Study of Droplets in converter slag

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Abstract: Droplets are of critical interest for many metallurgical processes. In the basic oxygen furnace metal droplets generated by the impinging gas jet increase the slag-metal contact and enhance significantly the rates of the decarburization and dephosphorization. However residence time and the nature of the droplets are still a matter of discussion. In the present work, the formation of droplets in the basic oxygen furnace was studied using cold model. A low melting point Ga-In-Sn alloy was used with hydrochloric acid on the top to simulate the slag. The sizes of the droplets were studied at different lance heights and flow rates. From observation of the metal droplet movements and their velocities, it was concluded that the residence time was greatly affected by the turbulent viscosity. In a converter, the droplets could stay in the slag for even 1 minute.

Key words: Droplets, Residence time

1. Introduction

The generation of droplets is of interest for the converter process. Droplets generated by the blowing would increase the metal-slag surface area thus promoting decarburization and dephosphorisation. The part of the total dephosphorization and decarburization that can be attributed to reaction with droplet is still unclear. Cicutti[1] suggested that 20-50% of the total decarburization was due to reaction with droplets. The effect of droplet would be largely affected by the amount droplets and their residence time in the slag. The residence time of droplets in the slag during the converter process has frequently estimated to about 1-2 minutes [2-4]. The residence time of droplets is still matter of discussion. He and Standish [5] investigated residence time of droplets in a mercury-glycerin model. They found residence time to increase with increased top lance blow rate and decrease the increased bottom stirring. Several models for the residence time of droplets have been proposed. A models based on the ballistics of droplets for calculating the residence time was developed by Subyago.[6] While other have introduced the concept bloating of droplets during decarburization.[7].

In the present work, the formation of droplets in the basic oxygen furnace was studied using cold model. A low melting point Ga-In-Sn alloy was used with hydrochloric acid on the top to simulate the slag. The sizes of the droplets were studied at different lance heights and flow rates. The movement and velocities were also studied.

2. Experimental

2.1 Experimental setup

The experimental setup is shown schematically in **Figure 1**. The vessel had dimensions of 290 mm x 480 mm x 16 mm. The small thickness (16mm) of the vessel would facilitate the observation of the penetration when the liquid was not transparent. A top lance was mounted above the liquid bath positioned in the center of the vessel. The nozzle was 2mm in diameter and made with a straight bore in bottom of the lance. The vessels and the lance were made of Poly methyl methacrylate (PMMA).

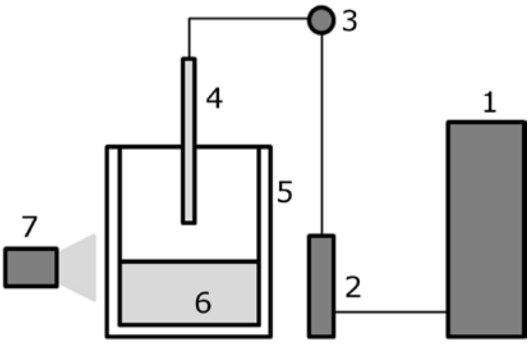

Fig. 1: Schematic experimental setup. 1) Gas supply 2) Rotameter 3) Pressure gauge 4) Top Lance 5) Vessel 6) Liquid 7) Camera.

In the experiments, Ga-In-Sn alloy which had a melting temperature of 283 K was used. The density and viscosity of the alloy are very similar to that of molten steel, see **Table 1**. Experiments were conducted with and without top liquid phase. The top liquid was HCl (10 volume%). To avoid oxidation of the Ga-In-Sn alloy, argon gas was employed in the experiments. A rotameter supplied by Brooks Instruments with a range of 60L/min for air was used to regulate the flow. To record the pressure of the gas, a pressure gauge was connected just before the lance. A video camera was employed to record the gas penetration and the droplet behavior.

Table 1: Physical properties of liquids used in the experiments

Material	Density Rho [kg/m^3]	Viscosity [mPas]
GaInSn	6361	2.1
Water	1000	1
Hydrochloric acid	1060	1

2.2 Droplet sizes and movement

The momentum of the gas jet would create metal droplets in the top liquid. The movements of droplets in the top liquid were investigated from the videos obtained in the penetration study. Droplets were identified and traced frame by frame. Trajectories and velocities of the droplets could be obtained by tracking the droplets frame by frame. In order to study the size distribution of droplets a number of photos were taken from each blow. The size distribution was studied for different lance height and flow rates.

3. Results

Although one original goal was to study the numbers of droplets generated at different flow rates, it was found in the experiments that the present facility could not make any reliable quantitative estimation. Still, it was observed qualitatively that high flow rate would result in bigger number of droplets. **Figure 2** presents the droplets accumulated at the interface between metal and top liquid after blowing time of about 1 minute. While a big fraction of the droplets would go back to the metal bulk, some of them as shown in the figure would stay at the interface for a period of time due to the film of HCl solution on their surfaces. **Figure 2a** and **b** show the photos for a lance height of 3 cm at flow rate of 32 l/min and 25 l/min. A comparison of the two figures reveals that higher gas flow rate leads to more droplets. Figure 2c presents the photo obtained for lance height of 5cm and at a gas flow rate of 32 l/min. A comparison of Figure 2a and 2c seems to suggest that lower lance position creates bigger number of droplets.

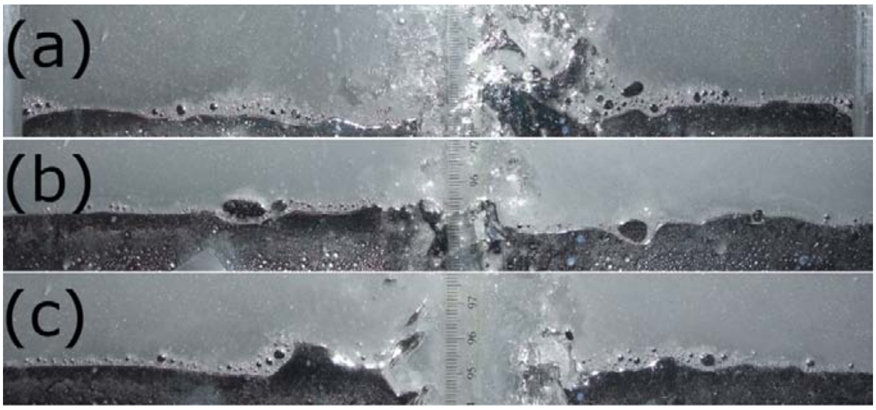

Fig. 2 Generated droplets stuck at the meta-acid interface

There were a large number of smaller droplets, usually less than 1 mm in diameter. These tiny droplets could be recognized by naked eyes, but could not be followed by video. The droplets visible to the video camera are in the range of 2 and 5 mm in diameter. Some typical examples of the droplets are presented in **Table 2**. The average velocities of these droplets are also listed in the table.

Table 2 Velocities and sizes of identified droplets

Droplet No	1	2	3	4	5	6	7	8
Terminal Velocity [m/s]	[26]	[32]	[24]	[10]	[6]	[17]	[20]	[20]
Average Velocity [m/s]	0.27	0.25	0.43	1.1	0.38	0.35	0.32	0.21
Diameter [cm]	0.43	0.47	0.41	0.27	0.2	0.34	0.37	0.37
Type	Falling	Falling	Falling	Falling	Falling	Falling	Falling	Spit
Destination	Center	Center	Center	Side	Side	Center	Center	Center

The droplets have different movement patterns. Figure 3 shows the ejection of two droplets at a low angle. This process goes very fast, like spitting. The droplets resulted from spitting have a short residence time in the slag, in this case less than 0.3 seconds.

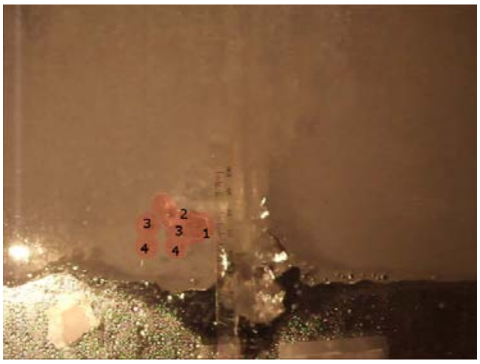

Fig. 3 The life of a typical spitting of 2 droplets

Figure 4 presents another type of droplet movement. The droplet is created and brought up to point 1 from where it falls back to the surface of the bath. In this case the full residence time of the droplet is unknown, while the falling back takes about 0.5seconds.

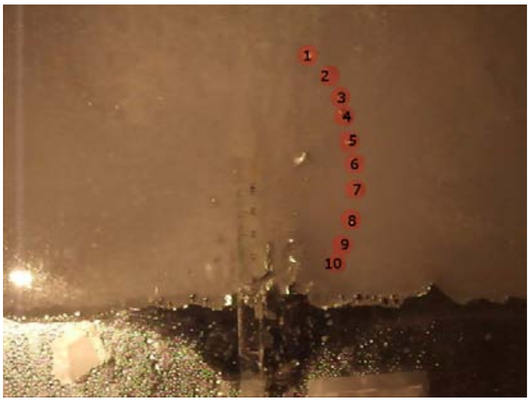

Fig. 4 The trajectory of a droplet falling back to the metal

3.1 Size distribution of Droplets

In **Figure 5-7** the droplet size distributions of droplets generated by blowing at a lance height of 1cm, 3cm and 5cm are presented. It can be seen that the majority of the droplets are smaller than 1mm while the droplets having size around 4mm are found much less frequently. From the figures it is seen that higher flow rates generate higher amount of droplets. Figure 5 and 7 also shows that higher flow rates generate smaller droplets. However similar trend is not seen in Figure 6.

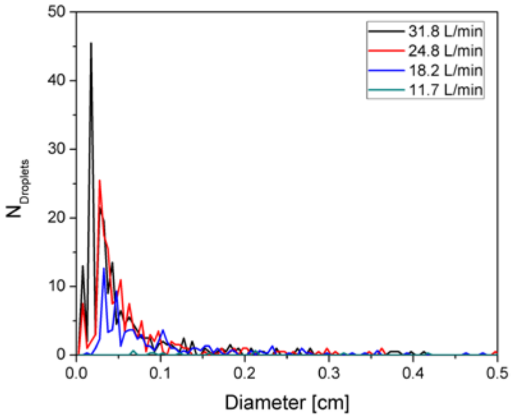

Fig. 5 Size distribution of droplet at a lance height of 1cm

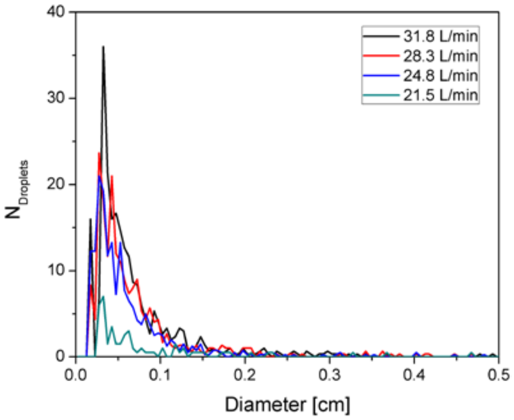

Fig. 6 Size distribution of droplet at a lance height of 3cm

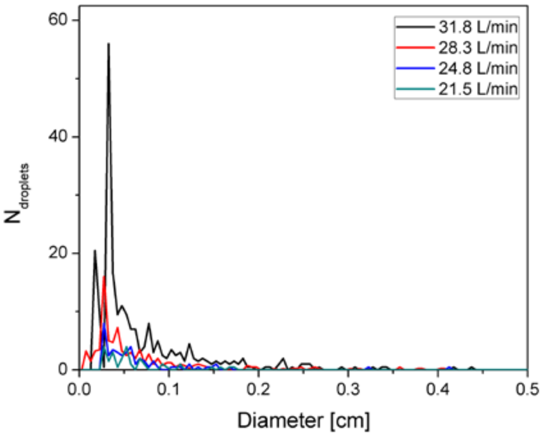

Fig. 7 Size distribution of droplet at a lance height of 5cm

4. Discussion

As discussed in the result part, it was very difficult to follow the movements of small metal droplets. Only the movements of droplets bigger than 2 mm could be followed by the video camera. However, the velocities of these bigger droplets are still interesting. In order to get better grip of the falling of the droplets, the terminal velocities of the droplets based on the dynamic viscosity of HCl are estimated and presented in **Table 2**. It is seen that the falling velocities of the droplets are far too small compared to the terminal velocity calculated based on the dynamic viscosity of HCl solution, being 2 orders of magnitude lower. Note that in a gas stirred bath, the flow is very turbulent. Using dynamic viscosity to estimate the terminal velocity would be very misleading. For this reason, the values are given in square brackets [ ] in **Table 2**. It is common knowledge that the effective viscosity (the sum of turbulent viscosity and dynamic viscosity) in a gas stirred bath would be 2 orders of magnitude higher than the dynamic viscosity. The observed velocities of the droplets are in fact in accordance with this reasoning. In the present cold model, the height of the top phase is only 15 cm. The residence time of a droplet is observed to be at the level 0.5-1 seconds in general. On the other hand, slag in an industrial converter has a dynamic viscosity of about 0.2 Pa.s, which is about 100 times of the HCl solution. Moreover, the violent stir of the oxygen jet along with the foaming nature of the slag would lead to very high effect viscosity. A droplet of 4 mm in diameter would have a terminal velocity of about 0.2 m/s, in the case of laminar flow in single liquid phase. In reality, the droplet velocity would be much smaller than the terminal velocity calculated using the dynamic viscosity, as revealed by the present observation. Hence, the residence time of a metal droplet in the foaming slag could range from a few seconds to even minute due to the large effective viscosity of the "slag". He and Standish [5] investigated the residence time in mercury-glycerin model. They found that the residence time increased with increased top blowing rate. This increase can well be explained by the increasing turbulent viscosity. The authors [5] further reported that a residence time about 1 minute in the slag to be reasonable. Furthermore, the droplets seen in the videos are relatively large compared to the majority of the droplets in present study. **Figure 8** displays the calculated terminal velocity for steel droplets in slag for a laminar and turbulent case over a range of droplet diameters.

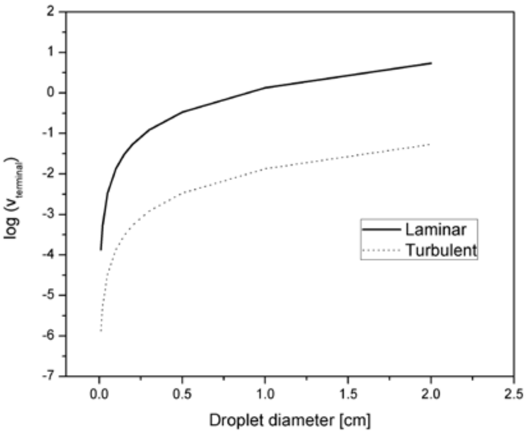

Fig. 8 The effect of steel droplet diameter on the terminal velocity in slag

For a typical droplet with a diameter of 0.2mm the terminal velocity would be very low at about 0.5 mm/s in the case of laminar flow. Following the reasoning made for turbulent viscosity in regards the larger droplet it is clear that these small droplets would stay in the slag for a very long time. It is feasible that these droplets could oxidize and enter the slag as FeO.

5. Conclusions

In present study, cold model experiments using liquid Ga-In-Sn alloy were carried out. Droplets generated by gas jet were identified. The velocities of the droplets and their size distribution were evaluated. It was found that the majority of the droplets were smaller than 1mm. It was found that for larger droplets, around 4-5mm, the droplet velocity was hundred times lower than the terminal velocity evaluated using dynamic viscosity. The huge difference could be well explained by the very large turbulent viscosity. The residence time of the droplets in slag could be as long as 1 minute in the BOF process according to the present reasoning. For very small droplets they would have the possibility to stay for much longer times.

References

[1] C. Cicutti , M.Valdez, T. Pérez, J. Petroni, A. Gómez, R. Donayo and L. Ferro: 6th Int. Conference on Molten Slags, Fluxes and Salts, Stockholm-Helsinki,2000

[2]D.J. Price: Process Engineering of Pyrometallurgy, M.J. Jones, ed., The Institution of Mining and Metallurgy, London, 1974, pp. 8-15

[3]P. Kozakevitch: JOM, 1969,vol 22 (7), pp. 57-68

[4]J. Schoop, W. Resch and G. Mahn: Ironmaking & Steelmaking, 1978, vol. 2, pp. 72-79

[5]Q. L. He and N. Standish: ISIJ International, 1990, Vol. 30, No 5, pp 356-361

[6]Subagyo, G.A. Brooks and K. Coley: Can. Metall. Q., 2005, vol 44, 1, pp 119-129

[7]G. Brooks, Y. Pan , Subagyo and K. Coley: Metallurgical and Materials Transactions B,2005, Vol. 36B, pp. 525-535