Mixing Time in a Side-Blown Converter

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The mixing time in a side-blown converter was studied using physical modelling. Water was used to simulate steel and a KCl tracer was added during the experiments. Thereafter, the mixing time was determined experimentally by measuring the electrical conductivity in the water bath. Experiments were done for two bath diameters of 200 mm and 300 mm, respectively. Furthermore, for gas flow rates between 30 cm³/s and 800 cm³/s as well as bath heights ranging from 106 to 314 mm. The mixing times were also calculated based on an expression involving the Strouhal and Reynolds numbers. The experimentally determined mixing times were found to be within ±20% of the theoretical values, which is considered to be good in physical modelling. Overall, the mixing time was found to be influenced by the gas flow rate and the vessel diameter, but not by the bath height.

KEY WORDS: physical modeling; mixing time; converter; side-blown; conductivity measurements.

1. Introduction

Several chemical reactions take place during the metallurgical treatment in Argon Oxygen Decarburization (AOD) converters. More specifically, these take place during the decarburization, desulfurization and recovery of valuable metals from the slag. The mixing of the steel bath will to a large degree influence the kinetics of these reactions. Thus, by obtaining more knowledge regarding the kinetics the productivity of the AOD process could be improved.

In the AOD process physical modeling of the mixing time on the actual system is difficult to perform. In, for example ladles, sampling of steel at different positions in the bath have been performed by Söder et al.1) in order to study concentration gradients, based on the composition determinations. This in turn provides information on the mixing time. However, during production these kinds of measurements would be very difficult to carry out in an AOD converter. It would be necessary to make measurements while the converter is in the sampling position, i.e. tilted. Maybe it would be possible to develop a sampling device connected to an automatic sampling device in order to sample at different positions, but it would be expensive.

An alternative to plant trials is to carry out physical modeling to obtain some new fundamental information on mixing times. Today, it is well known that this may be done by using, for example, a de-ionized water bath, a tracer addition and an electrical conductivity sensor. Here, water and molten steel have approximately the same kinematical viscosity, which makes water a good substitute for the steel phase. Usually a tracer in form of, for example, a chloride-based reagent is added to the water. Thereafter, the electrical conductivity of the water is measured to study the mixing of the tracer with time.

Zhu et al.2) has studied side-blown converters using physical modeling for different bath heights, bath diameters and gas flow rates. The emphasis was on the nozzle position and its effect on the resulting fluid flow. They also studied the mixing time for the different reactors in metallurgical vessels. In addition, Wei et al.3–7) have done some work to show the influence of tuyere position, numbers of tuyeres and gas flow rate in the AOD converter. Overall, this research group has not studied the combined influence of the bath height, the vessel diameter and the gas flow rate on the mixing time. Thus, none of the previous authors have presented a relationship describing the influence of bath diameter, bath height and gas flow rate on the mixing time.

In this study, physical modeling experiments have been done in two smaller models of the AOD converter. Similar to previous studies on the mixing time, a tracer in form of a KCl-solution was added to the water and thereafter, the mixing time was determined by measuring the electrical conductivity of the bath. Finally, an analytical expression for the mixing time was developed including the influences of bath height, bath diameter and gas flow rate on the mixing time.

2. Experimental Procedure

Two transparent cylindrical models made of acrylic resin were used for the experiments. The first vessel had a diameter of 200 mm and the bath height (H₁) was varied between 106 to 207 mm during the experiments. The other vessel had a 300 mm bath diameter (D). In this vessel the bath height (H₂) was varied between 163 to 314 mm. Water was
used to simulate steel and air to simulate argon/oxygen. The gas flow rates were determined by using the Froude number to scale the rate from a full scale converter to a physical model.

The different flow rates were calculated by using the Froude number similarity criteria:

\[
Fr_{m,r} = Fr_{m,m} \quad (1)
\]

where \( Fr_{m,r} \) is the Froude number in a real production converter and \( Fr_{m,m} \) is the Froude number in the physical model.

Thereafter, the following Froude number was used to scale down the nozzle diameter:

\[
Fr_{m1} = \frac{\rho_g Q_g^2}{\rho_l g D_1^5} \quad (2)
\]

where \( \rho_g \) is the density of air, \( Q_g \) is the gas flow rate, \( \rho_l \) is the density of water, \( g \) is the gravitational constant and \( D_1 \) is the nozzle inner diameter. In addition, the following Froude number was used to scale the gas flow rate:

\[
Fr_{m2} = \frac{Q_g^2}{g D_5} \quad (3)
\]

Equation (3) was used to scale the gas flow rate, compared to a real converter. When this is determined, Eq. (2) was used to scale the size of the nozzle. The size of the nozzle was determined to be 3.2 mm for the smaller physical model. From experience it was determined that the nozzle size has a very small influence on the mixing time in the same manner as observed in a bottom blown bath. The mixing time is mainly governed by the gas flow rate, although the penetration depth of bubbles in the horizontal direction is affected by the nozzle size as well as the gas flow rate. Thus, the same nozzle was used in the larger physical model.

A mass flow controller was used to regulate the gas flow rate during the experiments. Also, a conductivity probe was used to measure the change in conductivity. The probe was placed 30 mm from the bottom of the bath and near the side wall, as illustrated in Fig. 1. The output of the probe was fed to a conductivity meter and provided a 0 to 1 V DC output to a computer interface. In addition, the fluid flow was fully developed before the tracer injection of the KCl-solution was made. The solution had a concentration of 1 M KCl, and the amount added was 1 mL solution per 1000 mL of liquid in the bath. Furthermore, the injection was made by a syringe close to the wall of the vessel. The conductivity of the bath was measured with an interval of 100 ms.

The experimental mixing time was defined as the period required for instantaneous tracer concentration to settle within ±5% deviation around the final tracer concentration in the bath.

3. Results and Discussion

Experiments were done using two vessel diameters of 200 mm and 300 mm, respectively. In addition, experiments were done for bath heights varying from 106 to 314 mm. Air was injected at the bottom of a side wall, as illustrated in Fig. 1. Flow rates between 30 cm/s and 800 cm/s were tested during the trials. Based on Eq. (2) the inner diameter of the side nozzle was determined to be 3.2 mm.

A typical illustration of the fluid flow in the side-injected vessel is shown in Fig. 2. As can be seen, the air enters the water and penetrates the bath in the radial direction, before the flow is lifted to the bath surface. This is caused by the lower density of air in comparison to water, which buoyancy also drags the water close to the plume up to the surface. This movement results in a recirculation flow where water is directed to the side wall after reaching the surface. Thereafter, it is directed towards the vessel bottom as it reaches the vessel wall.

3.1. Output Signal of Sensor

In Fig. 3 a typical curve from the conductivity probe is shown. The voltage is plotted as a function of the measurement time. This is done in order to illustrate how the mixing time was defined in the current experimental work. More specifically, the mixing time is defined as the time when the measured voltage reaches a value that is within ±5% of the stable voltage.
3.2. Experimentally Determined Mixing Times

3.2.1. Data on Mixing Time

The mixing time was determined experimentally as illustrated in Fig. 3. For the vessel with a 200 mm nozzle diameter experiments using four different gas flows varying between 30 and 240 cm³/s were tested. Furthermore, four different bath heights varying from 106 to 207 mm were used in the experiments. For the larger vessel with a 300 mm diameter the corresponding values were the following: gas flow rates between 100 and 800 cm³/s and bath heights between 163 to 314 mm. All the experimentally determined mixing times are given in Table 1.

In Fig. 4 the experimentally determined mixing time for the 200 mm diameter vessel is plotted versus the gas flow rate and bath height. The mixing time is seen to decrease almost exponentially with an increased gas flow rate. In addition, the mixing time is seen to vary quite little with a changed bath height for the current experimental conditions. In Fig. 5, the experimentally determined mixing time for the 300 mm diameter vessel is plotted versus the gas flow rate and bath height. The results are very similar to those found in Fig. 4. Overall, the mixing time is seen to be more influenced by the gas flow rate than the bath height.

As shown in Fig. 2, a large-scale circulating flow exists in the side blowing bath. The central part of the bath looks like a stagnant region. The agitation of the bath therefore is governed mainly by the circulating flow. The measured values of the mixing time, $T_m$, in this study were hardly affected by the bath depth, as shown earlier. This is because the bath depths are roughly the same or lower than the bath diameter under the present experimental conditions. Furthermore due to that the circulating flow is governed by the bath diameter, $D$. Therefore, the scale of the circulating flow is represented by the vessel diameter rather than the bath depth.

It is useful to derive a theoretical expression for the mixing time in order to compare the predictions with the experimental data. This may be done as described below.

According to a previous study, the representative velocity of bubbles rising in a bubbling jet, $V$, is given by:

$$V = (g^2 Q_g)^{0.2}$$ .................................(4)

The liquid present beside rising bubbles is entrained into the wakes of the bubbles. As a result, an upward moving liquid flow is induced above the nozzle. This liquid flow further induces the above-mentioned circulating flow. The liquid velocity in the bubbling jet is approximately proportional to the bubble rise velocity, $V$, and the representative velocity of liquid flow is also given by Eq. (4).

### Table 1. Experimentally determined mixing times in seconds for two different vessels.

| Diameter (mm) | Bath Height (mm) | Flow Rate (cm³/s) |
|--------------|------------------|-------------------|
| 200          | 106              | 30                |
|              |                  | 60                |
|              |                  | 150               |
|              |                  | 240               |
| 300          | 163              | 100               |
|              |                  | 200               |
|              |                  | 300               |

**Fig. 3.** Definition of mixing time, $T_m$.

**Fig. 4.** Mixing time as a function of gas flow rate, $D=200$ mm.

**Fig. 5.** Mixing time plotted as a function of gas flow rate, $D=300$ mm.

The length of the locus of the circulating flow shown in Fig. 2 is approximately proportional to the bath diameter, $D$. The following circulation time, $T_c$, is introduced here:

$$T_c = \frac{D}{V}$$ .................................(5)

This time scale is defined as the period for a liquid once entrained into the bubbling jet near the nozzle to return to the same position in the bath. It is reasonable to say that the mixing time in an AOD converter subject to side gas blowing is closely associated with the circulation time. The liquid flow in the bath is highly turbulent. Hence, the Reynolds number is important to consider when discussing bath mixing. Therefore, the mixing time can be expressed as a function of the circulation time, $T_c$, and the Reynolds number, Re:

$$T_m = f(T_c, \text{Re})$$ .................................(6)

$$\text{Re} = \frac{v_m D}{v}$$ .................................(7)
where \( v_{sp} \) is the superficial velocity of air and \( v \) is the kinematic viscosity of water.

If results from a previous paper\(^{10} \) are used the functional relationship between the mixing time and the circulation time can be expressed as follows:

\[
\frac{T_m}{T_c} = k \text{Re}^n
\]  

(9)

where \( k \) and \( n \) are constants, being determined by, for example, the least-square method. Thereafter, the left-hand-side of Eq. (9) can be rewritten as follows:

\[
\frac{T_m}{T_c} = \frac{T_m V}{D}
\]  

(10)

The reciprocal of the right-hand-side of Eq. (10), \( D/(T_m V) \), represents a kind of Strouhal number. The Strouhal number, \( St \), is a dimensionless number describing an oscillating flow mechanism. It is often expressed as:

\[
St = \frac{f L}{v}
\]  

(11)

where \( f \) is the frequency of vortex shedding, \( L \) is the characteristic length and \( v \) is the velocity of the fluid. The frequency can be expressed as the inverse of time and the characteristic length is equal to the diameter of the vessel. If these data are inserted together with the expression of the gas velocity Eq. (4) into Eq. (8), the Strouhal number can be rewritten as:

\[
St = \frac{D}{T_m (Q g^2 \rho^2)}
\]  

(12)

The best-fitted values of \( k \) and \( n \) in Eq. (9) were found to be 86 and \(-1/5\) respectively, when using the least-square method on the data presented in Figs. 4 and 5. If these constants are used, Eq. (9) can be rewritten as:

\[
\frac{T_m (g^2 Q)^{0.2}}{D} = \frac{86}{\text{Re}^{0.2}}
\]  

(13)

By comparing Eqs. (12) and (13) it can be seen that the Strouhal number is related to the Reynolds number in the following manner:

\[
St^{-1} = 86 \text{Re}^{-0.2}
\]  

(14)

Figure 6 shows a plot of the inverse of the Strouhal number for a vessel with a 200 mm inner diameter. The inverted Strouhal number is seen to decrease with an increased Reynolds number. Predictions using Eq. (13) are shown together with measured data based on mixing times measurements inserted into Eqs. (7) and (12). Furthermore, lines for variations of the predictions with \( \pm 20\% \) are shown in the figure. As can be seen the experimental data are within \( \pm 20\% \) of the predictions, which is considered to be good in physical modelling.

Figure 7 also shows a plot of the inverse of the Strouhal number versus the Reynolds number as in Fig. 6, but for a 300 mm bath diameter. Data are shown for four different bath heights: 163 mm, 215 mm, 264 mm and 314 mm. Similar to the results in Fig. 6, the inverted Strouhal number is seen to decrease with an increased Reynolds number. Furthermore, the experimental data are within \( \pm 20\% \) of the predictions. Also, as was found in Fig. 5 the influence of the bath height on the mixing time is small. The data in Figs. 6 and 7 are summarized as can be seen in Fig. 8. This shows that the inverse of the Strouhal number decreases with an increased Reynolds number. Thus, it shows that the relationship between the inverse of the Strouhal number and the Reynolds number is valid independently of the bath diameter. However, it should be noted that the modified Strouhal number, derived using Eq. (12), increases with an increased bath diameter. Thus, overall it is seen that the two parameters which have the largest influence on the mixing time is the gas flow rate and the bath diameter. In addition, the overall conclusion is that all experimental data are within \( \pm 20\% \) from the predictions. This is a good agreement in physical modeling.

From Figs. 6 and 7 it can also be seen that the influence of the bath height on the mixing time is so small so that it can be neglected for the current experimental conditions. The Eq. (13) can be rewritten as follows in order to clarify what parameters influences the mixing time:

\[
T_m = 86D (g^2 Q)^{-0.2}
\]  

(15)

In order to rearrange the expression so that the mixing time only is a function of the gas flow rate and the diameter the following can be done. First, Eqs. (7) and (8) are inserted into Eq. (15). Then, the value of the kinematic viscosity is taken as \( 10^{-6} \text{m}^2/\text{s} \) and the equation is rewritten as:
It is seen from this equation as well as Fig. 6 that the gas flow rate has a large influence on the mixing time. Now, Eq. (16) is applied on the experimental results from this study. More specifically, the theoretical mixing time is plotted as a function of the experimental mixing time (evaluated as shown in Fig. 3) in Fig. 9. In the figure, two lines are also added to illustrate when the differences between the results are less than 20%. Thus, it can be concluded that Eq. (16) may be used to predict the mixing time in side-blown converters with an accuracy of 20%. In physical modelling this is seen as quite accurate, as also mentioned previously.

4. Conclusions

The mixing time in a side-blown converter was studied by physical modelling. Air was injected into water to simulate gas injection into steel. In addition, a KCl solution was added as a tracer. This influenced the electrical conductivity of the water so that by monitoring this change an experimental determination of the mixing time could be obtained for different experimental conditions. More specifically, for bath diameters of 200 mm and 300 mm. Furthermore, for gas flow rates between 30 to 800 cm³/s as well as bath heights ranging from 106 to 314 mm. The mixing times were also calculated based on an expression involving the Strouhal and Reynolds numbers. Overall, the mixing time was found to be influenced by the gas flow rate and the vessel diameter, but not by the bath height. In addition, the following specific conclusions may be drawn based on the results of the current study and for the current experimental conditions:

1) The experimentally determined mixing times were found to be within ±20% of the theoretical values. This is considered to be good in physical modelling.

2) Both the measurements and the predictions show that the influence of the bath depth on the mixing time is negligible.

3) Both the measurements and the predictions show that the mixing time decreases with an increased gas flow rate as well as a decreased vessel diameter. If the derived equation for calculation of the mixing time is applied for a production converter it can be seen that these mixing times are in the order of seconds. These are small numbers that are difficult to verify in a production scale. However, the equation could be used when designing dimensions of an AOD converter.

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