The Effect of Bottom Nozzle Configuration on the Bath Behaviour in the BOF

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The blowing behaviour of the BOF is affected in many ways by the behaviour of molten bath. Bottom blowing and its interaction with top blowing have a strong influence on splashing and spitting behaviour, bath homogenisation and bath oscillation. Therefore, three selected bottom nozzle configurations were studied by physical modelling, and the results were compared regarding splashing, homogenisation and oscillation of the bath. According to model tests, bottom nozzle positioning has a great influence on the amount and direction of splashing and spitting. Moreover, at lower lance gaps, the direction of splashes was changed because of bath oscillation. At low lance gap, when type A oscillation is dominant, correlation between the degree of overlap and stability of the bath was found. The bigger the degree of overlap, the more unstable the system as far as type A oscillation and splashing is concerned. The amplitude and oscillation frequency of the bath changed as a function of lance height. Blowing through bottom nozzles prevented the onset of so called type A oscillation. Bottom nozzle configuration of three nozzles resulted in shortest mixing time, lowest total splashing on model walls and longest starting time of type A oscillation.

KEY WORDS: steelmaking; combined blowing; nozzle configuration; bath behaviour; splashing; mixing; bath oscillation; physical modelling.

1. Introduction

In combined blown oxygen steelmaking converter top blowing is used to supply oxygen needed for removal of carbon and other impurities. Inert gases injected from the bottom of the vessel, on the other hand, serve to promote bath agitation and mixing of the bath. The action and interaction of above-mentioned gas flows have an influence on the behaviour of the molten bath; splashing and spitting, liquid flows, bath homogenisation and bath oscillation. Consequently, rate of decarburisation, metal losses, skulling of the converter cone and mouth, lance life and the wear of refractory lining are affected.

Numerous investigations concerning splashing in converter vessels have previously been carried out. The methods applied are almost equally versatile, ranging from absorbent papers and fan-shaped trays to even more complicated procedures. The authors have reviewed splashing studies in Refs. 15, 16 and measurement methods in Ref. 17. Measurement of mixing times or mixing efficiency in metallurgical vessels has understandably been very popular subject. Investigations made under combined blowing are, however, much more infrequent. Methods have varied from the measurement of variation of electrical conductivity or pH of the bath to chemical decolouration methods or even determining the mass transfer rate constant of a two phase system. Since bath motion affects e.g. blowing operation, intensifies metal ejections, stresses the construction and accelerates the wear of refractory lining, several studies have been carried out to clarify the phenomenon. Again, studies concerning combined blown vessels are few in number.

A physical model study of combined blown BOF was carried out in order to compare the effects of three different bottom nozzle configurations on splashing and spitting behaviour, mixing efficiency and bath oscillation.

2. Experimental Set-up

Due to the different nature of the required measurements, two separate water models were utilised. Both models have the same geometry and dimensions; scaled down to 1 : 7. The operational and geometrical parameters of the physical model and the prototype are presented in Table 1. Figure 1 shows the location of bottom nozzles for 3, 4 and 5 nozzle arrangements. The two lance positions used in splashing and oscillation studies are also displayed in the same figure.

2.1. Measurement of Splashing and Spitting

Splashing and spitting behaviour in the combined blown converter vessel was studied with the new method, which is previously described elsewhere in more detail. Since the whole model wall is perforated, the experimental set-up enables studying overall splashing distribution on the model wall. Spitting is referred to as water droplets collected from the mouth of the converter model by an absorbent cloth.

2.2. Measurement of Mixing Time

The experimental apparatus and auxiliary instruments for
determining the mixing times are schematically shown in Fig. 2. Model was filled with deionised water whose conductivity was adjusted to 10 μS/cm before the trials. Mixing time in the bath was measured by electrical conductivity method utilising so called 4-electrode conductivity technique. Aqueous solution of 1-M sodium chloride (20 mL) was injected below the surface near the model wall. The changes in the conductivity of the bath were monitored by TBI-Bayley TB451 conductivity sensor. The output of the transmitter (4–20 mA) was recorded by HP 34970A data acquisition unit. The conductivity sensor located opposite to the tracer injection point at 50 mm from the bottom and 40 mm from the wall. The mixing time was defined as the time that the conductivity of the water at the probe converges within ±1% of the steady state value.

2.3. Oscillation of the Bath

The amplitude of the wave at the bath surface was defined as the difference between the maximum height of the peak of wave and the bath level at rest i.e. when no oscillation occurs. Both the amplitude and frequency of oscillation was determined by visual observation. Stability of the bath between the studied bottom nozzle configurations was evaluated as how easily the bath starts to oscillate, i.e. time was measured when more violent, so-called type A, oscillation starts. The wave motion of type A was defined as liquid oscillation similar to the wave motion in U-shaped tube.\textsuperscript{46} The situation when waves repeat collision and repel alternately was called type B.

2.4. Similarity Considerations

The dynamic similarity between the model and the prototype was considered for both top and bottom blowing by using several dimensionless numbers. All the symbols and their meanings are given in Table 2. Following dimensional numbers were considered for lance blowing:

\[
\text{We} = \frac{\rho_k v^2}{(\rho_\text{L} \sigma)^{1/2}} = \frac{2p_k}{(\rho_\text{L} \sigma)^{1/2}} \quad \text{.........(1)}
\]

\[
\text{Mm} = \frac{\rho_k u^2 d_{j}^2}{\rho_\text{L} g h_{1}} \quad \text{.........(2)}
\]

\[
\text{Fr} = \frac{u^2}{g h} = \frac{\rho_k}{\rho_\text{L} g h_{1}} \quad \text{.........(3)}
\]

The Weber number expresses the ratio of the momentum intensity to the main liquid properties.\textsuperscript{57,58} The momentum number (Mm) is defined as the ratio between the jet mo-
momentum flow rate at different distances with the action of gravity on the same bath.\textsuperscript{59} The Froude number represents the ratio between the inertial forces to gravitational forces.\textsuperscript{60} One example of how the dynamic impact pressure of the jet on the metal surface can be calculated is presented in our earlier paper.\textsuperscript{16} Since the bath behaviour was studied, the emphasis was on similar conditions on jet momentum and consequently Reynolds or Mach number was not considered.

Table 3 shows a comparison of the dimensionless numbers between the physical model and the BOF. Since the ratio of forces in every dimensionless group is of same order of magnitude, it can be stated that an adequate similarity between the two systems was achieved.

Modified Fr number has been very popular when dynamic similarity for bottom blowing is considered. Furthermore, the kinetic and buoyancy energy of the injected gas are calculated, Table 4. The following respective equations are given\textsuperscript{61,62}:

\begin{align}
Fr &= \frac{\rho_b u_0}{\rho \sqrt{gH_b}} \quad \text{(4)} \\
E_k &= \frac{1}{2} \rho_b \frac{u_0 Q}{m_b} \quad \text{(5)} \\
E_b &= \frac{2Q p_s \ln \left( \frac{p_s + \rho_b g H_b}{p_s} \right)}{m_b} \quad \text{(6)}
\end{align}

3. Experimental Results

In the following, the experimental results on splashing behaviour, mixing time and bath oscillation are presented as a function of bottom plug arrangement, lance height, lance position and bottom gas flow rate.

3.1. Splashing Behaviour

Generally, introduction of bottom blowing increased the amount of measured splashing, Fig. 3. Our finding is therefore in agreement with previous studies.\textsuperscript{15,16,63} Due to the dissimilarities between the studied bottom nozzle configurations, no correlation between the number of nozzles and the amount of splashing was found. Normally, measured splashing maximum on the model wall coincides at the same location as lance nozzles point. However, when lower lance gaps, 0.14–0.16 m, were used, the location of maximum measured splashing was shifted about 45°. The shift is mainly caused by oscillation of the bath, which also changed the direction of splashes. Lance position has not significant effect on the amount of total splashing except for the lowest tested lance height.

Table 3. List of symbols.

| Symbol | Definition |
|--------|------------|
| dₜ | diameter of the nozzle exit, m |
| Eₜ | specific kinetic energy, W/kg |
| Eₜₑ | specific buoyancy energy, W/kg |
| Fr | the Froude number, - |
| g | acceleration due to gravity, m/s² |
| H | lance height, m |
| hₜ | axial lance height, m |
| Hₑ | height of the liquid bath, m |
| mₜ | weight of the liquid bath, kg |
| Ţₜ | the momentum number, - |
| pₑ | ambient pressure, Pa |
| pₑ | dynamic impact pressure at the surface, Pa |
| Q | gas flowrate, m³/s |
| wₑ | gas velocity in the tuyere, m/s |
| w | gas velocity, m/s |
| Wₑ | the Weber number, - |
| ρ | density, kg/m³ |
| T | surface tension, N/m |

Table 4. Comparison between dimensionless numbers in actual BOF and physical model for top blowing.

| | BOF | Model |
|---|---|---|
| Weber number, - | 155 – 215 | 151 – 214 |
| Momentum number, - | (2.1 – 5.8)×10¹⁷ | (7.3 – 21.2)×10¹⁷ |
| Froude number, - | 0.14 – 0.27 | 0.51 – 1.04 |

Fig. 3. Total splashing rate as a function of lance height with various bottom blowing gas flow rates.
Distinctive difference in splashing behaviour between the two lance positions is observed. When lance position 1 is used, the amount splashing increased linearly whereas when lance position 2 is used, the splashing behaviour is somewhat different. In the former case, only one lance nozzle is directed towards the trunnion area while in the latter case the measured splashing is a result of combined action of two nozzles, which makes the situation more complex. Similar trends can be observed when splashing on charge pad/tapping area is considered. Splashing on charge pad/tapping area was heaviest when 3-nozzle configuration was used. Relative position of bottom tuyeres and jet cavities in Fig. 1 explains pretty well the difference in splashing behaviour between the lance positions.

Figure 5 reveals the significance of the location of bottom stirring elements on spitting behaviour during top and combined blowing as a function of lance height. Four-nozzle configuration, i.e. when nozzles are placed in the centre of the bottom, shows the greatest spitting rate regardless of the lance height. Again, three- and five-nozzle configurations show similar trend to each other as a function of lance height. Lance position has a little effect on the amount of spitting.

### 3.2. Mixing Time

In all the experiments, top lance blowing was kept constant; lance height 0.18 m, gas glow rate 390 NL/min and supply pressure 5 bars. The results presented in the following figures are mean values from at least six trials. Figure 6 shows the effect of bottom gas flow rate on mixing time with all three bottom blowing configurations. Increasing the bottom gas flow rate clearly decreased the mixing time. According to the model tests, mixing is most effective when configuration of three nozzles was used. Figure 7 reveals that pure bottom blowing results in shorter mixing times than combined blowing.

### 3.3. Bath Oscillation

Depending mainly on the lance gap, two types of oscillation were observed; type A and B as Kato et al. defined them. On lower lance heights, when gas blowing was initiated bath movement started as type B and after varying time period changed to type A. Type A was dominant regardless of bottom nozzle configuration or bottom gas flow rate. When lance was raised type B became dominant and type A oscillation was not observed. The amplitude and frequency of the bath movement were almost solely dependent on the lance height. Figure 8 illustrates the amplitude and frequency of the bath movement.
frequency as a function of lance height when only top blowing (LP1) was used. When the lance height increases, the amplitude decreases sharply after lance height 0.16 m and simultaneously frequency increases and levels off at constant level of 1.6 Hz. The change in frequency level between lance heights 0.14–0.16 m indicates the change in the type of bath oscillation from type A to type B, which was also visually confirmed. Similar tendency in bath oscillation behaviour was observed also with all bottom blowing options.

According to Kato et al.\(^{46}\) wave motion of type A is more violent because of larger amplitude and longer damping time. Therefore tests were done in order to find out if there were any differences between the three bottom nozzle configurations when starting time of type A oscillation from the initiation of blowing is considered. Figure 9 shows the measured starting times for all three tested bottom nozzle configurations as a function of bottom gas flow rate. Lance height and top gas flow rate were kept constant in all the tests; 0.14 m and 390 L/min respectively. In general, measured starting times are clearly longer with all bottom-blowing options than with pure top blowing. Furthermore, LP1 seems to be slightly more stable (longer starting time) than LP2 with the exception of three-nozzle configuration where the difference between the lance positions is more distinctive. The bottom gas flow rate has only minor influence on starting times. However, when LP2 was used, 3-nozzle and 4-nozzle configurations showed divergent behaviour.

4. Discussion

4.1. The Effect of Blowing Parameters on Splashing

On the basis of our earlier studies, it was known that the introduction of bottom blowing increases splashing on the walls but decreases the amount of spitting.\(^{15,16}\) Furthermore, when bottom nozzles are set in the centre area of the bottom so that the lance jet cavity pattern lies outside of the bottom gas plumes, spitting rate is substantially increased.\(^{15}\) The same observations are also done in the present study, as can be seen in Figs. 3 and 5. According to Akdogan and Eric,\(^{36}\) off-centre configuration results in higher intensity of splashing than that with centre configuration. Their observation was found to be valid also with combined blowing, as shown in Fig. 3.

The amount of total splashing is almost constant when 3 and 5 nozzle bottoms are compared. However, when inspecting splashing on certain areas of the model wall some trends can be obtained. Again, both configurations show nearly identical behaviour with both lance positions but there are clearly differences in the amount of measured splashes, Fig. 4 and Fig. 10. It may therefore be concluded that the two bottom nozzles near the taphole (in five-nozzle bottom arrangement) hinder splashing on the taphole area esp. when LP2 was used, and promote splashing on trunnion area. According to the model tests, when spitting and splashing on the top collection level are inspected, the greatest skull growth in the converter cone and the highest metal losses through converter mouth are expected to occur when bottom nozzles are located at the centre of the bottom, Figs. 5 and 10. The effect of the studied parameters on splashing are summarised in Table 5. Increasing the value of parameter is symbolized with “↑” and its effect on measured variable with “↑” when parameter causes an increase in measured variable and with “↓” when an inverse effect is observed. Symbol “±” means that parameter has no effect on measured variable or the effect is insignificant. Both increasing the lance gap and bottom gas flow rate increase

\[ \begin{array}{cccc}
3 \text{ nozzles} & 4 \text{ nozzles} & 5 \text{ nozzles} \\
\text{Lance height} & ↑ & ↑ & ↑ \\
\text{LP1→LP2} & ± & ± & ± \\
\text{Bottom gas flow} & ↑ & ↑ & ↑ \\
\end{array} \]

* Ref \(^{36}\)

![Fig. 9. Measured starting times of type A oscillation as a function of total gas flow rate.](image)

![Fig. 10. Splashing rate on taphole area and on the upper part of the model.](image)
4.2. The Effect of Bottom Blowing Parameters on Mixing Efficiency

Since the purpose was only to find out the differences between the studied bottom nozzle configurations, mixing studies carried out in the present study were quite simple and not all the blowing parameters were investigated. According to the model tests, increasing the bottom gas flow rate clearly decreases the mixing time as found in many earlier studies. Singh and Ghosh, on the contrary, reported that the mixing time increases with increasing the bottom gas flow rate. Figure 11 shows mixing times as a function of mixing energy. Mixing energy is defined as the sum of the kinetic and buoyancy energy of the injected gas.

Configuration of three nozzles results the shortest mixing times when mixing energy (or gas flow rate) is low. Many researchers have earlier reported that eccentrically (or asymmetrically) arranged nozzles give shorter mixing times. Furthermore, many studies have previously shown that at a given flow rate, an increase in the number of tuyeres increases the mixing time. According to Oymo and Guthrie, the explanation could lie in the reduction of symmetry planes, which in turn reduces barriers to mixing. According to Ghosh and Singh and Koria and Lange, tuyere configuration had no significant effect on the mixing time but increasing number of tuyeres decreased mixing times sharply. Das et al. tried to clarify this anomaly, and according to them, increasing the number of basal tuyeres can indeed increase the mixing time but further increase in number of tuyeres over certain critical value results in a decrease in mixing time. The explanation proposed by them is that the individual cells probably overlap and the situation becomes better for overall mixing.

Figure 7 reveals that pure bottom blowing results in shorter mixing times than combined blowing. Similar results are also presented by Ajmani et al. at very high bottom gas flow rates and Oymo and Guthrie and Ghosh and Singh. Oymo and Guthrie suggested that, region between 0.2 and 0.35R in circular arrangement of tuyeres for combined blowing should be avoided. Obviously, the flow pattern in the bath is more complex under combined blowing, which may result in larger values of measured mixing times with the measuring method employed in the present study.

4.3. The Effect of Blowing Parameters on Bath Oscillation

As presented in Fig. 8, the amplitude and oscillation frequency of the bath changes as a function of lance height. Our finding concerning the change in frequency is therefore in disagreement with that presented by Lee et al. The discrepancy between the results may be explained by the differences between experimental set-ups.

Bath stability was evaluated by measuring the time from the initiation of gas blowing to the point where type A oscillation started. Compared to pure top blowing, measured starting times were clearly longer when bottom blowing was used indicating that bottom blowing hinders the onset of type A oscillation. Baptizmanskii et al. reported, on the contrary, that during combined blowing it is the top blowing that reduces the intensity of wave movements. The ratio between the amount of top and bottom blown gas in their study was, however, much smaller than in the present investigation. According to Kato et al., Xie and Oeters and Roth et al. starting time of the wave motion reduces quickly with increasing gas flow rate. In our experiments similar trend was observed only in two cases, Fig. 9. Furthermore, Xie and Oeters and Roth et al. reported that an increase in the number of nozzles served to stabilise the blowing behaviour. With an exception of 3-N/LP1 in Fig. 9, same tendency can be obtained also in our investigation. The effect of the studied parameters on the oscillation of the bath are summarised in Table 6.

Figure 12 displays starting time as a function of degree of overlap, which is determined as a ratio between area of overlapping from Fig. 1 to area of bottom blowing plumes at bath surface. According to the model tests, the smaller the degree of overlap, the longer the starting time, i.e. the more stable the system. Shown in Fig. 12 is also the influence of overlapping on total splashing rate. The bigger the overlapping, the greater the splashing rate. Figure 13 shows the correlation between total splashing rate and the stability of the bath, i.e. the time that indicates the change in type of oscillation from initiation of gas blowing. When the starting time is shorter (bath is less stable), the total amount of
splashing is larger. It has to be noted that no general correlation between total splashing rate and degree of overlap was found but only with lance height of 0.14 m. This may be in connection with the type A oscillation, which does not occur with higher lance gaps.

4.4. Comparison between Bottom Nozzle Configurations

In Fig. 14, bottom configurations are compared. It has to be noted that total splashing rate and starting time are done at lance height 0.14 m but mixing times at 0.18 m. It can be concluded that bottom nozzle configuration of three nozzles results in shortest mixing time, lowest total splashing and longest starting time. In Fig. 15, different bottom nozzle placements are compared when equal gas flow rates are used. Total splashing rates presented are same as in Fig. 14, i.e. with different total gas flow rates. Nozzle configuration of three nozzles shows the most advantageous performance also in this comparison.

5. Conclusions

The effects of top and bottom blowing on the bath behaviour in combined blown steelmaking converter are studied in the physical model and the results obtained are summarised as follows:

1. Lance position has only a minor effect on the amount of total splashing. However, clear local differences may be observed.

2. Oscillation of the bath changes the direction of splashes when lower lance positions are used.

3. Lance height determines the nature of bath oscillation under the conditions of the present work.

4. The amplitude and oscillation frequency of the bath changes as a function of lance height.

5. Blowing through bottom nozzles prevents the onset of type A oscillation.

6. At low lance gap, when type A oscillation is dominant, correlation between the degree of overlap and starting time and total splashing rate was found. The bigger the degree of overlap, the greater the rate of splashing and shorter the starting time of type A oscillation. Thus, the bigger the degree of overlap, the more unstable the system as far as type A oscillation and splashing is concerned.

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