kiln and is carried by Root Blower (RB) air. RB carrys the injection coal deep into the kiln while primary air acts as the main source of air for combustion. Additional air, called secondary air (SA), is injected at different locations along the length of the kiln. Fig. 2 depicts a typical flowsheet of the DRI production process (Chatterjee, 2010; Runkana et al., 2010).

Runkana et al. (2010) developed a detailed mathematical model of the process. It is rigorous and built on fundamental principles related to the various phyico-chemical phenomena taking place in the process, such as heat and mass transfer, reactions and flow of solids and gases. The ore which is predominantly hematite is assumed to be reduced to free iron in three reactions in series with magnetite, and wustite as intermediate products. Carbon monoxide and hydrogen act as the reductants. Other important reactions typical of this system such as Boudard reaction, coal combustion, water gas shift reaction were considered in this model. Model is one-dimensional in nature and it is meant for steady-state simulation of the process. Drying of ore and coal, and coal devolatization were also incorporated. The overall kiln model includes appropriate sub-models for kinetics of reactions involving hematite, magnetite, wustite, carbon, oxygen, carbon monoxide and hydrogen, along with flow of solids inside the kiln. Inputs for the model can be sub-divided into specifications of ore, coal, air and kiln geometry and dimensions. Ore properties are mainly flow rate, size distribution, hematite content and moisture. For coal, in addition to flow rate(s), size distribution and moisture content, proximate analysis and reactivity are considered. Air streams are specified by their flow rate, pressure, temperature and relative humidity.