Effect of Bottom Nozzle Arrangement on Splashing and Spitting in Combined Blowing Converter


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Wear of refractory lining, skulking of converter cone and metal losses were studied by splashing and spitting measurements in physical model during combined blowing. The aim of the present study was to determine the effect of the bottom nozzle arrangement and lance height as far as on harmful splashing and spitting in combined blowing converter are considered. The investigation has concentrated mainly on the initial period of blowing.

According to the model tests, total splashing on the converter walls increases as a function of number of bottom nozzles (with increase of total gas flow rate) both initial and final period of blowing. At the initial period of blowing, combined blowing produces maximum measured total splashing and large reaction area as a form of droplets. The nozzles arranged at the centre of the vessel increase metal losses and skulking of the converter cone especially with lowered lance height. The introduction of outside of lance cavities arranged bottom nozzles decreases metal losses and skulking of converter cone compared to the top lance blowing at final period of blowing. The usage of high lance height and several bottom nozzles accelerate wear of the refractory, especially at the knuckle area and charge pad area. It is possible to reduce splashing to the knuckle areas with certain lance gaps by positioning bottom nozzles directly between the cavity and knuckle area with remarkable (approximately 30-40 %) overlap.

KEY WORDS: converter; lance; bottom blowing; combined blowing; splashing; spitting; refractory wear; metal losses.

1. Introduction

In general, the splashing of slag and metal in the BOF is considered to have negative effects on the productivity, i.e. on the increase of refractory wear, the metal losses and the converter mouth build-up. On the other hand, the increase of interfacial area between gas and liquid phases enhances decarburisation reactions during blowing.

The important role of lance jet momentum for cavity profile and splashing is reported by many researchers. The direction of splashes is mostly dependent on the profile of the cavity. The depth of the jet cavity is solely governed by the mechanical forces of the oxygen jet. This verifies that the shape and the depth of the cavity in steel bath can be predicted from dynamically scaled water models.

According to Kuznetsov and Nazyuta, 9–24 % of the kinetic energy of the lance jet is consumed on the formation of the interface surface and acceleration of metal and slag drops. The generation rate of metal drops (kg/s) achieves its maximum at the beginning of blowing. The drops are mainly metal drops during the first period of blowing. If the formation of liquid slag does not take place rapidly enough at the beginning of blowing, the skulking of converter cone increases.

In combined blowing, Standish and He found two mechanisms of drop generation, dropping and swarming, which can be described as a function of blowing rate from top lance and bottom nozzles. According to their study, the mean drop size and the rate of droplet generation increased by introduction of bottom blowing. Mesalkin et al. determined the empirical correlation for the height of splashes in top and combined blowing. They discovered that introduction of coaxial arranged bottom nozzles lowered the height of the splash.

Paul and Ghosh studied splashing and mixing in LD and Q-BOP with the water model. They found out that splashing (washing effect around the walls) was in its maximum and mixing most effective when bottom nozzles were arranged on the centre of the vessel. In that case, nozzles located on a circular with 1/4 radius of the vessel. Furthermore, bottom blowing generated sloshing and fluctuation of bath surface. Both increasing the number of nozzles, and increasing the distance between the nozzles serves to stabilise blowing behaviour and eliminate sloshing.

A large number of different splashing studies are presented, but mainly for top blowing. Furthermore, the effects of splashes on the wear of lining are reported. O’Rourke et al. studied the localised wear of...
refractory lining in the knuckle area by means of the physical model. Results of their work indicated that waves, which are generated by lance blowing, may have a role in localised wear. According to Okhotskii and Shramko, the initial and the final period of blowing are the most aggressive for refractory. In this paper, the wear of refractory lining, skulking of converter cone and metal losses were investigated with the help of splashing and spitting measurements in physical model during combined blowing. The aim of present study was to determine the effect of bottom nozzle combination as far as harmful splashing and spitting in combined blowing converter are considered. The action of six (6) different bottom nozzle combinations (number and arrangement) with multi-hole lance were studied.

The present investigation is focused mainly on the beginning of the blowing because skulking of the converter cone, wear of refractory lining and metal losses as a form of dusts occur mainly during the initial period of blowing. During the decarburisation period, the foamy protective slag acts as a filter and consequently reduces above-mentioned detrimental effects. The final period of blowing is also shortly discussed because of decreased foaming of the slag in the actual process.

2. Experimental Set-up

A novel approach is utilised to estimate splashing distribution on the walls of the model. The splashing and spitting were investigated by 1:9 scaled physical model (Fig. 1) with 5-port lance and six (6) different bottom nozzle combinations. The geometrical and operational parameters of the model and actual process are presented in Table 1. Splashing of water was measured from four levels on the inner walls of the model. Every measuring level has 15 sampling points on a periphery with 24 degrees angle distances. The model has totally 60 sampling points. The lowest measuring level was positioned on the level of knuckle area in the actual converter. Dynamic similarity between the model and actual process were considered by dimensionless numbers and summarised in the Table 2.

The experiments were made with varied lance distances simulating blowing periods. The gas flow rate from 5-port de Laval lance was constant. The normal practice of bottom blowing operation was simulated, i.e. gas flow rate from bottom nozzles in a model was 5 Nl/min/nozzle. It should be noted that the increase in number of bottom nozzles increased also total gas flow rate. The splashed water was accumulated in the bottles during blowing and weighed after tests. The spitted water which simulated metal losses through the mouth of the converter was collected by an absorbent textile (Fig. 1). Since initial and final periods of blowing are investigated, the effect of foamy slag (layer) on splashing was neglected.

Figure 2 shows the studied bottom nozzles arrangements. Furthermore, the diameter of lance cavities at two distances from bath level (0.16 and 0.22 m) are presented in same figure. According to Chatterjee, the diameter of the cavity at the bath surface can be calculated from a knowledge of the jet spreading angle and the lance height. The spreading angle of lance jet is 12° on the supersonic core zone and 18° on the subsonic portion. Generally, 17° is
used for the approximated average spreading angle. The cone angle of bottom plume was assumed to be 22° in the model.\textsuperscript{29}

3. Experimental Results

3.1. Total Splashing on the Walls

According to the model tests, the introduction of bottom blowing increased total splashing on the walls, especially in the vicinity of the bath level (Table 3). Higher proportion of splashes directed to the lower part of converter because of the flatter cavity shape. The increase of number of bottom nozzles (with increase of total gas flow rate from bottom) enhances splashing on the walls of converter (Fig. 3). Above mentioned is a result of increased mean drop size and shear force on the surface\textsuperscript{8} and higher degree of overlap of lance cavities and bottom blowing plumes (Fig. 4). The clear correlation between the degree of overlap and total splashing was found. Total splashing increased as a function of lance height until it achieved \(H_h/\)0.20 m. When the lance was further raised, the total splashing became even or faintly decreased with combined blowing. Without bottom blowing, splashing decreased radically when lance height was higher than \(H_h/\)0.20 m. Strong splashing is not only harmful because high drop generation rate provides large reaction area during slag formation and refining. Model tests indicated that high lance distance from the bath (soft blowing) and usage of bottom blowing enhanced drop generation.

3.2. Skulling of Converter Cone

The arrangement of nozzles has strong influence on the amount of upward directed splashes. Splashing on the upper part of the converter is described in the Fig. 5. Figure 5 shows that bottom nozzles arranged at the centre of vessel (1N & 2N), increased the skulling of the cone. Above mentioned is a result of interaction of bottom blowing plumes and lance cavities. Figure 6 illustrates that the interaction of the cavity and the plume possibly changed the shape of the cavity and moved the direction of the splashes more upward (angle \(\beta\) is larger than angle \(\alpha\)). When nozzles were arranged outside of lance cavities (5N, 6N, 7N & 8N),

<table>
<thead>
<tr>
<th>Distance From the Bath Level</th>
<th>Lance Only</th>
<th>1N</th>
<th>2N</th>
<th>5N</th>
<th>6N</th>
<th>7N</th>
<th>8N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40m</td>
<td>83</td>
<td>89</td>
<td>87</td>
<td>67</td>
<td>77</td>
<td>78</td>
<td>74</td>
</tr>
<tr>
<td>0.30m</td>
<td>273</td>
<td>322</td>
<td>320</td>
<td>251</td>
<td>271</td>
<td>295</td>
<td>296</td>
</tr>
<tr>
<td>0.20m</td>
<td>1293</td>
<td>1433</td>
<td>1436</td>
<td>1324</td>
<td>1399</td>
<td>1442</td>
<td>1436</td>
</tr>
<tr>
<td>0.10m</td>
<td>5933</td>
<td>6493</td>
<td>6620</td>
<td>7370</td>
<td>7264</td>
<td>7529</td>
<td>7795</td>
</tr>
<tr>
<td>Total</td>
<td>7582</td>
<td>8337</td>
<td>8463</td>
<td>9012</td>
<td>9010</td>
<td>9344</td>
<td>9601</td>
</tr>
<tr>
<td>0.40m (%)</td>
<td>3.1</td>
<td>3.1</td>
<td>3.0</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0.30m (%)</td>
<td>3.6</td>
<td>3.9</td>
<td>3.8</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
<td>3.1</td>
</tr>
<tr>
<td>0.20m (%)</td>
<td>17.1</td>
<td>17.2</td>
<td>17.9</td>
<td>14.7</td>
<td>15.5</td>
<td>15.4</td>
<td>15.0</td>
</tr>
<tr>
<td>0.10m (%)</td>
<td>78.3</td>
<td>77.9</td>
<td>78.2</td>
<td>81.8</td>
<td>80.6</td>
<td>80.6</td>
<td>81.2</td>
</tr>
</tbody>
</table>

Fig. 3. Total splashing to the walls of the model with different nozzle arrangements as a function of lance height.

Fig. 4. Total splashing and the degree of overlap of lance cavities and bottom blowing plumes at the lance height 0.22 m.

Fig. 5. Splashing to the upper part of the model with different nozzle arrangements as a function of lance height.

Fig. 6. Schematic picture of direction of splash with b) and without a) interaction of bottom blowing plume and lance cavity.
skulling decreased compared to lance blowing besides lance height 0.22 m. Skulling of the cone was at minimum with 5N configuration. According to the tests, more skulling takes place with hard blowing. On the other hand, during decarburisation, when hard blowing is used, foamy slag acts like filter.\textsuperscript{13} At the initial period of blowing (soft blowing) the differences between the bottom nozzle configurations are minor.

3.3. Metal Losses

In addition to the skulling of the cone, the upward directed splashes cause also metal losses. Consequently, the influence of bottom configuration on metal losses (spitting) is analogous to the skulling behaviour. With hard blowing, when nozzles are arranged at the centre of bottom (1N & 2N), metal losses are 91–122% higher than with the 5N configuration (Fig. 7). If nozzles are arranged outside of the lance cavities (5N, 6N, 7N & 8N), the introduction of bottom blowing decreases the metal losses with all lance distances. At the beginning of blowing, when lance distance from surface is high, the differences between bottom nozzle configurations are minor.

3.4. Wear of Refractory Lining

Working life of BOF lining is often limited by wear of knuckle areas.\textsuperscript{30} Figure 8 shows that it is possible to reduce splashes on the knuckle area with certain lance heights.

This depends on two factors; the degree of overlap and the position of the plume in proportion to the lance cavity.\textsuperscript{31} If bottom nozzle is arranged suitably far from the centre of the bottom and positioned directly between lance cavity and knuckle area (in 6N configuration), it is possible to reduce splashing. In that case, the protection sector is formed behind the plume and splashing is reduced.\textsuperscript{31} With 6N configuration this situation is achieved when lance height 0.20 m was used (Fig. 9). If overlap is too high splashes can ‘fly’ across the plume and splashing on the wall increased.\textsuperscript{31} The splashing profile (in Fig. 9 and Fig. 10) was made by utilising cubic interpolation for measured splashing values. If nozzle is arranged too far from the centre, as in the case of 7N and 8N configuration, the overlap of cavity and plume was diminished (Fig. 11) and the protection sector is not formed. Consequently, splashing on the knuckle area is slightly increased. With 5N configuration the demanded degree of overlap was achieved but the position of bottom nozzle was not directly between cavity and knuckle area. When top blowing was used at high lance height ($H = 0.22$ m), splashing on the walls was even around the lining (Fig. 10). In that case splashing rate on the knuckle area also decreased (Fig. 8). Introduction of bottom blowing changes flows in liquid bath and increases splashing rate and refractory wear on the knuckle area. According to the experiments, in combined blowing, splashing on the knuckle area was maximum at the beginning of blowing and decreased during processing with lowered lance height.
Another interesting area of refractory lining is the charge pad. According to the model tests, splashes which fall to the charge pad are impossible to avoid with studied nozzle arrangements. The usage of bottom blowing increases remarkably splashing rate on the charge pad (Fig. 12). Injection of gas through the bottom nozzles changes flow patterns in the bath and generates heavy splashing on the charge pad area with 5N, 6N, 7N & 8N configuration. With high lance gap (soft blowing), splashing reached maximum values and decreased when lance height decreased in combined blowing.

4. Discussion

In the present study, the maximum splashing rate for lance blowing at certain lance height was found like in some earlier studies.\(^1,5,8,9\) The usage of bottom blowing, especially with high lance heights (initial period of blowing), increases remarkably splashing as He and Standish\(^9\) in model test and Jahanshahi and Belton\(^22\) in industrial scale tests discovered. At the initial period of blowing the increase of splashing was +38% with nozzles arranged at the centre of the vessel and +49% with outside of lance cavities arranged nozzles compared to the lance blowing (Fig. 13). According to the model tests, splashing rate on the walls achieved maximum at the initial period of blowing when high lance height is used. This agrees well with the results of hot model.\(^7\) Wear rate of lining is fastest at the beginning of blowing when protective foamy slag has not yet formed.\(^7,13\) The splashing rate was clearly strongest at the lowest measuring level (distance from the bath surface 0.1 m). Splashing decreases rapidly in the upper part of vessel as is shown from Table 3. This agrees with the hot model studies.\(^21\)

The bottom blowing influences on drop generation in two ways, viz., by a direct and by an indirect effect.\(^8\) The direct effect means direct interaction between the bottom gas bubbles and the lance cavity when the bubbles rise up. The introduction of bottom blowing changes fluid flows in the vicinity of lance cavity and its shape. In the studied bottom nozzle configurations, both effects (direct and indirect) existed during combined blowing.

Since foamy slag layer was not simulated, the differences in splashing behaviour between nozzle configurations are probably emphasized. Bock et al. have reported\(^13\) that it is important to rapidly generate a liquid foamy slag because foamy slag acts as a filter. If liquid foamy slag is not formed, skulming of cone (+12%) and metal losses (+18%) are increased compared to the lance blowing with hard blowing period (lowered lance height) by nozzles arranged at the centre of the vessel (Fig. 13). The operation at low lance height, produces splashing in the upper part of converter and the formation of skulls that are mostly steel in actual process.\(^33\) When nozzles are positioned outside of lance cavities metal losses reduced ~30% and skulming of cone ~9% compared to the lance blowing (Fig. 13). According to Bock et al.,\(^13\) the optimum position for bottom nozzles, as far as mixing of the bath is considered, at near the centre of the vessel. However, as discussed above our results show that metal losses and skulming of cone increased remarkably when the nozzles are arranged at the centre of the vessel. The decrease of splash height with introduction of bottom blowing is analogous than Meshalkin et al.\(^14\) have reported.

The wear of refractory in dolomite, magnesia or carbon added magnesia lined\(^34\) BOF vessel is a result of chemical, thermal and mechanical factors.\(^30\) The reduction of Fe-oxides by carbon contained in the bricks on the surface of the lining, causes the wear of the refractory on the knuckle area.\(^30,35\) The increase of the temperature and slag volume...
which is in touch with the refractory lining, increases the wear rate. The surface of the ejected metal drops is covered with the layer of FeO.\(^{36}\) This causes the chemical stress on refractory because the activity of FeO around the metal droplet is greater than in the bulk slag.\(^{36}\) Okhotskii and Shramko\(^{7}\) discovered by hot model tests that splashing profile on the walls is analogous between slag and metal. An increase in the lance height leads to an increase in the FeO content of the slag.\(^{36}\) However, it should be remembered that the slag with correct composition (with low FeO content) is able to protect refractory.\(^{37}\) The purpose was to achieve even splashing rate against to the refractory lining and avoid splashing peaks especially on knuckle areas and charging pad. Experiments showed that top blowing at high lance distances produced least and furthermore most uniform splashing (Fig. 10). Splashing on the knuckle area increased +5%...+35% and on the charge pad +27%...+57% depending on the lance height with nozzles positioned at the centre of the bottom (Fig. 13). With outside of lance cavities positioned nozzles (5N, 6N, 7N & 8N) the increase of splashing was +19%...+31% on the knuckle area and +54%...+72% on the charge pad. According to the tests, the best alternative of studied bottom configurations was 6N system. In above-mentioned configuration, the overlap of plume and cavity was 38% with lance height 0.20 m (Fig. 11). It must be noticed that reducing of splashing on the knuckle area is possible only at certain lance gaps.

O'Rourke et al.\(^{23}\) found out that high lance distance from the bath level increased splashing on the converter walls. The identical phenomenon was discovered in the present work. The lowered shape of lance cavities at high lance height causes lower trajectories for splashes. At lower lance heights, splashes from the jet cavity tend to be entrained back into the cavity considerable more often than at higher lance heights.\(^{23}\) The introduction of bottom blowing lowers the lance cavities and the height of splash as Meshalkin et al.\(^{14}\) have also stated.

In addition to the splashing behaviour, there are other factors (mixing, degree of slag–metal reactions, oscillation of bath and operational aspects) which are influenced by the bottom nozzle configuration. Traditionally, mixing effectiveness has been one of the most important factors for determining the arrangement of bottom nozzles. The nozzles arranged at the centre of the vessel stimulate mixing, because the quiescent region below the jet cavities is eliminated.\(^{23}\) Singh and Ghosh\(^{38}\) discovered that the degree of slag-metal reaction achieved its maximum when nozzles were arranged near the centre of the vessel (r/R=1/4). On the other hand, during hard blow period of combined blown steelmaking cycle, it may not be necessary to stir the bath through the bottom nozzles because of produced CO gas.\(^{39}\) Furthermore Paul and Ghosh\(^{15}\) has reported excessive splashing in a water model when bottom nozzles were arranged at the centre of the vessel.

According to Koria and George,\(^{40}\) the arrangement of nozzles and gas flow rate from plugs are critical when optimum mass exchange conditions between slag and steel were determined. They presented that nozzles should be arranged asymmetrically on circular with 0.7r distance from the centre of the vessel.\(^{40}\) However, positioning nozzles closer to the walls shear stress was increased and lining life shortened.\(^{41}\) Bock et al.\(^{13}\) have reported increased lining wear in the area of the slag line but also in the section between the slag line and the bottom, if nozzles are arranged too far from the centre of vessel.

Furthermore, in real processes there are many operational aspects (e.g. tilting), which also determine the arrangement and number of bottom nozzles as their own aspects.

5. Conclusions

According to the model tests, following conclusions have been achieved based on the splashing and spitting measurements.

1. Total splashing on the converter walls increases as a function of number of bottom nozzles (with increase of total gas flow rate) both initial and final period of blowing.
2. At the initial period of blowing (H=0.20...0.22 m), combined blowing produces maximum measured total splashing and large reaction area as a form of droplets.
3. The nozzles arranged at the centre of the vessel increase metal losses and skulking of the converter cone especially with lowered lance height.
4. The introduction of outside of lance cavities arranged bottom nozzles decreases metal losses and skulking of converter cone compared to the top lance blowing at final period of blowing.
5. The usage of high lance height and several bottom nozzles accelerate wear of the refractory, especially at the knuckle area and charge pad area.
6. It is possible to reduce splashing to the knuckle areas with certain lance gaps by positioning bottom nozzles directly between the cavity and knuckle area with remarkable (approximately 30–40\%) overlap.

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