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Novel Flash Ironmaking Technology

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Abstract **–**Despite the dominance of the blast furnace ironmaking process, increasing attention is paid to the development of a new technology with lower energy consumption and CO_2 emissions. An ideal process would also use widely available iron ore concentrate. It should also require much less capital investment than the blast furnace/coke oven combination. At the University of Utah, we are working on a drastically novel process for an alternative technology to meet these demands. In response to increasing concerns about energy consumption and atmospheric emissions from the conventional and other emerging ironmaking plants, especially carbon dioxide, we are developing the Flash Ironmaking Process. This novel technology eliminates the highly problematic cokemaking and pelletization/sintering steps by directly utilizing iron ore concentrates, which are in abundance in the United States and elsewhere. In this paper, some recent advances on this work are discussed.

Keywords**:** Flash ironmaking, Suspension reduction, Natural gas, Hydrogen

1. Introduction

The Flash Ironmaking Process is an innovative process that uses iron ore concentrates directly without further treatment. The fineness of the concentrate particles allows a very rapid reaction rate, thus requiring residence time measured in seconds instead of the minutes and hours it takes to reduce pellets and even fines.

Other processes for the gaseous reduction of iron oxide can be grouped into two broad types: (1) shaft furnaces (Midrex (Cheeley, 1999) and Energiron (Duarte et al., 2010)) and, (2) fluidized-bed reactors (FINMET and the earlier FIOR (Hassan et al., 1994), CIRCORED Process (Husain et al., 1999), and SPIREX). Shaft furnaces require pellets or sinter, which are 10-12 mm in size and require minutes or even hours to be fully reduced. The fluid bed processes use "iron ore fines", particles in the range of +0.1 mm to -10 mm. These processes are slow because they cannot be operated at high temperatures, under which they suffer the problems of sticking and fusion of particles. Processes that can replace the blast furnace must be sufficiently intensive to meet the large production rates required for economic competitiveness. The Flash Ironmaking Process reduces iron ore concentrates of < 100 μm sizes, which are even smaller than fines, by one or two orders of magnitude. Historically, fluidized bed processes using iron ore fines have been less than successful. Compared with concentrate particles, even ore 'fines' used in a fluidized bed take much longer time to reduce than the time available in a flash reduction process.

The Flash Ironmaking Process removes many of the limitations associated with other processes discussed above. Specifically, (1) it uses iron oxide concentrates directly without the need for pelletization or sintering; (2) coke ovens are not required; (3) high temperatures can be used because there will be no particle sticking or fusion problems (and thus, the process can be operated at high temperatures); (4) it is possible to produce either solid or molten iron; and (5) the raw materials can be fed easily. The process also has the possibility of direct steelmaking in a single unit, as depicted in Figure 1.

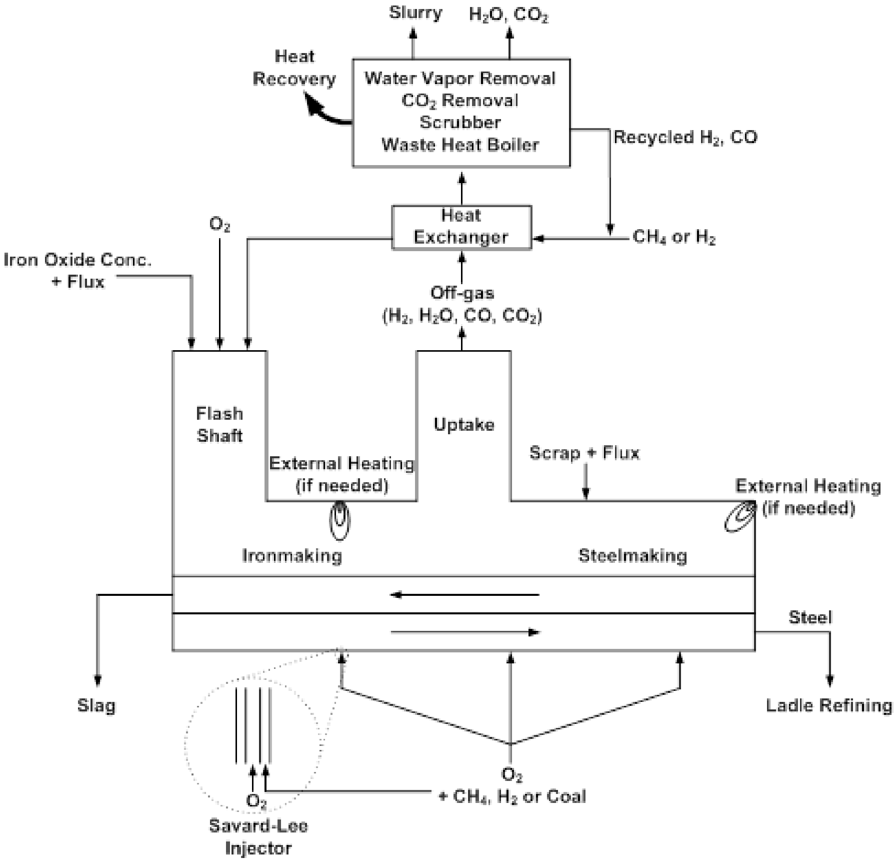

Fig. 1. A schematic diagram of a possible direct steelmaking process based on the Flash Ironmaking Process (Sohn and Choi, 2012)

2. Research Progress on the Flash Ironmaking

In this paper we will describe on major progresses made so far on the Flash Ironmaking research, especially on the kinetics of the reduction process, the chemistry of the slag, and the economic and environmental aspects of the process.

2. 1. Kinetics of Flash Reduction of Iron Ore Concentrate

As an integral part of the development of this novel process, Sohn and coworkers (Choi and Sohn, 2010; Choi et al., 2006; Wang and Sohn, 2013) have investigated the gaseous reduction of magnetite concentrate particles aimed at generating a database to be used for the design of a flash ironmaking reactor—before their work, there had been little research reported on this subject under the conditions of the Flash Ironmaking Process. Their work included the measurement of the particle kinetics of the hydrogen reduction of magnetite concentrate particles in the temperature range of 1423 - 1673 K (Choi and Sohn, 2010; Wang and Sohn, 2013). Most importantly, they have established that magnetite concentrate can be reduced to a degree higher than 90 pct within several seconds, which presents sufficiently rapid kinetics for a flash reduction process. They obtained the following rate expression for hydrogen reduction of magnetite concentrate particles based on the nucleation and growth kinetics:

$$[-Ln\,(1-X)]^{1/2} = 9.90\times 10^{14}\times e^{\frac{-463000}{RT}}\times[(pH_2)^{1/2}-(\frac{pH_2O}{K})^{1/2}]_{am}\times(d_p)^s\times t \qquad (1)$$

where

$$s = \frac{2.73\times 10^8}{T^2} - \frac{345930}{T} + 109.5 \quad ; \quad T = 1423 \text{ to } 1573 \text{ K}$$

$$s = 0 \quad T \geq 1573 \text{ K}$$

where R, the universal gas constant, is 8.314 J/mol·K; T, temperature, is in K; p, partial pressure, is in atm; t, time, is in seconds; and the subscript *am* stands for the arithmetic mean of the hydrogen driving force. As the rate equation shows, an Avrami parameter $n = 2$ best fitted the data. They also found that the magnetite reduction rate had a half-order dependence on the partial pressure of hydrogen.

Although the Flash Ironmaking Process is being developed for magnetite concentrate, it is expected to be equally applicable to hematite concentrate. Thus, Sohn and coworkers (Chen et al., 2015) studied the hydrogen reduction kinetics of hematite concentrate particles of average size 21.3 µm in the temperature range 1423 K to 1623 K. The results clearly indicated that the hematite concentrate can also be reduced to greater than 90 pct degree by hydrogen in the several seconds of residence time typically available in a flash reactor. In their work (Chen et al., 2015), results at various temperatures and partial pressures of hydrogen showed that the nucleation and growth rate equation with an Avrami parameter of 1 well describes the kinetics of hematite reduction. The reduction rate has a 1^{st}-order dependence on the partial pressure of hydrogen. The activation energy of hydrogen reduction of hematite concentrate is 214 kJ/mol (Chen et al., 2015). The following rate equation was obtained, which satisfactorily represent the reduction kinetics of hematite particles:

$$-Ln(1-X) = 4.41\times 10^7 \times e^{\frac{-214000}{RT}} \times (pH_2 - \frac{pH_2O}{K})_{lm} \times t \qquad (2)$$

where R is 8.314 J/mol·K, T is in K, p is in atm, and t is in seconds.

Compared with the activation energy of the hydrogen reduction of magnetite concentrate of 463 kJ/mol in the temperature range 1423 to 1673 K (1150 to 1400 ˚C), the reduction of hematite concentrate has a lower activation energy of 214 kJ/mol in the similar temperature range. Overall, the reduction of hematite particles is faster than that of magnetite particles as shown in Figure 2.

The study of the kinetics of the flash reduction continues to determine the rate equation for the reduction of magnetite and hematite concentrate with mixtures of CO and H_2 gases to be used in designing flash reactor that will run on natural gas.

On the other hand, Sohn and co-workers (Yuan and Sohn, 2014; Yuan et al., 2013) studied the kinetics of the re-oxidation of iron particles produced by the Flash Ironmaking Process in various oxidizing gas mixtures. As the gas-particle mixture cools down in the lower part of the flash reactor, the re-oxidation of iron could take place because of the decreasing equilibrium constant and the high reactivity of the freshly reduced fine iron particles. The last stage of hydrogen reduction of iron oxide, i.e. the reduction of wustite, is limited by equilibrium. The effects of temperature (823 – 973 K) and H_2O partial pressure (40 – 100 pct.) on the re-oxidation rate were examined. The nucleation and growth model was shown to best describe the re-oxidation kinetics. Pressure dependence was first order with respect to water vapor, and the activation energy was 146 kJ/mol. A complete rate equation that adequately represents the experimental data was developed (Yuan et al., 2013). For oxidation in O_2-N_2 gas mixtures, effects of temperature (673 – 873 K) and O_2 partial pressure (5 – 21 pct.) were studied and the nucleation and growth model was used to describe the initial period of oxidation. Pressure dependence was first order with respect to oxygen and the activation energy was 14.4 kJ/mol (Yuan and Sohn, 2014). Moreover, they studied the oxidation in pure CO_2 gas was investigated in the temperature range of 873 – 1073 K. Their findings indicated that within several seconds of residence time typically available in a flash reduction process the re-oxidation degree of iron particles in water vapor should be < 0.24 % in the temperature range of 823 – 973 K and the results implied that the oxidation will be negligible in the flash reduction process where CO_2 from partial combustion of natural gas with oxygen accounts for less than 10% in the gas mixture. In the collector where product iron particles may be kept for up to one hour at around 673 K, the expected re-oxidation degree would be around 0.02 % (Yuan, 2013; Yuan and Sohn, 2014; Yuan and Sohn, 2013).

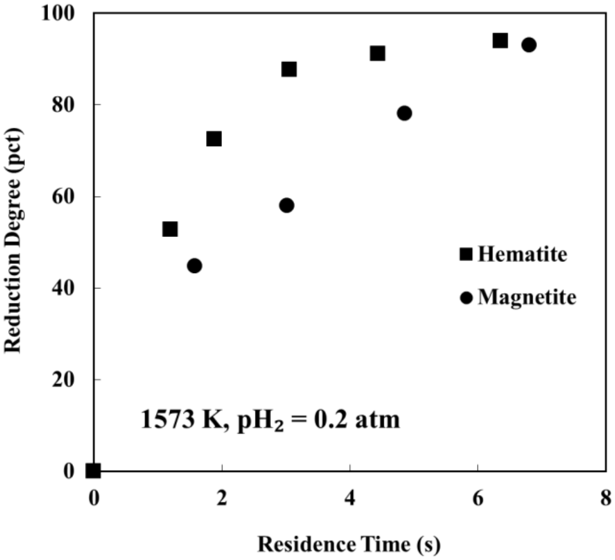

Fig. 2. Experimental reduction degrees of hematite and magnetite vs residence

2. 2. Slag Chemistry

Sohn and coworkers (Mohassab Ahmed et al., 2014; Mohassab-Ahmed and Sohn, 2013; Mohassab-Ahmed and Sohn, 2014a,b; Mohassab and Sohn, 2014a,b) have applied a number of analytical techniques to determine the structures and properties of slags. These techniques have been proved to be highly useful for this purpose. Several features of such instrumental analysis have direct correlations with important properties of slag such as its affinity to impurities. These techniques were applied to slags of interest for a novel Flash Ironmaking Process, especially in terms of the effects of water vapor expected to be present in high contents in the new process (Mohassab-Ahmed and Sohn, 2013). Water vapor was found to be advantageous for lowering FeO uptake (Mohassab-Ahmed and Sohn, 2014a). They also found that water vapor had a significant impact on the equilibrium distribution of elements such as sulfur (Mohassab and Sohn, 2014), phosphorus (Mohassab and Sohn, 2014), and manganese (Mohassab-Ahmed and Sohn, 2014b) in addition to the impact on iron and magnesium oxides activities in the slag. Moreover they found that water vapor in the atmosphere of the new process would keep lining wear low based on the low MgO solubility in slag under its expected operating conditions (Mohassab Ahmed et al., 2014).

2. 3. Process Simulation

Process simulation for the Flash Ironmaking Technology was carried out by Sohn and coworkers using the METSIM software to assess the economic feasibility for different process configurations (Pinegar et al., 2012a,b;2011; Sohn and Choi, 2012). Major results are summarized in Figures 3 and 4. Figure 3 shows potential higher energy savings, lower carbon footprint, and economic feasibility (except when purchased H_2 is used) relative to the BF. However, application of a \$50 per ton of CO_2 credit should make the use of hydrogen economically feasible at the 2010 price of hydrogen, as Figure 3 indicates (Pinegar et al., 2012a,b;2011; Sohn and Choi, 2012).

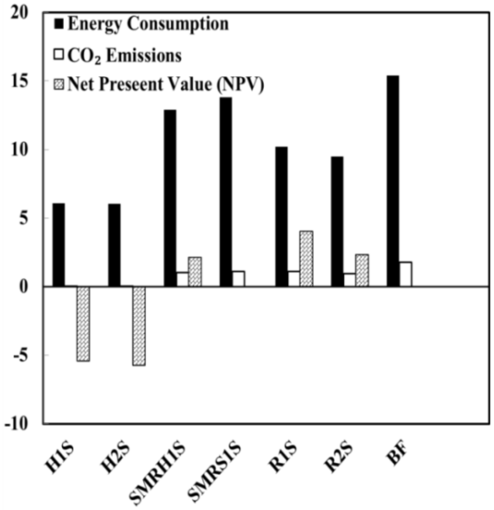

Fig. 2. Energy consumption (GJ/ton of iron), CO_2 emission (tons/ton of iron), and NPV (in 2010 dollars and conditions) in million dollars for a 1 Mt/year plant of the different configurations of the Flash Ironmaking Process in addition to the blast furnace applying \$0 CO_2 credit. [H1S: H_2-based 1-step process, H2S: H_2-based 2-step process, SMRH1S: 1-step process with hydrogen production from SMR (Steam-Methane Reforming), SMRS1S: 1-step process with syngas production from SMR, R1S: Reformerless1-step process, R2S: Reformerless 2-step process] (Pinegar et al., 2012a,b;2011; Sohn and Choi, 2012).

4. Concluding Remarks

A novel Flash Ironmaking Process is under development at the University of Utah. This transformative technology has significant energy savings and reduced CO_2 emissions compared with the Blast Furnace process. It has been proved that iron particles of more than 95% metallization can be obtained by reduction with hydrogen or a mixture of carbon monoxide and hydrogen in 2-7 seconds at temperatures of 1573 K or above. The product of flash ironmaking at temperatures higher than 1273 K is significantly less reactive towards oxygen compared with DRI produced by the current technologies. Also, the molten iron to be produced by the Flash Ironmaking Process will contain less impurities and the relevant slag would be less corrosive to furnace lining.

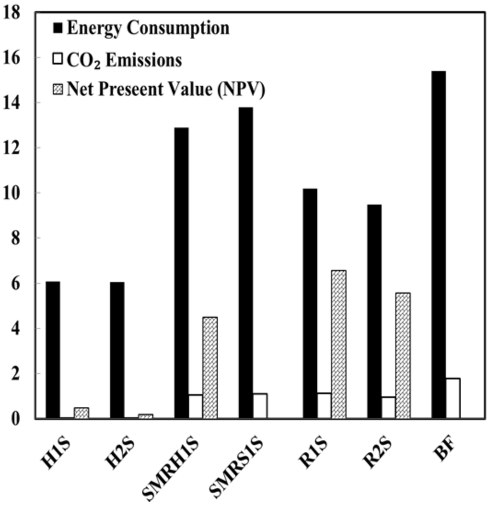

Fig. 3. The energy consumption (GJ/ton of iron), CO_2 emission (tons/ton of iron), and NPV of the different configurations of the Flash Ironmaking Process in addition to the BF applying \$50 CO_2 credit (Pinegar et al., 2012a,b;2011; Sohn and Choi, 2012).

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