

Physical Modeling of the Mixing Time in the IronArc Pilot Plant Reactor

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Abstract

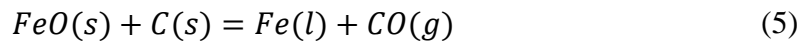
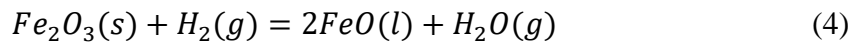
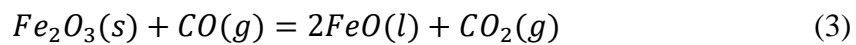
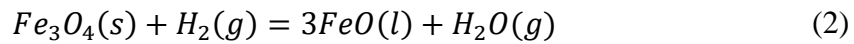
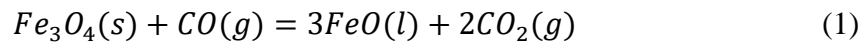
Mixing time measurements were carried out in a pilot-scale reactor of the IronArc process based on conductivity measurements. During the experiment, compressed air was injected through submerged nozzles into the water and a saline solution was added as a tracer. Thereafter, the time for the tracer to homogenize in the water was determined, i. e. the mixing time. The overall results showed that the mixing times for a 95% and a 99% homogenization degree were 8.5 s and 14 s, respectively. The mixing time of 8.5 seconds for a 95% degree of homogenization in the pilot-scale reactor was also in line with mixing time results reported earlier for trials performed with slag, as well as results for earlier small-scale physical model experiments.

Keywords: IronArc, Mixing time, Conductivity measurements, Pilot plant trials

Introduction

IronArc is a new technology for pig iron production, which is developed by ScanArc in Hofors, Sweden [1]. The aim with this emerging technology is to reduce the CO₂ emission and energy consumption, compared to the existing blast furnace technology.

Today, this process exists in a pilot scale, but the future goal is to continuously scale up this process into an industrial scale furnace. In short the process can be described as follows. First, the material is charged, melted and a slag is created (consisting of hematite and magnetite) in a cylindrical reactor: During this step a hot carrier gas is injected through a plasma generator (PG). The injected gas is a mixture of Air and LPG (Liquefied Petroleum Gas), which is heated to a temperature of approximately 20000°C in the PG. Thereafter, the gas is injected into the slag with a temperature of 3500 - 4000°C. However, the experience is that the gas will obtain the slag temperature fast. The created CO- and H₂-gas, created from combustion of the injected gas mixture is used as the reductant for the first reduction step to transform hematite and magnetite to wustite. Then, the FeO slag will be further reduced into Fe by using carbon as the reductant. The reactions that occur during this reduction process are given in equations (1)-(5):



There are many advantages with this new process compared to the blast furnace process. Specifically, the PGs use electric energy, which gives the possibility to use input energy from renewable resources. Also, the shape and physical properties of the charged material is not of big importance due to that all of the material is melted in the reactor. Furthermore, preliminary calculations have shown that an Industrial scale IronArc process have the possibility to reduce the energy consumptions as well as the CO₂ emissions compared to existing technologies [1].

Since this is a new process there is not many investigations that have been made. However, this process has been investigated in three earlier studies [2-4]. In the first study, physical modeling experiments were performed and the mixing times and penetration depths were determined under different conditions [2]. The mixing time for a 95% degree of homogenization was determined as 7.6 seconds when one inlet was used. This was compared to the mixing time obtained from 3 gas inlets using the same flow rate. It was shown that 3 inlets gave a much calmer surface compared to the case when using one gas inlet. Furthermore, it was shown that the average mixing times were increased by 15.8% and 17.6%, respectively, for a 95% and 99% degree of homogenization in the three-inlet case compared to the one-inlet case. In study number two, the penetration depth of the injected gas was investigated numerically [3]. It was

determined that the penetration depth of the gas in the slag reaches approximately to the center of the cylindrical pilot plant reactor. This, in turn, gives a good energy usage of the injected gas as well as less refractory wear. In the third study, the mixing time was determined by using industrial trials in the pilot plant reactor during operation of the process [4]. MnO_2 powder was used as a tracer and the mixing times were investigated by taking continuous samples of the slag, from which the MnO amount was determined. The results showed that it was possible to get an estimation of the mixing time and that it was equal to or less than 8 seconds.

For several metallurgical processes (AOD, ladle, converters etc) gas blowing is used through a top lance, submerged injected through bottom plugs or horizontally injected through nozzles. In all of these the processes the mixing and stirring is important, since the injected gas creates stirring in the bath, which increases the kinetics, distributes the reduction agents, the refines the bath, as well as for the inclusion removal. Furthermore, the mixing time is often used as a measurement of the mixing efficiency in liquid baths [5-16]. Typically, the physical water modeling is made in a small scale version of the actual full scale industrial process in all of these cases referred to. Furthermore, in the literature there is no information regarding water modelling in the actual converters or pilot plant converters.

In the current study the mixing time was investigated in the IronArc pilot plant reactor by conductivity measurement when the pilot plant was partially filled with water. This was done in order to understand the fluid flow and stirring of the process, when using known parameters of the liquid water and injected gas. Also, this investigation complements the results from the previous studies [2] and [4] and helps to further validate the results of the mixing time in the reactor.

Methodology

The industrial test was performed similarly as for the conductivity experiments performed in the 1/3 scaled acrylic plastic model [2]. It was only possible to perform one trial. Also, the main differences from the small scale physical water model experiments were that the probes were positioned at the same side and also that the tracer were added on the right side of the nozzle, where in the small scale experiments it was added on the left side of the nozzle. It was possible to perform this measurement due to that the reactor was rebuilt and during that period it was possible to fill it with water and perform mixing time experiments. Specifically, the experiments were done before the reactor was charged with slag and hence no freeze lining were present. Water was added to the pilot plant reactor so that it was partially filled with water. During the experiment, the conductivity was measured in the water during the submerged gas blowing before, during and after a 20wt% NaCl solution was added. The room temperature gas was injected with a flow rate of 230 Nm³/h through a side wall nozzle submerged under the surface of the water. The conductivity was continuously measured and logged in the water and thereby the concentration at the measurement points in the reactor was determined throughout the experiment. The experimental setup can be seen in figure 1.

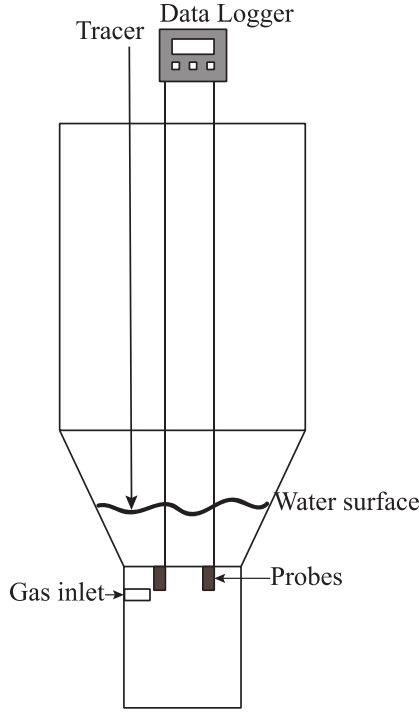


Figure 1. Experimental setup for the conductivity measurements performed in the IronArc pilot plant reactor

This concentration of tracer was as similar as possible to the conductivity measurements performed in the small-scale acrylic plastic model [2]. The mixing time was determined as the time for the measurement points to reach a homogenization degree that was 95% of the final conductivity value in the water. The time to reach a 99% degree of homogenization was also determined. In other words, this was determined as the time to reach the uniformity value, H , to reach values between 0.95 and 1.05 for a 95% degree of homogenization. In addition, the time to reach a 99% homogenization degree in the bath was determined. In that case it represents be the time for H to reach values between 0.99 and 1.01. The definition of H can be seen in Equation (6):

$$H = \frac{C(t)}{C_f} \quad (6)$$

where H is the degree of homogenization, $C(t)$ is the concentration at time t , and C_f is the final concentration value in the water after a complete homogenization.

The mixing time to reach both 95% and 99% degrees of homogenization was based on the average time for both probes to reach this degree of homogenization, according to equation (7):

$$t_{mixing} = \frac{t_{p1} + t_{p2}}{2} \quad (7)$$

where t_{mixing} is the mixing time, t_{p1} is the mixing time for probe 1, and t_{p2} is the mixing time for probe 2. This was applied for both 95 and 99% degrees of homogenization, respectively. The probes were fastened onto anchoring's that were welded onto the inside of the reactor. The tracer was poured from 2 buckets at the top of the reactor on the right side of the gas inlet. The tracers from both buckets were added at approximately the same location in the water. More information regarding the tracer and the gas flow are provided in table 1.

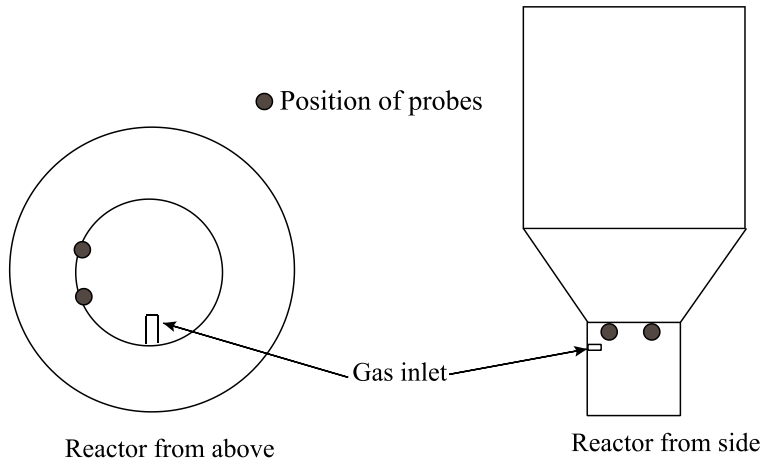


Figure 2. Position of conductivity probes in the IronArc pilot plant reactor.

Amount water(l)	Amount NaCl(g)	Amount of water solvent(l)	Flow rate (Nm³/h)
~740	2400	10	230

Table 1: Setup for industrial mixing time test by conductivity measurements.

Results and discussion

The results from the conductivity measurements can be seen in the Figure 3. This figure shows the conductivity values for probes 1 and 2. As soon as the sodium chloride tracer was added into the water a rapid response in conductivity was found. The conductivity increased quickly for both probes and the final value was reached after seconds from the time of the tracer addition. The conductivity values over time differ for the probes, as well as the time before the final value is reached. This is expected, since the probes are located at different positions, i.e. the flow field is different at these positions. Therefore, the average value for when the two probes had reached the respective homogenization degree was used. Figures 3 and 4 show the normalized conductivity values for both probes. The time to reach a 99% degree of homogeneity at the measurement points in the water was reached after approximately 14 seconds. For a 95% degree of homogenization, it took 8.5 seconds to reach the time when an

average value was reached at both probes. Hence, according to these results the mixing times are 8.5 seconds to reach a 95% degree of homogenization and 14 seconds to reach a 99% degree of homogenization.

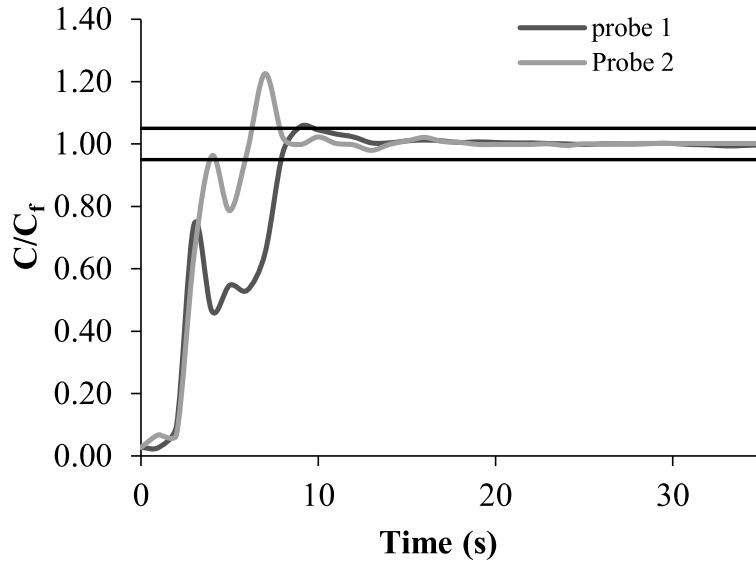


Figure 3: Normalized conductivity values for the two probes

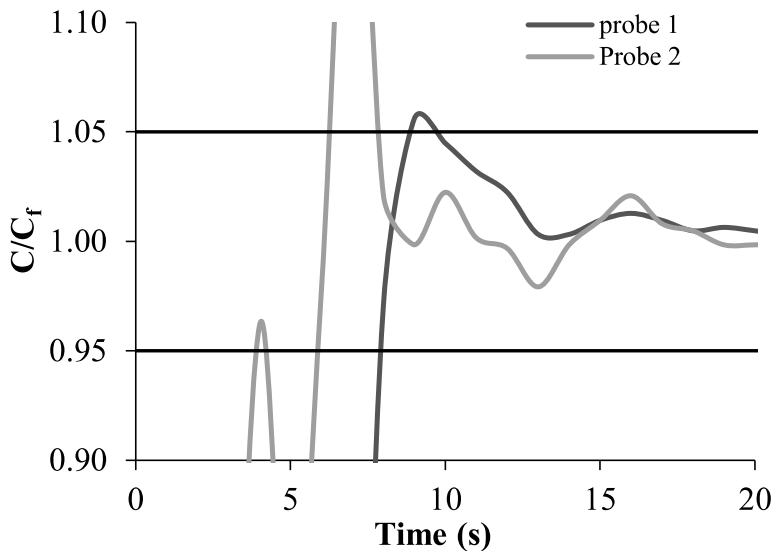


Figure 4: Normalized conductivity values for the two measurement probes. Inside the horizontal lines at 1.05 and 0.95 represents the area where the concentration of the tracer is within a 95% degree of homogenization.

The results in Figures 3 and 4 are very interesting, since they can be compared with the results from the 1/3 scaled acrylic plastic model where mixing time experiments were performed [2]. However, there are some differences between the small-scale conductivity experiments compared to this pilot-scale investigation. Firstly, the probes were positioned at the same side

(left of the gas inlet) in the pilot scale but not in the small scale. Moreover, the saline solution tracer was added at different places (opposing sides of the gas inlet), which possibly may affect the results of how the sodium chloride solution is distributed in the water. The velocity of the water flow is most likely not similar at these two different places, due to the overall irregularity when observing the water movements. Also, the water was falling a longer distance from the top of the reactor to the water surface. This, in turn will, result in a higher velocity of the water, which affects the tracer distribution in the water bath. The probes position is not at the exact same places in the pilot-scale and the small-scale experiments. Also, in the industrial test the two probes were placed at the left side of the gas inlet. This can be compared to the small-scale model, where the probes were positioned at respective side of the inlet, one on the left and one on the right side of the inlet.

Since the freeze lining in the reactor were not in place, there were bolts sticking out from the inner reactor walls, which is not the case in the water model. These bolts probably won't affect the flow to a large extent, but it is still worth to mention since their effect of the flow is unknown. Another difference is that the flow rate of $230\text{Nm}^3\text{h}^{-1}$ that was used in the industrial test is slightly lower than the $265\text{Nm}^3\text{min}^{-1}$ flowrate used in the small-scale physical model of 282Nlmin^{-1} is scaled from. However, the calculation of the flow rate in the pilot reactor was based on slag and not on water, as the liquid medium in the pilot plant. Furthermore, the flow rate difference between the small-scale and the pilot plant scale is a 15% higher flow rate for the pilot plant. The mixing time difference was 10.6% faster for a 95% degree of homogenization in the pilot reactor compared to the small-scale reactor. Furthermore, mixing time was 27% shorter for a 99% degree of homogenization for the pilot-scale compared to the small-scale reactor. According to this comparison, the 10% difference in mixing time for a 95% degree of homogenization is closer to the 15% difference in flow rate than the 27% difference in mixing time for the 99% degree of homogenization.

Overall, the small-scale experiments were done six repeated times and the conductivity measurements in the pilot reactor were only done one time. It would have been useful if it would have been possible to carry out more pilot experiments to get a clearer picture. Nevertheless, there are small differences between the conductivity measurements in the pilot plant and the small-scale model. The mixing time for a 95% degree of homogenization differs by approximately only 1 second between the pilot-scale and small-scale experiments. This is a small difference that strengthens the result and conclusion that the mixing time in the pilot plant is below 10 seconds for a 95% degree of homogenization. The present mixing time results can also be compared to the mixing time results from another earlier investigation [4]. In that investigation a tracer powder was added to the slag and thereafter samples were continuously taken. Based on the chemical composition determinations of these slag samples, the mixing times were determined to be less than 10 seconds. These results are in line with our results. Overall, our results show that the mixing time in the pilot plant for a 95% degree of homogenization is below 10 seconds.

Conclusions

The mixing time was determined in the IronArc pilot plant by conductivity measurements in the actual reactor. This was possible during a reconstruction of the pilot plant. During the experiment, the pilot plant was partially filled with water and thereafter compressed air was injected through submerged nozzles. A saline solution was added as a tracer and the time for the tracer to homogenize in the water was determined, i. e. the mixing time. The following conclusions can be drawn from this experiment:

- The mixing times were determined for two different homogenization degrees. It was 8.5 seconds for a 95% degree of homogenization and 14 seconds for a 99% degree of homogenization.
- Compared to earlier investigations made in a 1/3 scale acrylic plastic model of the pilot plant, the small-scale model had a 10% shorter mixing time for a 95% degree of homogenization for a flow rate that corresponded to 265 Nm³/h. This was slightly higher than the 230 Nm³/h that was used for this investigation, which is 13 % lower than the flow rate of 265 Nm³/h.
- The mixing time of 8.5 seconds in the pilot-scale reactor was also in line with a mixing time experiment that was performed in an earlier study, where the mixing time was less than 10 seconds for this reactor.

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