Physical Model Study of Selective Slag Splashing in the BOF

Matti J. LUOMALA, Timo M. J. FABRITIUS, Esa O. VIRTANEN, Tero P. SIIVOLA, Tapio L. J. FABRITIUS, Heikki TENKKU and Jouko J. HÄRKKI

University of Oulu, Laboratory of Process Metallurgy, PO Box 4300, FIN-90014 UNIVERSITY OF OULU, Finland.
E-mail: matti.luomala@oulu.fi

(Received on May 2, 2002; accepted in final form on June 29, 2002)

Steelmaking converter vessels do not usually wear evenly. Often, the higher wear rate in the trunnion area determines the lining life of the vessel. On the other hand, major skull growth may occur in other parts. In order to ensure consistent BOF performance, maintaining the vessel geometry by selective slag coating is important. Since selective slag splashing is difficult to perform by conventional oxygen lance, the effect of e.g. plugging one or two lance nozzles on the amount and direction of splashing was investigated by physical model experiments. Furthermore, the model was used to predict the influence of lance height, lance position, bottom blowing configuration and liquid viscosity on splashing behaviour. Lowering the lance increased the rate of splashing to a certain lance height beyond which it decreased. Similar behaviour was found to apply also to the slag wash coating mechanism. At low lance distance, plugging one lance nozzle increased the amount of splashing on charge pad and trunnion areas and decreased on slag hole side. Generally, bottom blowing increased the amount of slag drops considerably. Positioning of bottom stirring plugs had a clear effect on the direction of splashes.

KEY WORDS: steelmaking; slag splashing; physical model; selective coating; plugging lance nozzles; lining life.

1. Introduction

Slag splashing is a simple and an effective method to increase lining life of BOF vessel. After the heat is tapped, and when necessary the slag is conditioned, nitrogen is blown at high flow rates to splash the remaining slag onto the walls of the vessel. The solidified slag then serves as a consumable refractory layer. In addition to extended lining life,1 a large number of benefits are reported: decreased gunning consumption, an increase in the furnace availability and higher productivity and yield.2 In spite of numerous advantages associated with slag splashing, several operating problems such as phosphorus removal, yield, bottom build-up, difficulties with bottom tuyeres and lance skulking are also reported.2 Furthermore, the maintenance aspects of the vessel ancillary equipment, e.g. BOF hoods and gas-handling systems, has to be taken care of.2,3

Although the slag splashing procedure itself is quite simple, there are always some minor differences between the melt shops such as geometry of the vessel, lance design, wear profile of the refractory lining, bottom stirring arrangement etc., that consequently affect how the slag splashing is carried out. It is possible to find reasonably good operational parameters through trial and error, but it also may be very expensive. Therefore, by case-specific physical modelling of slag splashing, it is possible to achieve considerable cost savings. However, compared to the operational and economical results from several melt shops1,2,4-14 only a few results of physical modelling of slag splashing are reported in the literature. In a 2-dimensional slice model, Peaslee15 investigated the effect of liquid viscosity, lance momentum flow rate, height and angle on washing and ejection mechanisms of slag coating. Later Garg and Peaslee16 extended the modelling work in a 1/8-scale model of an actual BOF. The flow rate and slag viscosity were found to have the greatest influence on the overall splashing. Guidelines for selective coating were also given. In a recent paper, Ghosh et al.14 developed optimum lancing parameters for slag splashing based on cold model studies. The height of the splash and the amount of splash hitting the wall were determined by absorption technique.

The refractory lining of the converter vessel under study does not wear evenly. The wear rate is highest at the trunnion area and at the taphole area. In this case, the wear of the taphole area is particularly high because due to the melt shop layout charging of materials and tapping of raw steel are done on the same side of the vessel. On the other hand, major skull growth takes place on the lower part of the wall opposite to taphole, which will be referred to as slag hole side in this paper. The skull is formed by the slag which is ejected by the pneumatic slag stopper at the end of every tap. Since maintaining the vessel geometry is important for consistent BOF performance, the physical modelling study was carried out in order to investigate the possibilities to control slag splashing procedure in such a way that vessel shape could be maintained, i.e. to splash on charge pad and trunnion areas and to avoid splashing on slag hole side. The aim was to clarify the effect of different splashing parameters and fluid viscosities on the location and quantity of splashed slag.

© 2002 ISIJ
2. Experimental Set-up

Figure 1 shows a schematic description of the model used in the research. The operational and geometrical parameters for the physical model and industrial BOF process are presented in Table 1. Compressed air was blown through the 5-hole lance to splash the liquid. The rate of splashing was measured by weighing the amount of liquid collected during the blow in the collecting boxes. The weight was divided by the blowing time which will referred to as splashing rate in this paper. The total amount of collecting boxes was 34, 17 in two rows, around the inner wall of the model.

The boxes located in the areas where heavier wear of refractory lining normally takes place and consequently where the slag splashes were desired. Figure 2 shows the location of the collecting boxes and critical areas, i.e. charge pad/taphole, trunnions and slag hole side on the model wall. Figure 3 shows the dimensions of the splash collecting boxes. Three different artificial slags were tested according to Table 2.

3. Modelling Considerations

The dynamic similarity between the physical model and industrial converter was considered by the following dimensionless numbers. All the symbols and their meanings are given in the Table 3.

The Reynolds number:

\[ \text{Re} = \frac{u_0 d_0 \rho}{\mu} \]  

Momentum number:

\[ \text{Mn} = \frac{\rho u_0^2}{\rho g h'^3} \]  

The Weber number:

\[ \text{We} = \frac{\rho u_0^2}{(\rho g \sigma)^{1/2}} \]  

The Morton number:

\[ \text{Mo} = \frac{\rho u_0^4}{\sigma h'^4} \]  

Reynolds number can be used to compare flow exiting the lance nozzle. Momentum number is defined as the ratio between the jet momentum flow rate at different distances with the action of gravity on the same bath. The Weber number expresses the ratio of inertial force to surface tension force. The Morton number is a function of the properties of the liquid and represents the relationship between gravitational and viscous forces to surface tension force.

| Table 1. The geometrical and operational parameters. |
|-----------------------------------------------------|
| BOF | Model |
| Diameter of the vessel, mm | 4300 | 487 |
| Height of the vessel, mm | 7200 | 809 |
| Height of the slag layer, mm | 200-300 | 35 |
| Charge weight, kg | 5.101 | 2.3 |
| Lance height, m | 1.44-2.52 | 0.16-0.28 |
| Number of nozzles | 5 | 5 |
| Diameter of lance throat, m | 0.029 | 0.0016 |
| Diameter of lance outlet, m | 0.040 | 0.00185 |
| Nozzle angle, ° | 15 | 15 |
| Gas supply pressure, bar | 10 | 5 |
| Gas flow rate, Nm3/min | 340 | 0.6 |
| Atmospheric pressure, Pa | 101325 | 101325 |
| Gas density, kg/m3 | 1.429 | 1.239 |
| Liquid density, kg/m3 | 2800-3100 | 1000-1230 |
| Diameter of bottom nozzles, m | 0.004 | 0.001 |
| Bottom gas flow rate, Nm3/min | 1.5-3.0 | 0.05-0.06 |

Fig. 1. Schematic description of splashing mechanism and measuring method.

Fig. 2. Location of collecting boxes and critical areas on the model wall.
Instead of experimental measurements of industrial slag properties, estimations based on literature were used. Viscosity of slag was estimated to vary between 0.4–1.2 P and density and surface tension between 2,800–3,100 kg/m³ and 0.4–0.6 N/m, respectively.

Table 2. Main physical properties of investigated slags.

| Composition        | Viscosity kg/m/s | Surface tension N/m | Density kg/m³ |
|--------------------|------------------|---------------------|---------------|
| Water              | 1.0·10⁻³         | 72.6·10⁻²           | 1000          |
| 78-wt% water-glycerol | 50·10⁻³       | 67.7·10⁻²           | 1200          |
| 88-wt% water-glycerol | 150·10⁻³      | 66.5·10⁻²           | 1230          |

Table 3. List of symbols.

Table 4. Comparison of dimensionless numbers between the converter and the physical model.

|                     | BOF               | Model              |
|---------------------|-------------------|--------------------|
| Reynolds number, -   | 20.5·10⁴          | 5.3·10⁴            |
| Weber number, -      | 3.95·10⁴          | 6.5·10⁴            |
| Momentum number, -   | 1.79·10⁴          | 2.6·10⁴            |
| Morton number, -     | 3.8·10⁶·1.1·10⁻⁵ | 2.6·10⁻⁴·1.4·10⁻⁷ |
depending on the lance height when LP2 was used. It has to be noted that the total amount of gas exiting the bottom nozzles also increased.

### 4.2. Plugging Lance Nozzles

When bottom blowing was not used, plugging one lance nozzle (LP2) increased splashing on charge pad and on trunnion areas especially at lance heights of 0.16–0.20 m and decreased on slag hole side at all lance heights. Although one lance nozzle was plugged, the total amount of measured splashing increased clearly with both bottom blowing configurations. Figure 6 shows the splashing rate in slag hole side and trunnion and charge pad areas as a function of lance height. According to Fig. 6, lance height 0.20–0.22 m is optimal for slag splashing because the quantity of collected splashes is large on trunnion and charge pad areas and relatively small on slag hole side. Splashing behaviour with 6·10 l/min bottom plug arrangement is analogous with Fig. 6.

Plugging two lance (LP1) nozzles reduced the total amount of splashing markedly. The reduction was from 28 to 60% depending on the lance height. The three remaining gas jets turn about 10° towards the charge pad area. Moreover, bottom blowing plugs (5·10 l/min) direct splashes to charge pad area. Consequently, splashing decreased on trunnion area, and was almost negligible on slag hole side. On the other hand, splashing on charge pad area increased when the lance height was 0.16–0.20 m.

### 4.3. Properties of Artificial Slag

The original idea was to study the effect of liquid viscosity on splashing behaviour. However, changing liquid viscosity with glycerol, the values of surface tension and density varied also to some extent as shown in Table 2. Consequently, three slags with different viscosities, densities and surface tensions were investigated. According to the model tests, the amount of splashing is strongly dependent on the properties of the liquid. Figure 7 shows the amount of total splashing as a function of lance height.

### 4.4. Slag Wash Coating

In addition to slag ejection studies, some experiments were done in order to find an optimal lance height for slag wash coating. Since the height of the liquid bath in the model was only 35 mm, the jet impinged directly on the bottom of the model and swept the water off the bottom re-
sulting water to wash lower parts of the model as shown in Fig. 1. Figure 8 shows the height of the artificial slag film wetting the model wall through slag wash coating mechanism as a function of lance height. According to model tests, the maximum washing height of the liquid film was achieved with lance height of 0.23–0.25 m which corresponds to 2.10–2.25 m in the industrial system. Figure 8 also reveals that the maximum splashing rate is obtained at approximately same lance distance.

5. Discussion

Generally, lowering the lance increased the rate of splashing to a certain lance height beyond which it decreased. Our finding is thereby in agreement with e.g. those of Chatterjee and Bradshaw\(^{19}\) and Standish and He.\(^{20}\) In the present study, similar behaviour was found to apply also to the slag wash coating mechanism. Introduction of bottom blowing increased the rate of splashing significantly. Standish and He.\(^{20}\) have suggested that bottom blowing influences the droplet generation by a direct effect and by an indirect effect. Since the height of the bath was so low in this study, neither of the suggested mechanisms applies. Presumably, strong bottom blowing itself directly assists the drop generation and consequently causes an increase in measured total splashing. Furthermore, He and Standish\(^{21}\) observed that maximum droplet generation was achieved when the position of bottom tuyeres was at the outside of the impingement zone. In the present study, no attempt was made to find an optimal bottom plug positioning as far as slag splashing is considered. The location of bottom tuyeres in relation to jet cavities changed only as a function of lance height, and so no solid conclusions of the influence of the distance of bottom plugs in proportion to impingement zone were made.

At low lance distance 0.20–0.22 m, plugging one lance nozzle (LP2) increased the amount of splashing on charge pad and trunnion areas and decreased on slag hole side. Plugging two lance nozzles (LP1) is suitable when efficient selective coating of charge pad is desired. Not only the bottom plugs direct splashes on the charge pad area, but the gas jets itself turn 7–15° degrees towards that area, which was studied by further experiments without bottom blowing.

It is evident that the properties of the liquid influence not only on the sticking characteristics but also significantly on the amount of splashing. A clear shortcoming of the present study is, however, that the effect of single liquid property was not investigated. Since the values of density and surface tension were only slightly changed, the effect of viscosity on the amount of total splashing is probably dominant in Fig. 7. Garg and Peaslee\(^{16}\) suggested that the reduction is a consequence of higher forces being required to break up a more viscous fluid and form droplets. Due to the fluctuations in temperature or composition of final slag, viscosity presumably has the widest range of variation and consequently the greatest influence on splashing also in the industrial operation.

The most appropriate alternatives of the studied options for slag splashing operation, insofar as splashing on critical areas is considered, are presented in Fig. 9. Generally, LP2 was found to be more suitable for slag splashing than LP1. Furthermore, the model tests conducted in the present study show that the best solution seems to be plugging one lance nozzle. In that particular case, splashing on the slag hole side is naturally lower than with normal nozzles. Moreover, splashing on trunnion and charge pad areas is high.

If plugging of lance nozzles proves to be too difficult to implement in practice, i.e. changing the lance height is the only way to control slag splashing, splashes on slag hole side are difficult to avoid. According to Fig. 7, maximum amount of slag splashed can be achieved when slag splashing is started at lance gap 0.24 m, and by gradually lowering the lance as the slag slowly cools down and solidifies. Since above-mentioned procedure splashes slag maximally, it may advantageous as far as bottom growth is concerned. However, the skulling of the cone may become a problem.

The results presented in this paper were used to design safe and practical plant trials before implementation of slag splashing practice. Some of the experiments performed by the physical model may, however, be difficult to carry out in practice. Problems concerning simple and fluent method for plugging one or more lance nozzles are yet to be solved. Additionally, directing slag splashes through bottom blowing in the industrial scale may differ substantially from that
in the physical model.

6. Conclusions

An experimental physical model study was carried out to determine the influence of lance height, lance position, two bottom blowing configurations, liquid viscosity and plugging lance nozzles on the amount and direction of splashed slag. The following conclusions may be drawn from the results obtained:

1. Using bottom blowing increases the amount of slag drops considerably.
2. Positioning of bottom stirring plugs has a clear effect on the direction of splashes.
3. Lance position LP2 is more appropriate for slag splashing than LP1.
4. Plugging one nozzle from LP2 further improves splashing properties. At low lance distance (0.20–0.22 m), the amount of splashing increased on charge pad and trunnion areas and decreased on slag hole side.
5. If the lance height is the only variable for splashing procedure, splashes on slag hole side are difficult to avoid when protection for trunnion and charge pad areas is desired.
6. Slag properties, especially viscosity, have a strong influence on the amount of splashing.

Acknowledgements

This work was carried out under a project subsidised by the ECSC. The authors would like to thank the Management of Rautaruukki Steel and ECSC for permission to publish this paper. Special thanks are due to Marko Petäjäjärvi and Antti Kajjalainen for their assistance in the experimental work.

REFERENCES

1) R. O. Russell, N. Donaghy, E. C. Meyer and K. M. Goodson: 1st European Oxygen Steelmaking Cong., VDEh, Düsseldorf, (1993), 220.
2) K. M. Goodson, N. Donaghy and R. O. Russell: Proc. of 78th Steelmaking Conf., ISS/AIME, Warrendale, PA, (1995), 481.
3) J. Schriefe: New Steel, 12 (1996), No. 5, 48.
4) S. R. Balajee, B. J. DeTineo, K. L. Charleston and J. E. Bradley: Iron Steelmaker, 16 (1989), 24.
5) D. B. Hoffman and C. Ziegler: Proc. of 78th Steelmaking Conf., ISS/AIME, Warrendale, PA, (1995), 499.
6) L. Greco and A. McGowan: Proc. of 80th Steelmaking Conf., ISS/AIME, Warrendale, PA, (1997), 97.
7) J. A. Terblanche and J. P. Pienaar: 2nd European Oxygen Steelmaking Cong., AIM, Milano, (1997), 323.
8) D. L. Amoss: Refract. Eng., (1998), s.22.
9) H.-U. Schmidt, W. Holzhey, E. Kuschke, T. Daum and K. Müller: Steel Times, 226 (1998), 286.
10) Y. Wenyang, Z. Congjie, D. Kun, W. Jindong, C. Jian, G. Zhenbin and F. Zhongliang: Asia Steel, (1999), 99.
11) F. A. Lima, J. E. Pinto, S. S. Hanashiro, H. A. Quintão and S. M. Carvalho: Proc. of 83rd Steelmaking Conf., ISS, Warrendale, PA, (2000), 251.
12) D. Zorlescu, I. Ungureanu and F. Zaman: 3rd European Oxygen Steelmaking Conf., IOM, London, (2000), 477.
13) C. Jian, Y. Wenyuan and Z. Congjie: Iron Steelmaker, 27 (2000), No. 7, 39.
14) S. Ghosh, S. Majumdar, M. M. Prasad and S. K. Mozumdar: Proc. of 85th Steelmaking Conf., ISS, Warrendale, PA, (2002), 603.
15) K. D. Peaslee: Iron Steel Eng., 73 (1996), 33.
16) A. K. Garg and K. D. Peaslee: Proc. of 80th Steelmaking Conf., ISS/AIME, Warrendale, PA, (1997), 87.
17) H.-D. Dörfler: Colloid Polymer Sci., 257 (1979), 882.
18) A. K. Garg and K. D. Peaslee: Iron Steelmaker, 25 (1998), No. 7, 57.
19) A. Chatterjee and A. V. Bradshaw: J. Iron Steel Inst., 208 (1972), 179.
20) N. Standish and Q. L. He: ISIJ Int., 29 (1989), 455.
21) Q. L. He and N. Standish: ISIJ Int., 30 (1990), 305.