

# Status of the Development of Flash Ironmaking Technology

H.Y. Sohn, Y. Mohassab, M. Elzohiery, D.-Q. Fan and A. Abdelghany

**Abstract** The Flash Ironmaking Technology being developed at the University of Utah is aimed at producing iron directly from iron oxide concentrate. In this technology, the concentrate is reduced by  $H_2$  and CO gas mixtures formed from the partial oxidation of natural gas in a flash reactor. Natural gas represents an economically and environmentally superior reductant/fuel for the flash ironmaking. The rate equations for the reduction kinetics by  $H_2$ , CO and  $H_2 + CO$  gas mixtures were determined in the temperature range 1150–1600 °C. These rate equations were applied to experimental results from a laboratory flash reactor using Computational Fluid Dynamics CFD simulation. A new mini-pilot reactor, which is capable of operating at 1150–1550 °C with a concentrate feeding rate of 2–5 kg/h, has been installed. Commissioning of the reactor with an emphasis on preheating of the reactor, production of reducing gas mixtures and the feeding and collection of iron ore concentrate and product particles has been completed.

**Keywords** Flash reaction · Magnetite concentrate · Reduction kinetics · Hydrogen reduction · Ironmaking · Natural gas

## Introduction

Blast furnace (BF) produces over 90% of the world iron from iron ore. Ironmaking via BF is a multi-step process, involving sintering/pelletization, cokemaking, and decarburization, which consume energy and produce hazardous emissions and greenhouse gas  $CO_2$ . The Flash Ironmaking Technology being developed at the University of Utah [1–8] aims at producing iron directly from iron oxide concentrates by a gas-solid flash reaction utilizing natural gas as the reductant and fuel in the temperature range of 1200–1600 °C. The direct use of iron ore concentrate

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(<100  $\mu\text{m}$ ) will bypass pelletizing and sintering steps, thus lowering energy consumption by 30% compared with the average blast furnace process [9].

The use of inexpensive and abundant natural gas will eliminate the cokemaking step, thus reducing the  $\text{CO}_2$  gas emissions by  $\sim 40\%$  compared to an average blast furnace [4]. As a part of developing this process, reduction kinetics of magnetite concentrates by hydrogen and carbon monoxide gas mixture in the temperature range of 1150–1600  $^{\circ}\text{C}$  was studied. In order to establish the reduction kinetics with the gas mixture, the reduction kinetics by the single gases were first determined. A laboratory-scale flash reactor was then built and used for producing iron directly from iron oxide concentrate using hydrogen or natural gas partially combusted with oxygen serving as a source of heating as well as reductant. Electric power was used to compensate for heat loss due to the high surface area to volume ratio in this small reactor. This was the first experimental realization of the flash ironmaking technology. CFD was used to apply the developed rate equation to the results of this lab scale flash reactor and good agreement was achieved. These promising results obtained by the lab scale reactor lead to designing a mini-pilot reactor that is heated completely by a natural gas flame. This reactor is able to operate in the temperature range of 1150–1550  $^{\circ}\text{C}$  with a concentrate feeding rate 2–5 kg/h.

## Reduction Kinetics Determination

The reduction of iron ore concentrate by  $\text{H}_2$  and  $\text{CO}$  was investigated previously by many researchers, but the investigations were mainly focused on large particles or pellets at temperatures lower than the temperature to be used in the flash ironmaking process (1250–1550  $^{\circ}\text{C}$ ). Most of the kinetics studies were performed on hematite ore [10–13].

The magnetite concentrate to be used in the flash ironmaking process contains oxide gangues that were found experimentally to lower the melting point of the particles to 1350  $^{\circ}\text{C}$ . Therefore, the reduction mechanism in the solid state at temperatures below 1350  $^{\circ}\text{C}$  is different from that at higher temperatures. Thus, the reduction kinetics were determined below 1350  $^{\circ}\text{C}$  separately from those above 1350  $^{\circ}\text{C}$ .

Experiments were designed and rate equations were formulated for the reduction of magnetite by  $\text{H}_2$ ,  $\text{CO}$  and  $\text{H}_2 + \text{CO}$  mixtures in the temperature range 1150–1350  $^{\circ}\text{C}$  within which the particles remain solid and at 1350–1600  $^{\circ}\text{C}$  within which the particles experience fusion and melting. The samples produced in this work were analyzed by an ICP method, which was developed in this laboratory to determine the iron content in the samples. This method has high accuracy in determining iron content in the samples containing high amounts of oxide gangues as in the concentrate used in this work [14].

The formulated rate equations are important in developing the flash ironmaking process as they will be used for analyzing the data obtained from a laboratory scale

flash reactor and also for designing an industrial flash reactor. In both reactors, natural gas is partially oxidized with industrial oxygen thereby forming a mixture of CO and H<sub>2</sub> gas, in which H<sub>2</sub> will be the main reducing agent. The reduction kinetics by each gas was determined before investigating the reduction rate with H<sub>2</sub> + CO mixtures.

### ***Reduction Kinetics in Temperature Range 1130–1350 °C***

For each experiment, the reduction degree was calculated based on the amount of removed oxygen from the sample before and after reduction. Magnetite reduction by hydrogen was determined to follow the nucleation and growth kinetics equation with the Avrami parameter  $n = 1$ . The dependence on the H<sub>2</sub> gas partial pressure was found to be of the first order with activation energy of 193 kJ/mol. The complete rate equation obtained for the reduction of magnetite with hydrogen in the temperature range 1150–1350 °C was

$$[-\ln(1 - X)] = 8.65 \times 10^6 \times e^{\frac{-193,000}{RT}} \times \left[ p_{\text{H}_2} - \frac{p_{\text{H}_2\text{O}}}{K_{\text{H}_2}} \right]_{\ln} \times t \quad (1)$$

where  $X$  is fractional removal of oxygen combined with iron,  $R$  is the gas constant 8.314 J/mol K,  $T$  is temperature in K,  $p$  is partial pressure in atm,  $K_{\text{H}_2}$  is equilibrium constant for the hydrogen reduction of wustite,  $t$  is time in s and  $\ln$  stands for logarithmic mean.

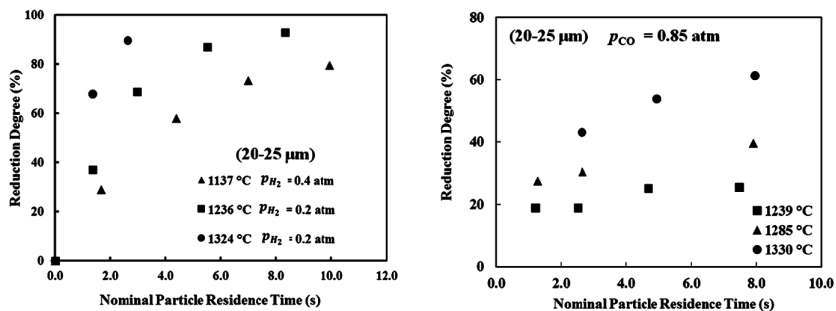
The reduction rate by CO was much lower than by hydrogen. The CO reduction also followed the nucleation and growth model with the Avrami parameter  $n = 0.4$ . The Avrami parameter is typically greater than 1, but there are examples of reactions with  $n$  less than 1, in which the nuclei growth rate decreases with growth [15]. Wunderlich [16] has analyzed a large amount of data on the rates that follow the Avrami equation, and reported that the Avrami parameter can range from lower than 1 to greater than 6.

The dependence on CO partial pressure was found to be of first order and the activation energy was 479 kJ/mol. The complete rate equation obtained for the reduction of magnetite with carbon monoxide gas in the temperature range 1150–1350 °C was

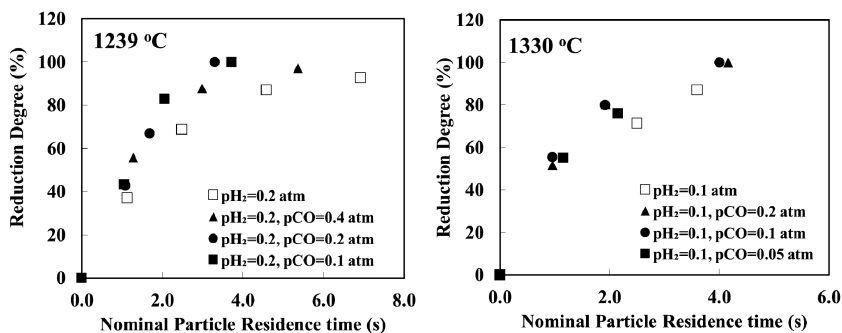
$$[-\ln(1 - X)]^{1/0.4} = 3.41 \times 10^{14} \cdot e^{\frac{-479,000}{RT}} \cdot \left[ p_{\text{CO}} - \frac{p_{\text{CO}_2}}{K_{\text{CO}}} \right]_{\ln} \cdot t \quad (2)$$

in which all other symbols have been defined after Eq. (1) except that  $K_{\text{CO}}$  stands for the equilibrium constant for the reduction of wustite by CO.

In both cases, there was no effect of particle size on the reduction rate within the size range tested (20–53 μm). The most likely reason for the absence of size effect is that the particles experience thermal stress and develop cracks of similar



**Fig. 1** Reduction degree of magnetite as a function of residence time by  $H_2$  and CO singly under different conditions in the temperature range 1130–1350 °C



**Fig. 2** Reduction degree of magnetite as a function of residence time by  $H_2 + CO$  mixtures under different conditions in the temperature range 1200–1350 °C

dimensions when rapidly heated as they are fed into the reactor at a high temperature. The reaction rate thus depends on the dimension of the solid between the cracks and no longer on the original size. Figure 1 shows some of the results obtained from the experiments.

These rate equations were used to develop a rate equation for the reduction kinetics by  $CO + H_2$  gas mixtures. The presence of CO increased the reduction rate to be higher than the sum of the rates by individual gases. The results obtained are shown in Fig. 2.

### ***Reduction Kinetics in Temperature Range 1350–1600 °C***

The 1st order model in term of the fraction of solid remaining unreacted, equivalent to the nucleation and growth kinetics with  $n = 1$ , best describes the reduction kinetics of magnetite concentrate by  $H_2$  in this temperature range. The reaction

kinetics had a first-order dependence on the hydrogen partial pressure. Particle size had a significant effect on the reduction, as expected for the reaction of a molten/fused sphere. The activation energy was 177 kJ/mol. The complete rate equation obtained for the reduction of magnetite with hydrogen gas in the temperature range 1350–1600 °C is

$$[-\ln(1 - X)] = 4.2 \times 10^7 \times e^{\frac{-177,000}{RT}} \times (d_p)^{-1} \left[ p_{H_2} - \frac{p_{H_2O}}{K_{H_2}} \right]_{lm} \times t \quad (3)$$

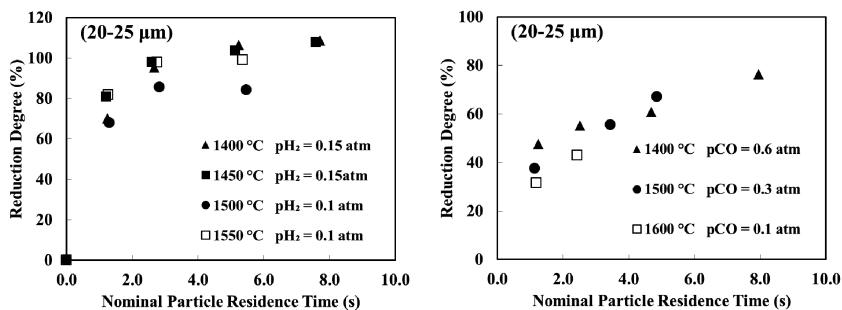
where  $R$  is 8.314 J/mol K,  $T$  is in K,  $d_p$  is the particle size in  $\mu\text{m}$ ,  $p$  is in atm, and  $t$  is in s.

In the case of reduction by CO, the nucleation and growth model also described the reduction kinetics. Similarly to the lower temperature range, an Avrami parameter  $n = 0.5$  was found to best describe the results. The dependence on CO partial pressure was found to be of the first order and the activation energy was 49 kJ/mol. The results showed the same dependence on particle size as in the case of reduction by hydrogen, which is consistent with the fact that the size dependence originates from the geometrical factor. The complete rate equation obtained for the reduction of magnetite with carbon monoxide gas in the temperature range 1350–1600 °C is

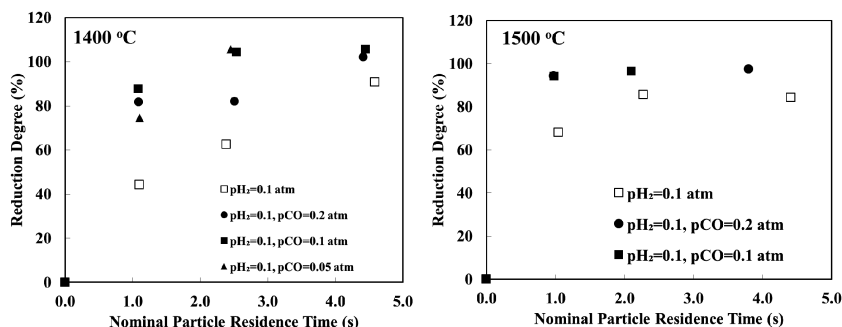
$$[-\ln(1 - X)]^{1/0.5} = 4.2 \times 10^2 \times e^{\frac{-49,000}{RT}} \times (d_p)^{-1} \left[ p_{CO} - \frac{p_{CO_2}}{K_{CO}} \right]_{lm} \times t \quad (4)$$

where  $R$  is 8.314 J/mol K,  $T$  is in K,  $d_p$  is in  $\mu\text{m}$ ,  $p$  is in atm, and  $t$  is in s.

Figure 3 shows some of the results obtained from the experiments. These rate equations were used to develop a rate equation for the reduction kinetics by CO + H<sub>2</sub> gas mixtures. The increase in reduction rate due to the presence of CO over the sum of the rates by individual gases was even greater in the higher temperature range than in the lower temperature range, as shown in Fig. 4.

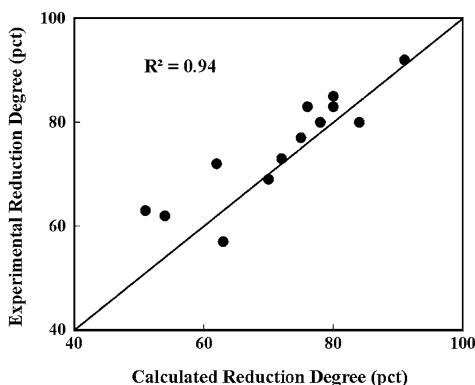


**Fig. 3** Reduction degree of magnetite as a function of residence time by H<sub>2</sub> and CO singly under different conditions in the temperature range 1350–1600 °C



**Fig. 4** Reduction degree of magnetite as a function of residence time by  $H_2 + CO$  mixtures under different conditions in the temperature range 1350–1600 °C

**Fig. 5** Comparison between the calculated reduction degrees by CFD versus experimental results [17]



## Laboratory Scale Flash Reactor

A laboratory scale flash reactor [17] was used to verify the rate expressions under an actual flash reaction condition. In this reactor, hydrogen or methane were used as the fuel/reductant by producing a non-premixed flame. Due to the high volume to surface ratio, electrical heating was used to compensate for the heat loss in the reactor. A three-dimensional computational fluid dynamics (CFD) model was developed to simulate the reduction of magnetite concentrate by hydrogen in which the fluid flow, heat transfer, and chemical reactions involved were incorporated. The governing equations for the gas phase were solved in the Eulerian frame of reference, while the particles were tracked in the Lagrangian framework. The partial combustion of  $H_2$  injected through a non-premixed burner was simulated and the temperature profiles and reduction degrees obtained from the simulations had a satisfactory agreement with the experimental measurements, as shown in Fig. 5. The magnetite reduction by  $H_2 + CO$  mixtures produced from the partial oxidation of natural gas is now under investigation.

## Mini-pilot Scale Flash Reactor

A mini-pilot flash reactor was built in the University of Utah for the flash reduction of magnetite concentrate. The new reactor has an inner diameter of 0.8 m and a reaction zone length of 2.3 m. This reactor has an 18 cm thick refractory layer to minimize heat loss. The reactor is preheated by full combustion of natural gas with oxygen through a preheat burner with a heating rate of 90–95 °C/h. The operating temperature range is 1200–1550 °C.

The new reactor is controlled completely with an automated system with a high built-in safety measures. The reactor vessel is designed to withstand a pressure up to 3.4 atm, and is equipped with an off-gas duct with a rupture disk that allows the gas to escape from the reactor if the pressure inside the reactor exceeds 0.7 atm. The concentrate feeding rate is 2–5 kg/h.

The reactor is equipped with a main burner by which natural gas is partially combusted with oxygen to produce a mixture of  $H_2$  and CO reducing gases as well as  $H_2O$  and  $CO_2$ . This main burner produce a swirl in the produced gas for better distribution of the reducing gases and heat in the reactor as well as increasing the residence time of the particles. When the main burner is used, the off-gas is flowed through a flare stack where all the remaining  $H_2$  and CO gases are completely burned before releasing to the atmosphere. An industrial gas analyzer is used to measure the contents of  $H_2$ , CO,  $CO_2$ ,  $O_2$  and  $CH_4$  in the gas stream; to ensure the complete combustion during the preheat mode; and to check the  $H_2$  and CO amounts produced during the experiment by the main burner.

The preheating and main burner components are water cooled to avoid any damage to them during the experiment. Alternative powder feeding ports are available on the roof of the reactor for different feeding modes.

## Conclusions

The reduction kinetics of magnetite concentrate particles by  $H_2$ , CO and  $H_2 + CO$  gas mixtures was investigated in the temperature range of 1150–1600 °C. The rate equation of the magnetite reduction by each gas singly was obtained. The nucleation and growth model was used to describe the reduction kinetics by each gas in two temperature ranges of 1150–1350 °C and 1350–1600 °C. For magnetite reduction with CO gas, an Avrami parameter of less than 1 was determined, indicating a possible restriction on the nuclei growth by diffusional effects in them. These rate equations were used to formulate a rate equation for reduction by  $H_2 + CO$  mixtures. A laboratory scale flash reactor was used to verify the kinetics results under actual flash reaction conditions in which  $H_2$  or natural gas is partially combusted with oxygen to produce the reductant and heat. CFD simulation was used for comparing the kinetics model to the experimental results and good agreement was achieved. A mini-pilot flash reactor that can operate in the

temperature range 1200–1550 °C has been built and commissioned. The new reactor is preheated by complete combustion of natural gas with a heating rate of 90–95 °C/h. The magnetite concentrate feeding rate ranges from 2 to 5 kg/h. Experimental tests using this mini-pilot reactor is scheduled to begin in the near future.

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