Model Study of Bath Mixing Intensity in Ferroalloy Refining Processes

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Abstract

An experimental study is performed to investigate the bath mixing intensity induced by a high-strength submerged jet in a bottom blown air-stirred one-seventh water model of CLU (Creusot-Loire Uddeholm) reactor using three different tuyere configurations. Experimental results have been discussed in terms of the mass transfer rate between two immiscible liquids, paraffin and water simulating slag and metal, respectively.

In the model the transfer of benzoic acid, from a gas stirred water bath, to paraffin oil is investigated as a function of the gas injection parameters. The bath mixing intensity was characterized by the value of the mass transfer rate constant. The rate constant of mass transfer between metal and slag was found to increase with gas injection rate and decrease with bath height.

Introduction

Most of the chemical reactions taking place in gas stirred metalurgical vessels are controlled by liquid phase mass transfer between metal and slag. For calculation of the rates of these reactions, information on the two phase mass transfer parameter is crucial.

Although there are number of studies done on liquid/liquid mass transfer in gas stirred ladles, top and combined blown metallurgical vessels, there is little reported on bottom blown stainless steel making and ferroalloy refining reactors. Despite several studies done, question still exists concerning the optimum stirring conditions to achieve optimum liquid phase mass transfer since the various process and technological parameters such as metallurgical characteristics at turndown, the process of slag formation during gas injection and the rates of carbon, phosphorus removal as well as sulphur elimination are controlled mostly by the extent of liquid phase mixing[1-4]. Cold model studies of this nature are required in order to investigate the effect of gas flow rate, bath height, location and number of tuyeres on the mass transfer rates of liquid/liquid as well as gas/liquid.

In literature, most of the previous studies were concerned with ladles where the gas injection rates are much less than those of high-strength bottom , top or combined blown metallurgical vessels. However, among some of the studies related to vessels where high gas flow rates used, Paul and Ghosh[5], in an attempt to investigate the differences in mixing and mass transfer rates between LD and Q-BOP furnaces on the basis of cold model experiments, correlated the mixing time with gas flow rate and number of tuyeres. They also reported that the mass transfer for bottom blowing was higher than that of top blowing. In recent studies[6,7] the mixing conditions in a top and combined blown steelmaking bath were successfully simulated in a water model by measuring the transfer rate of a tracer from water to a simulated slag phase. In a more recent study by Akdogan and Eric[8] , the mixing intensity induced by gas jets during ferroalloy refining has been simulated by a water model of CLU. They found that the mixing time to decrease with increasing gas flow rate and increase with bath height.

In a gas stirred physical model of a steel ladle, Kim and Fruehan[9] argued that the single phase mixing time is not a good parameter in predicting the two phase mass transfer. They also found a critical gas flow rate which was a function of tuyere position, slag volume.

The present study was therefore undertaken to investigate the effect of bath stirring on the metal-slag reactions of high-strength bottom blown processes and to shed light on degree of dependence of the mass transfer parameter on operating system variables such as bath height and tuyere pattern.

Experimental

The experimental set-up employed a cylindrical clear PVC tank, which is one-seventh model of a CLU converter tapered from 0.5m in diameter at the top to 0.35m in diameter at the bottom. It was filled with distilled water. Figure.1 is a schematic illustration of the experimental set-up. Air was purged into the bath through three nozzles placed at the bottom of the tank. Three different nozzle orientations, namely Off-center, Center, and Triangular, were employed as illustrated in Figure 2.

For the model study, the dimensions of an actual 60t CLU converter were scaled down by a factor of 7. During experiments the air flow rates varied from 0.00599 m^3/sec to 0.01081 m^3/sec. The modified

Froude number was considered as the similarity criterion to correlate the gas flow rate between the scale model and full scale system. The modified Froude number was in the range $4x10^3$-$1x10^4$.

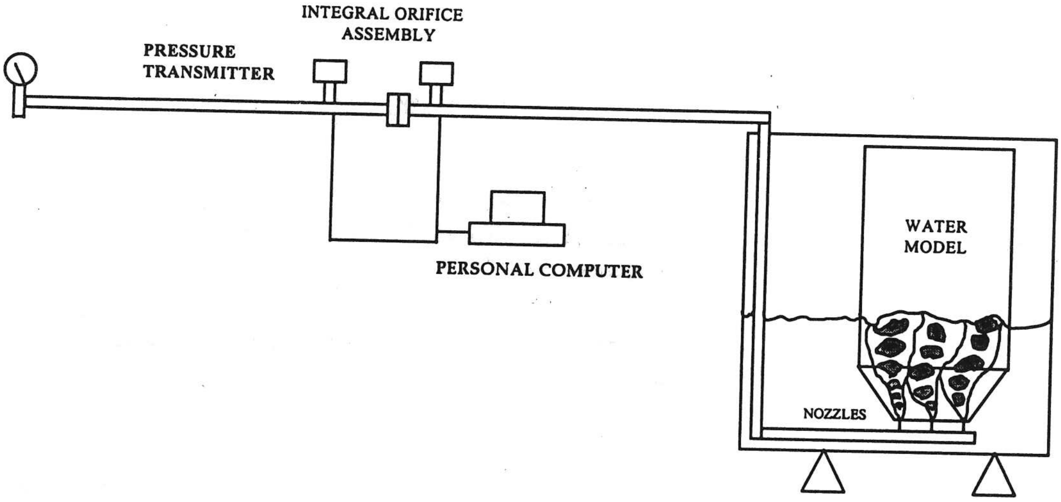

Fig. 1. Schematic representation of experimental apparatus.

Mass Transfer Measuring Technique

In the present work, the anology of pure water to liquid metal and light paraffin oil to that of slag was used. The model bath consisted of benzoic acid solution. Benzoic acid was dissolved in water and the concentration was kept constant at between 1.5 and 2 g/l for all experimental runs. The model metal bath depth was varied from 0.20m to o.29m and the simulated slag layer was 0.02m. Air was injected through three nozzles inserted at the bottom plate. At predetermined time intervals about 25ml of solution was taken out and titrated against a standard KOH solution. The transfer of benzoic acid from water to oil phase was followed for about 20 minutes. For each experiment, fresh solution of benzoic acid and paraffin oil was used. Four experiments for each operating condition were performed and the mean value of final concentration of Benzoic acid was taken. The location of the tracer sampling was also kept fixed at a position where the sampler was in the simulated metal phase.

In order to check the reproducibility of the measurements, experimental runs were repeated several times under identical conditions. It was found that the variation in mass transfer rates between run to run was less than 10 percent.

Results and Discussion

The transfer of of benzoic acid from water to oil phase can be expressed as[7] :

$$Ln\frac{C_t - C_e}{C_1 - C_e} = -(\frac{bA}{V})t \qquad \text{..............................} (1)$$

$\frac{bA}{V}$ is equal to the mass transfer rate constant (k) , time^{-1}. An increase in the value of (k) indicates better mixing the bath which results in faster approach to equilibrium mass transfer conditions.

C_t, C_1, and C_e are concentrations of benzoic acid at time (t), initial, and equilibrium respectively. Since it was not possible to determine experimentally the interfacial area created during the process, the mass transfer coefficient (b) could not be calculated. The mass transfer rate constant (k) was therefore determined instead to represent the results of the process of mass transfer occuring between the two immiscible phases.

In the following, the experimental results are presented according to the parameters, which were found to influence the mass transfer processes, such as gas injection rate, bath height and tuyere pattern.

Effect of Gas Injection Rate

Figures 3 to 5 illustrate the variation in fractional concentration change of benzoic acid (C_t/C_1) in water at different gas injection rates as a function of time. As seen in the figures, fractional concentration decreases with time. The decrease in (C_t/C_1) at any time becomes greater as the gas flow rate increases. It may also be noted that initially there is a continuous decrease and then the value of fractional concentration starts to level off as the process approaches to equilibrium. This observation is in agreement with those reported in literature[6,7,9]. However, the increased gas flow rates did not always increase the fractional transfer of the benzoic acid. This can be seen in Figure 4 which shows the variation of fractional transfer when the center tuyere pattern was employed for bath height at 0.23m.

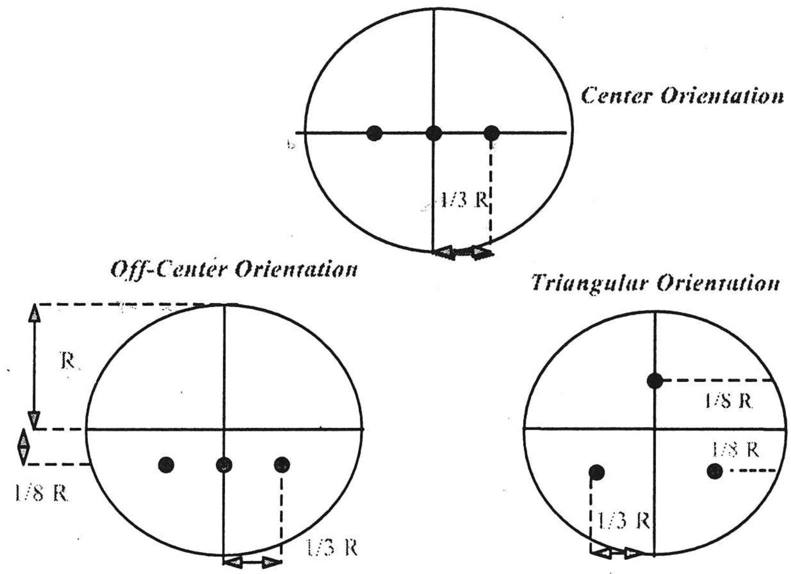

Fig. 2. Three different tuyere configuration

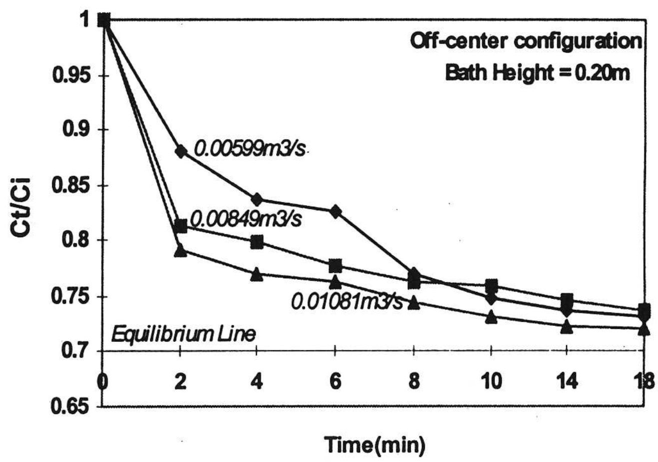

Fig. 3. Effect of gas flow rate on mass transfer as a function of time for off-center.1 tuyere configuration

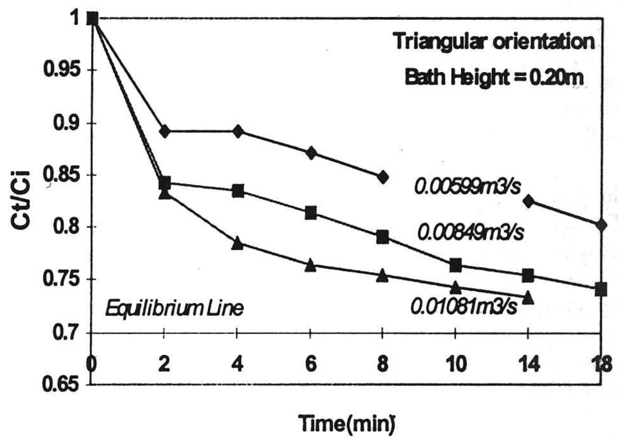

Fig. 5. Effect of gas flow rate on mass transfer as a function of time for Triangular tuyere configuration

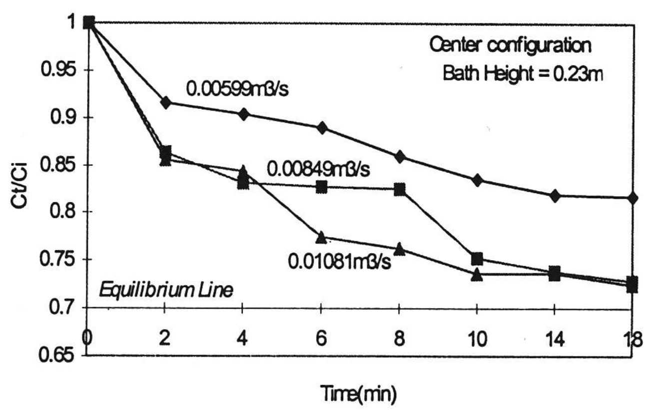

Figure 4. Effect of gas flow rate on mass transfer as a function of time for Center tuyere configuration

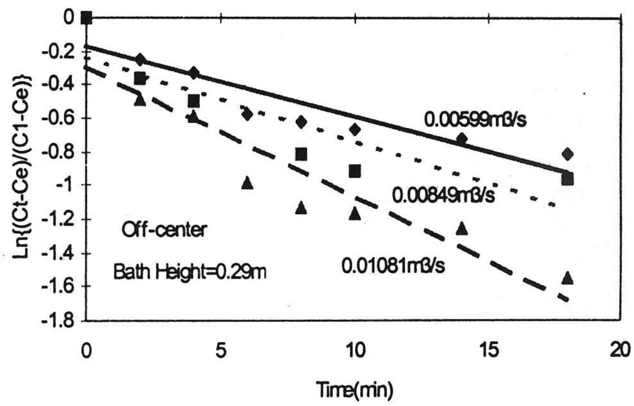

Figure 6. Relationship between LHS of mass transfer Equation (1) and time for off-center configuration

The experimental results, when plotted according to Equation 1 gave straight lines for all cases. Figure 6 shows typical plots where the least square analysis was used and the k-values obtained from the slope of the lines. As can be seen, k-values increases as the gas injection rate increases.

At low gas flow rates, it has been observed that the slag (paraffin) layer and water (metal) phase were two distinguishable layers and considerable foaming took place. As the gas flow rate is increased, the paraffin droplet formation in the water phase increased. Slag and water phase began to look like turbulent , uniformly mixed-single layer. This type of change in the slag behaviour corresponded to the increase in the reaction rates. This can be deduced from the above figure showing that as the gas injection rate increases, the slopes increases and thus the mass transfer rate becomes faster.

It has been reported in many studies[6,10,11] that the sudden increase of reaction rate between slag and molten steel as bottom gas flow rate exceeds a certain value was believed to associate with abrupt emulsification of slag in steel.

Effect of Bath Height on Mass Transfer

Figures 7 to 9 show the variation of the fractional transfer of benzoic acid from water to oil phase with respect to bath height. As can be seen, for a given gas flow rate the mass transfer decreases with increasing bath height. This finding is also in line with the previous work by Akdogan and Eric[8] on the effect of bath height on the mixing time which showed that the mixing time increased with increasing bath height.

In Figure 10 the variation of Left Hand Side of the mass transfer Equation (1) with time is compared with different bath heights. In general slopes of the lines increase with decreasing bath height. Visual observations indicated that as the bath height decreased the oil layer broke into the droplets more easily due to stronger circulation inside the oil layer and then almost complete dispersion of oil droplets in the water phase occured. That was considered to play a major role in increasing the mass transfer rates. It is generally believed that the large interfacial area caused by the dispersion of one liquid phase into the other is responsible for the fast overall reaction rates found in BOF and Q-BOP processes.

Effect of Tuyere Configuration on Mass Transfer

Figure 11 shows that for a given gas injection rate and bath height almost the same mass transfer rates were observed just after gas injection started. However, after 2 minutes, off-center configuration was more effective in mass transfer than the other two arrangements.

This is also in very good agreement with the results of previous investigation[8] in which the investigators argued that as the position of the tuyere moved from the center to the wall side of the vessel the mixing times decreased.

Variation of Mass Transfer Rate Constant(k) with Gas Injection Rate

The rate constant (k) for the transfer of benzoic acid from water to oil phase was calculated from the graphs showing the relationship between LHS of the Equation (1) as a function of time. The value of (k) was determined by regression analysis and the values of correlation coefficients varied from 0.96 to 0.99.

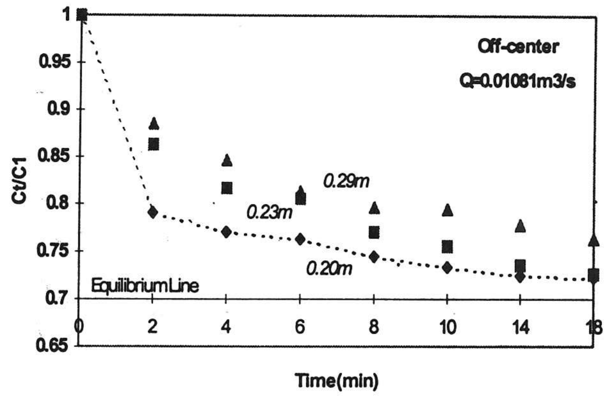

Fig. 7. Effect of bath height on mass transfer as a function of time for off-center configuration

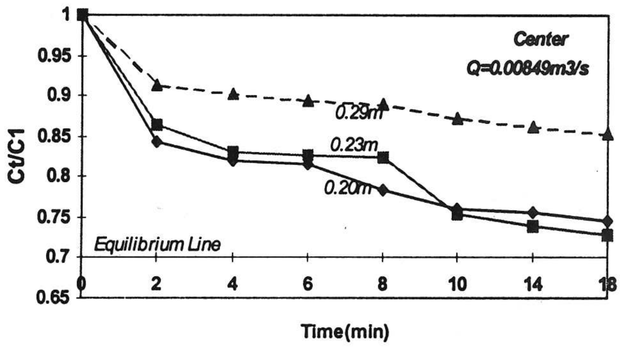

Fig. 8. Effect of bath height on mass transfer as a function of time for center configuration

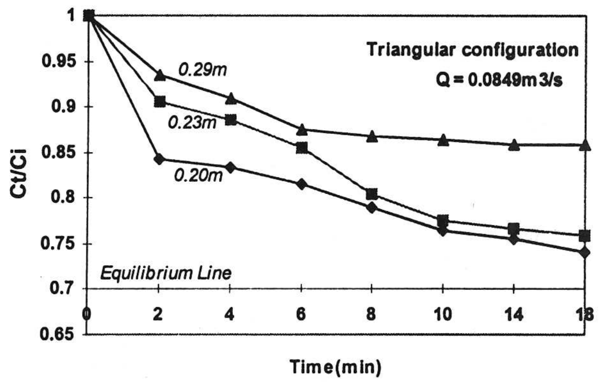

Fig. 9. Effect of bath height on mass transfer as a function of time for Triangular configuration.

In Figure 12 values of (k) are plotted against the gas injection rate for different bath heights of center tuyere configuration. It can be noted that k-values increases as the gas injection rate increases for bath heights 0.20m and 0.23m, however, the degree of increase for 0.23m is higher than that of the bath height 0.20m when the gas flow rate increases to 0.00849m3/s. It might also deduced that at bath heights higher than 0.23m any increase in gas injection rate would adversely affect the mass transfer rates.

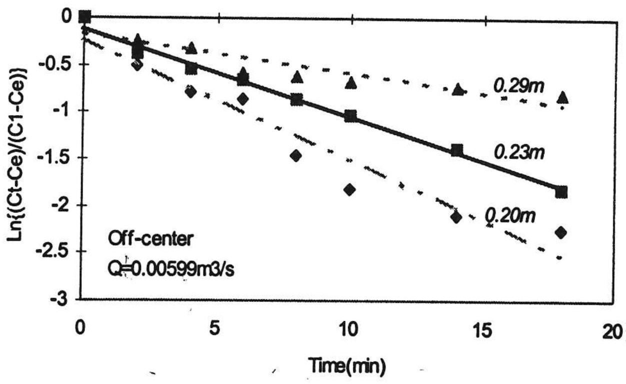

Fig. 10. Relationship between LHS of mass transfer Equation (1) and time at different bath heights for off-center configuration.

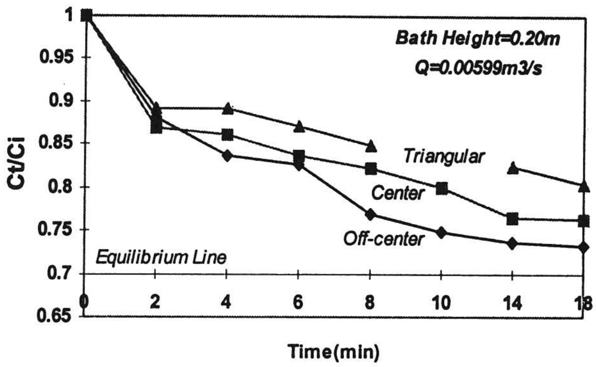

Fig. 11. Effect of tuyere pattern on mass transfer as a function of time

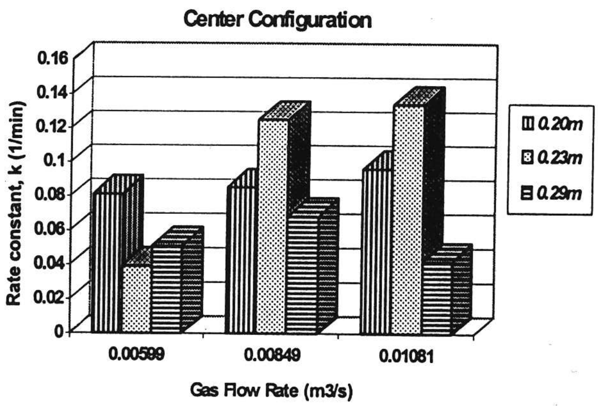

Fig. 12. Effect of gas injection rate on the mass transfer rate constant with respect to bath height.

Conclusion

A cold model study using 1/7 scale of a CLU vessel, stirred with air blown from the bottom of the vessel through three straight circular nozzles, was conducted as to investigate the influence of gas injection parameters on the mass transfer of benzoic acid from water to oil caused by high-strength bottom gas injection. It has been found that the transfer of benzoic acid depends on the gas injection rate, bath height and tuyere configuration. From the fractional concentration change of transferring species with respect to time, the value of the mass transfer rate constant was determined. The rate constant was found to increase with increase in gas injection rate, with decrease in bath height. It has also been observed that as the tuyere configuration becomes off-centered the mass transfer rate constant tends to incraese. From these results, it can be inferred that the mass transfer rate can be effectively controlled by varying the tuyere configuration and gas injection rate at a constant bath height. However, at a constant gas injection rate, the time to reach equilibrium conditions might be shortened by using off-center tuyere pattern at moderate bath heights.

The work is in progress to simulate the transfer of sulphur from metal phase to slag in refining of ferrochromium. It appears that there is a good correlation between the predictions of the water model and practical desulphurization data.

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