Note

Mixing Time in RH Ladle with Upleg Size and Immersion Depth: A New Correlation

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1. Introduction

Mixing in a RH vessel has been a subject of study for many researchers in the academics as well as in the industry due to its industrial impact of high production rate of low carbon steel in a short time. The RH process can be seen pictorially in the work of Ajmani *et al.*¹⁾ Alloy addition is done towards the end of the RH process. So knowledge of mixing time in the RH process becomes very important prior to its operation because the operator must know for how long he has to make the RH process run. In order to know the mixing time apriori one has to use a correlation which is already developed from either numerical or experimental model. In the numerical model the steady state flow field inside the RH ladle and vessel is solved first and then a tracer is injected to see its variation with time. From the tracer dispersion curve one can then compute the mixing time as has been shown in the work of Ajmani *et al.*¹⁾ Here it must be mentioned that the flow field in the RH vessel is probably not very important because it does not influence the flow field in the RH ladle where mixing takes place. So in the study of mixing, only the RH ladle is taken for CFD simulation. In the work of Ajmani *et al.*¹⁾ there has been a correlation for mixing time for the RH ladle and this correlation was based on 3 parameters (downleg immersion depth, downleg size and downleg velocity appearing through Re) influencing the process. In the work of Ajmani *et al.*¹⁾ there was no consideration of upleg immersion depth and upleg size. However in the present work all these parameters are taken into consideration and it has been seen that the upleg immersion depth has a profound effect on the mixing time and hence could not be neglected while developing a correlation. So the present work considers a 5 parameter (downleg immersion depth, downleg size, upleg

immersion depth, upleg size and downleg velocity appearing through Re) correlation for the mixing time in the RH ladle taking a wide variation of each parameter as shown in Table 1.

2. Results and Discussion

The CFD model used for the RH-ladle was run for different conditions as mentioned in Table 1. The governing equations and the boundary conditions used in the simulation were exactly identical to that of Ajmani *et al.*¹⁾ and hence are not shown in the present work. Simulations were carried out to investigate the effect of downleg size, upleg size, downleg immersion depth, upleg immersion depth and liquid steel velocities in the downleg on mixing in the RH ladle. At the onset of the simulation a steady flow field inside the RH ladle was tried to be obtained because the flow field normally remains steady inside the ladle (flow visualization of the steady field can be seen from the literatures^{1–5)}). After this the tracer was added to the ladle through the inlet port for only 5 s. The time duration of tracer addition is normally too short compared to the mixing time in the RH ladle, so the flow field inside the ladle will not change during the tracer addition process. The tracer dispersion in the ladle was solved in a transient manner and the concentration of the tracer was monitored at 9 different points in the ladle. From the graph of these concentration *versus* time curves one can determine the mixing time in the RH ladle (typically a 95% mixing time is normally sought after).

2.1. Effect of Downleg Immersion Depth

Figure 1 shows the effect of downleg immersion depth on mixing time as a function of the downleg velocity. This parameter has the highest effect on the mixing time. From Fig. 1 it can be seen that there is an optimum downleg immersion depth (2 000 mm) (when upleg immersion depth is 500 mm) where mixing time is the minimum. This can be expected in reality because the incoming jet hits the bottom pretty strongly and creates good amount of circulation in the ladle compared to other cases. If the downleg immersion depth is 100 mm then the jet impact is less on the bottom of the ladle but the jet suction is too much in the ladle for which the circulation in the ladle remains rather high. So the mixing time is close to the case of 2 000 mm downleg immersion depth. But when the downleg immersion depth increases from 100 to 500 mm then the jet suction length falls in the ladle (although the impact strength of the jet rises a little on the bottom) so induced suction falls in the ladle causing mixing time to rise. So it is expected that

Table 1. Parameters chosen for mixing time in the RH ladle.

Downleg Size (mm)	Upleg Size (mm)	Downleg Velocity (m/s)	Downleg Immersion depth (mm)	Upleg Immersion depth (mm)
225	225	0.7	100	500
300	300	1.0	500	1000
375	375	1.2	1000	1500
450	450	1.4	1500	
			2000	
			2500

Fig. 1. Variation of mixing time with downleg immersion depth at different downleg velocities, upleg size=450 mm, downleg size=225 mm, upleg immersion depth=500 mm.

Fig. 2. Variation of mixing time with downleg immersion depth at different downleg velocities, upleg size=300 mm, downleg size=450 mm, upleg immersion depth=500 mm.

the mixing time curve may show an increasing-decreasing and increasing pattern with downleg immersion depth when the incoming jet is pretty strong with the downleg size remaining at the lowest value of 225 mm.

Figure 2 shows the effect of downleg immersion depth on mixing time when downleg size is 450 mm. Because the downleg size has now increased so the strength of the jet has fallen a bit but the suction due to the jet has increased in the ladle. This case shows an increasing trend in mixing time till a downleg immersion depth of 500 mm and after that there is a marginal decrease in the mixing time and after 1000 mm the mixing time remains more or less constant. For all these cases the optimum mixing time is observed at 100 mm of downleg immersion depth.

2.2. Effect of Upleg Immersion Depth

Figure 3 shows the effect of upleg immersion depth on mixing time as a function of downleg size. Normally with the increase in the downleg velocity the mixing time decreases with the upleg immersion depth. So for this reason plots with respect to downleg velocity are not shown rather downleg size has been chosen as the parameter. From Fig. 3 it can be seen that the upleg immersion depth has a minor

Fig. 3. Variation of mixing time with upleg immersion depth at different downleg sizes, upleg size=225 mm, downleg velocity=1.4 m/s, downleg immersion depth=100 mm.

Fig. 4. Variation of mixing time with upleg immersion depth at different downleg sizes, upleg size=225 mm, downleg velocity=1.0 m/s, downleg immersion depth=500 mm.

Fig. 5. Variation of mixing time with upleg immersion depth at different downleg sizes, upleg size=300 mm, downleg velocity=1.4 m/s, downleg immersion depth=1000 mm.

effect on the mixing time when the downleg immersion depth is 100 mm. But when the downleg immersion depth increases to 500 mm then profound effect of upleg immersion depth on mixing time can be observed from **Fig. 4**. In **Fig. 5** the downleg immersion depth has been increased to 1000 mm and we see a very different response of mixing time compared to Fig. 4. The mixing time increases with upleg immersion depth and after 1000 mm of upleg immer-

Fig. 6. Variation of mixing time with upleg immersion depth at different downleg sizes, upleg size=300 mm, downleg velocity=1.4 m/s, downleg immersion depth=1 500 mm.

sion depth the mixing time again falls. Just the opposite trend can be seen in Fig. 6 when the downleg immersion depth has been increased to 1 500 mm. It can be seen that there is an optimum upleg immersion depth for minimum mixing time in the ladle.

2.3. The Correlation for Mixing Time

A dimensionless correlation has been developed for the prediction of mixing time based on the above results generated under different operating conditions. The dimensionless correlation developed is as follows

$$t_{\text{mix}}(Q/V) = 0.31616 \left(\frac{S_u}{H} \right)^{0.0273} \left(\frac{S_d}{H} \right)^{0.0799} \times \left(\frac{D_u}{D} \right)^{-0.0165} \left(\frac{D_d}{D} \right)^{1.1347} (\text{Re})^{0.279} \dots (1)$$

The above relation has been developed from 664 data points. 67% of data points have error less than 10% and 83% of data points have errors less than 15%. Figure 7 shows the predicted (from Eq. (1)) and actual mixing time for all the data points. The predicted and the actual values seem to be matching reasonably well.

$$t_{\text{mix}}(Q/V) = 1.3(\text{Re})^{0.06} (\text{SID}/H)^{-0.52} (D_d/D)^{1.02} \dots (2)$$

The correlation given by Ajmani *et al.*⁽¹⁾ (Eq. (2)), which was developed based on 25 data points, shows a dependence of Re to the power of 0.06 but the present relation shows a stronger dependence of Re on mixing time. There was no effect of upleg immersion depth and upleg size on mixing time in the relation given by Ajmani *et al.*⁽¹⁾ but the present relation takes into account all these effects. It is believed that the present relation is more generic in approach and covers a wide spectrum of parametric variation com-

Fig. 7. Predicted mixing time vs. actual mixing time.

pared to the relation given by Ajmani *et al.*⁽¹⁾ hence the present relation can have more utility in the industry.

3. Conclusions

A correlation for mixing time in the RH ladle has been developed taking 5 parameters (S_u , S_d , D_u , D_d and Re) into account with 664 data points which covers all the different cases those have been solved in the present work. It has been found that the upleg immersion depth has a profound effect on the mixing time and there exists optimum upleg immersion depth where mixing time is the minimum. Similarly for the downleg immersion depth also there exists optimum downleg immersion depth where mixing time is the minimum.

Nomenclature

- D : Diameter of ladle (mm)
- D_d : Downleg size (mm or m)
- D_u : Upleg size (mm)
- H : Height of ladle (mm)
- Q : Volume flow rate of liquid steel (m^3/s)
- SID : Snorkel immersion depth (mm)
- S_d : Downleg immersion depth (mm)
- S_u : Upleg immersion depth (mm)
- t_{mix} : Mixing time (s)
- V : Volume of steel in ladle (m^3)
- V_d : Fluid velocity in downleg (m/s)
- Re: $D_d V_d \rho / \mu$ = Reynolds number
- μ : Viscosity ($\text{Pa} \cdot \text{s}$)
- ρ : Density (kg/m^3)

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