Analysis of Droplet Generation in Oxygen Steelmaking

Neslihan DOGAN, Geoffrey BROOKS and Muhammad Akbar RHAMDHANI

Faculty of Engineering and Industrial Science, Swinburne University of Technology, Hawthorn, VIC 3122, Australia.
E-mail: ndogan@swin.edu.au

Knowledge of droplet generation during oxygen blowing, which can be characterized by a blowing number (N_B), is crucial for better understanding of the fundamentals of the kinetics of oxygen steelmaking. A mathematical model has been developed considering the influence of surface tension on the blowing number (N_B) using plant data from the study of Holappa and Jalkanen. The model predicts the droplet formation as a function of carbon, sulphur and oxygen contents in the metal, the temperature profile of the metal bath and lance height. This study includes a sensitivity analysis to investigate the effect of the changes in the oxygen concentration throughout the process. It has been found that the rate of droplet generation increases with increasing jet momentum onto the metal bath and with decreasing surface tension of the liquid metal. The model also suggests that generally the variation in oxygen and sulphur contents in liquid bath has relatively little influence on droplet generation compared to the effect of blowing parameters. However, in the case of low carbon steels (<0.05 mass% C), the blowing number increases by more than 50% at the end of the blow due to lowering of surface tension.

KEY WORDS: droplet generation; blowing number; oxygen steelmaking; gas impingement.

1. Introduction

Droplet generation is a crucial part of the process kinetics of oxygen steelmaking because it contributes to large interfacial area during the blow which in turn affects the mass transfer between metal and slag. Accordingly, the blowing number, N_B, has been used to quantify the influence of the generation of droplets on the kinetics of oxygen steelmaking.[1] This dimensionless number relates the jet momentum intensity and the properties of liquid metal and given by the following equation,

$$N_B = \frac{\rho_g U_G^2}{2\sqrt{\gamma g \rho_L}} \quad \text{.............................(1)}$$

There have been several experimental studies and mathematical models investigating the influence of the intensity of jet momentum on the metal droplet generation established in the past three decades.[1–6] However, there is still limited knowledge on the effects of liquid properties, such as surface tension, on droplet generation compared to the effect of operating conditions in oxygen steelmaking.

In this study, the influence of surface tension of liquid metal as a function of temperature and composition of the liquid metal on the generation of metal droplets has been analysed by using the industrial data from the study of Jalkanen and Holappa.[7] This is the only study in the literature that provides data on the variation in oxygen content in the bath complete with important process parameters such as lance height, metal and slag compositions and oxygen blowing rate. The aim of this study is to contribute a better understanding of the influence of surface tension on droplet generation in top-blowing oxygen steelmaking processes.

2. Mathematical Modelling

2.1. Theoretical Background

The blowing number is based on Kelvin–Helmholtz instability criteria.[1] On the basis of this criteria, the interface between gas and metal phases is postulated to be unstable due to the motion of phases with different velocities on each side of the interface for top blown oxygen steelmaking systems. Accordingly, gravity and surface tension forces tend to stabilize the interface, whilst the inertial force tends to destabilize the interface. Under dynamic blowing conditions, inertial forces dominate other forces. Therefore, the interfacial flow increases the frequency of surface waves until, at a certain point, surface waves break up and metal droplets are torn off, which leads to the formation of emulsified phase.[8,9]

For a better understanding of the droplet generation, it is necessary to investigate the factors affecting the behaviour of interfacial flow. One of the important factors is the surface tension. It is assumed that the surface tension of liquid iron is considered instead of interfacial tension because in the impact region of the furnace the slag is not in contact with the metal. Although the factors governing the surface tension of liquid metal include temperature, concentration of solutes (particularly surface active elements) and electric potential, only the effects of temperature and concentration of the liquid metal were taken into account in this study.

A comprehensive overview of the surface tension of pure

liquid iron was made by Keene.[10] He suggested a correlation for surface tension of liquid iron as a function of temperature. Surface tension of alloys is dependent on both temperature and composition of the alloy. For example, the presence of surface active elements, such as oxygen and sulphur, affect the surface tension considerably. Poirier and Yin[11] further developed the correlation by Keene to include the effects of sulphur and oxygen on surface tension of liquid iron. This correlation is obtained by averaging the correlations proposed by previous researchers.[12–16] Chung and Cramb[9] related the effect of sulphur and oxygen contents on surface tension of iron with the carbon level in the bath as a function of temperature by using the approach of Belton[17] and of Sahoo et al.[18] This correlation, which is based on Gibbs–Langmuir adsorption isotherm, is used in this study, and is given by:

$$\gamma = 1\,913 + 0.43[1\,823 - T_b] + 67.75[wt\% \, C] \\ - 0.10T_b \ln[1 + K_S a_S] - 0.153T_b \ln(1 + K_O a_O) \quad ....(2)$$

K_O and K_S are the adsorption coefficients for oxygen on liquid iron alloys and for sulphur on liquid Fe–4mass%C alloys, respectively and they are given by[9];

$$\log K_O = 11\,370/T_b - 4.09 \quad ....(3)$$

$$\log K_S = 10\,013/T_b - 2.87 \quad ....(4)$$

The activity of oxygen is calculated from the activity coefficients by using the following equation.

$$\log f_O = e_O^O(mass\% \, O) + e_O^S(mass\% \, S) + e_O^C(mass\% \, C) \quad ....(5)$$

where e_O^O, e_O^S, e_O^C are the first order interaction parameters, and are obtained from the literature.[19]

Equation (2) represents the surface tension of liquid iron as a function of carbon, sulphur and oxygen contents and bath temperature at equilibrium. Although the system is non-equilibrium, we have assumed that the sulphur and oxygen contents are in equilibrium with carbon monoxide for the purpose of these calculations.

In order to predict the influence of surface tension of liquid metal to analyse the droplet generation, it is necessary to estimate the variations in concentration of oxygen and sulphur, and temperature of the liquid metal. It is known that the temperature of metal bath (T_b) increases linearly during the oxygen blow as has been shown in previous studies.[20,21] The metal temperature can be approximated using;

$$T_b = z \cdot t + T_{b,0} \quad ....(6)$$

Sulphur has a small variation with low content during the blow. Conversely, oxygen has a relatively higher variation because oxygen is the driving force for refining reactions, particularly for decarburization during the blow. However, towards the end of the blow, oxygen is consumed mainly by iron, phosphorus and manganese due to a decrease in carbon content. Consequently, the oxygen content during the blow is low and builds up towards the end of the blow.[22] Oxygen concentrations in the metal vary from 0.002 to 0.16 depending on the composition of the metal bath, blowing practice and sampling methods.[22–24]

2.2. Numerical Analysis

Combining the mathematical modelling with theoretical basis, the blowing number can be calculated as a function of bath temperature, oxygen, sulphur and carbon contents to analyse the droplet generation under the given operating conditions for a 55 ton top-blowing oxygen steelmaking process.

In Eq. (1), the critical gas velocity is related with jet centreline velocity at the metal surface which can be obtained using the equation for the dynamic impact pressure of the jet at the metal surface given in the literature.[1,25] Numerical results were obtained under the conditions given in **Table 1**. The data in this table were taken from the study of Jalkanen and Holappa.[7,26] The inclination angle of nozzle was not given in their study. In the present study, the inclination angle of nozzle was assumed to be 15°.

Figure 1 shows the industrial data for maximum and minimum values of the oxygen, sulphur and carbon concentrations in the metal bath with the progress of top blowing.[7] However, oxygen content at the end of the blow was not given in the study by Jalkanen and Holappa. Turkdogan[22] evaluated the available industrial data and suggested the following relationship between carbon and oxygen contents in the bath at the end of the blow.

$$[ppmO]\sqrt{\%C} = 135 \pm 5 \quad ....(7)$$

This correlation is valid at low carbon contents (below

Table 1. Data for numerical calculation.

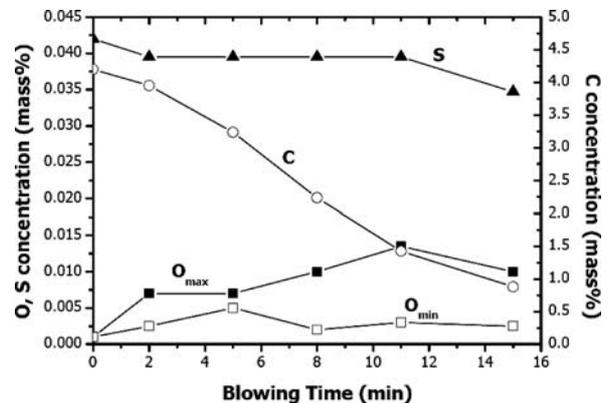|	
Furnace capacity	55 t
Blowing time	18 min
Oxygen flow rate	130 Nm³/min
Supply pressure	8 atm
Number of nozzle	3
Diameter of throat	24 mm
Lance height	0.9-1.25 m
Initial hot metal temperature	1330°C
Tapping temperature	1640-1700°C

Fig. 1. The change of oxygen, sulphur and carbon content (in mass%) of metal bath throughout the blow, from Jalkanen and Holappa.[7]

0.05 mass%). For higher carbon contents, the oxygen content can be approximated by the following equation developed by Turkdogan.[22]

$$[ppmO][\%C]=30 \quad ....(8)$$

In this study, average values for oxygen concentration were used for the calculations. The temperature of molten metal was determined by modifying Eq. (6) for the study by Jalkanen and Holappa given as:

$$T_b=19 \cdot t+1\,330 ....(9)$$

3. Results and Discussion

3.1. Effect of Operating Conditions

The blowing number is calculated as a function of gas flow rate, nozzle diameter, lance height, surface tension and density of liquid metal and the results are presented in **Fig. 2**. The lance height is the only variable changing with time and the other parameters of lance design remain constant in this particular practice. The lance was kept close to the converter in the early part of the blow, followed by an increase in lance height during the main blow. Towards the end of the process, the lance height was decreased again. As can be seen in Fig. 2, when the lance height decreased, the transfer of jet momentum from gas to liquid phase increased and therefore the blowing number increased.

The calculated blowing number as a function of lance dynamics ranges from 6 to 8.5. For example, the maximum value for blowing number occurs in the initial period of the blow when the lance height is 0.9 m. The blowing numbers obtained in the present study are consistent with those obtained by Subagyo et al.[1]

3.2. Effect of Surface Tension

The effect of surface tension of liquid iron as a function of temperature and oxygen, sulphur and carbon contents in the liquid iron was investigated and the results are given in **Fig. 3**. The surface tension of liquid iron, relative to the surface tension of pure iron decreases as the temperature of bath and the oxygen content of liquid iron increase. Although the temperature of the bath increases linearly, the surface tension increases due to a decrease in both sulphur and oxygen concentrations towards the end of the blow.
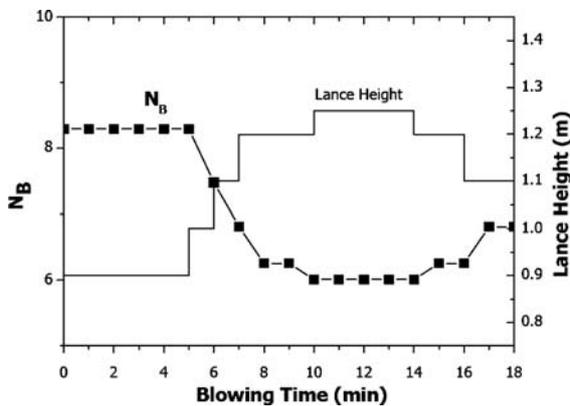
The results of the blowing number calculations as a function of the variations of surface tension changing with time are given in **Figs. 4** and **5**. The decrease in surface tension increases the blowing number, particularly for the first 4 min of the blow as the lance height remains constant. However, the change in the position of lance height has more effect on droplet generation compared to the effect of the change in surface tension.

Figure 5 shows the difference between the blowing numbers calculated by considering constant and variable surface tension throughout the blow. It can be seen from Fig. 5 that
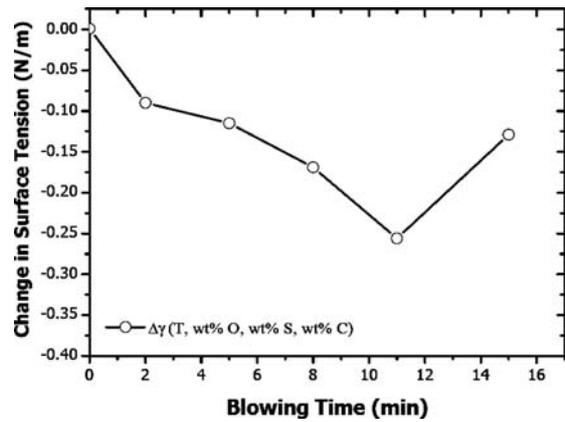
Fig. 3. The change of surface tension with time as a function of bath temperature, oxygen, sulphur and carbon contents.
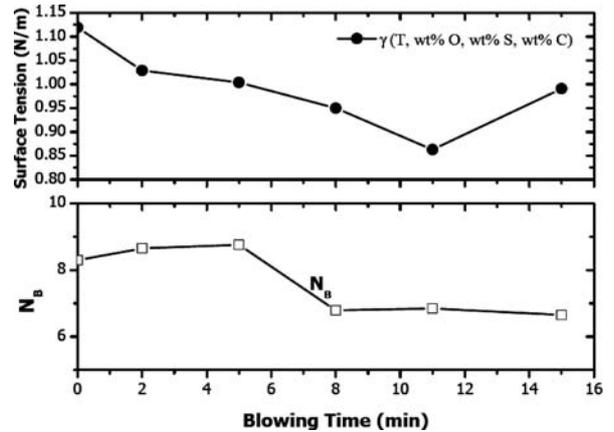
Fig. 4. The blowing number and surface tension as a function of time.

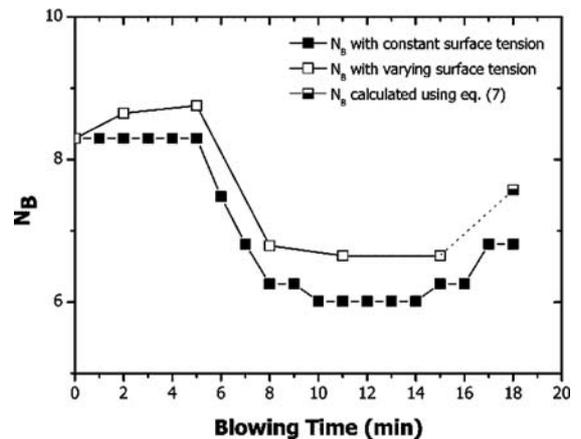**Fig. 2.** Blowing number as a function of lance height and blowing time.[7]

Fig. 5. The blowing number determined using constant and varying surface tension.

they are close to each other which implies that the transfer of jet momentum is the crucial factor for droplet generation compared to the changes in physical properties of liquid iron in top blowing practice. These calculations were repeated using the maximum oxygen content value presented in Fig. 1 and same conclusion was reached. If blowing parameters such as lance height and oxygen flow rate remain constant, then variations in the surface tension of liquid iron become more important.

3.3. Effect of Carbon Content at the End of the Blow

It is known that oxygen concentration in the liquid metal increases with decreasing the rate of decarburization at the end of the blow. As more oxygen dissolved in the metal, the surface tension will be much lower and results in more droplets generation towards the end of the blow. This effect was considered for the present industrial data using Eq. (7). Accordingly, blowing number as a function of surface tension at the end of the blow was obtained, *i.e.* the data point at 18 min as shown in Fig. 5. As seen, blowing number increases to a higher value at the end of the blow. It can be said that the effect of surface tension of the liquid metal, thereby, the composition of the liquid iron becomes more significant towards the end of the blow.

The relationship between the end carbon and oxygen contents was investigated using Eqs. (7) and (8). The end carbon content in liquid metal was selected ranging from 0.25 to 0.01 mass%, and the corresponding oxygen contents were calculated. The calculated oxygen contents (along with the bath temperature, the carbon contents and an assumed sulphur content of 0.03 mass%) were then used in considering the change in the surface tension for calculating the blowing numbers prior to the end of the blow. The results of the calculations for different lance height are shown in **Fig. 6**. As the end carbon level of the liquid metal decreases, blowing number increases for a given lance height. Blowing number increases from 8.3 to 14.5 when the end carbon level decreases from 0.25 to 0.01 mass% for a lance height of 1 m.

These findings are important in the modelling of oxygen steelmaking because it allows the oxygen content of the bath, a quantity that is difficult to measure and predict, to be largely ignored in calculating the droplet generation rate
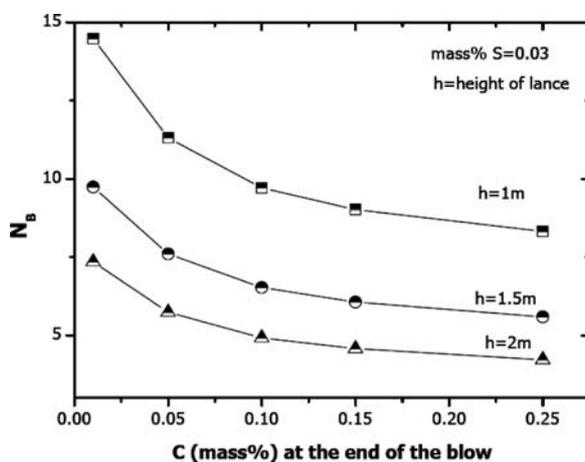
with time. In the case of low carbon steels, the authors suggest droplet generation becomes more dependent on the composition of steel required only towards the end of the blow. It should be noted that this result is based on only one set of industrial data, however, the authors expect this finding would be duplicated in similar industrial studies. Further industrial trials are required to fully quantify this effect.

The authors also expect the oxygen content at the impact zone to be higher than the bulk oxygen content in liquid bath. Therefore, the calculations based on bulk data will tend to underestimate droplet generation. However, there is no data available in the literature to quantify this suggestion.

4. Conclusions

To establish the effects of the operating conditions and liquid properties on droplet generation for top-blowing oxygen steelmaking process, a mathematical model was developed in this study and the conclusions reached are as follows:

(1) The blowing number increases with decreasing the lance height due to an increase of the intensity of jet momentum.

(2) The surface tension has an influence on droplet generation. During the blow, the droplet generation increases with decreasing surface tension of liquid metal.

(3) We proposed that the droplet generation in top blown oxygen steelmaking is mainly dominated by the blowing conditions, not by the physical properties of liquid metal. However, the composition of the steel does strongly effect the generation of droplets for low carbon steels towards the end of the blow.

Further studies are required to verify these conclusions, particularly focusing on the simultaneous effect of temperature and oxygen content on the surface tension of liquid metal, and the variation of oxygen content in iron during steelmaking process.

Nomenclature

U_G : Critical gas velocity (m/s)
g : Gravitational constant (m/s^2)
ρ : Density (kg/m^3)
h : Lance distance (m)
N_B : Blowing number
t : Time (min)
T_b : Bath temperature (K)
$T_{b,0}$: Bath temperature at $t=0$ (K)
γ : Surface tension (N/m)
z : Constant varying from one practice to another practice

Subscript

L : Metal
g : Gas

Fig. 6. The relationship between end carbon content in liquid iron and N_B.

REFERENCES

1) Subagyo, G. A. Brooks, K. S. Coley and G. A. Irons: *ISIJ Int.*, **43** (2003), 983.
2) G. A. Brooks and Subagyo: Yazawa Int. Symp. on Metallurgical and Materials Processing: Principles and Technologies, San Diego, CA,

USA, (2003), 965.

3) Q. L. He and N. Standish: *ISIJ Int.*, **30** (1990), 305.

4) S. C. Koria and K. W. Lange: *Ironmaking Steelmaking*, **10** (1983), 160.

5) K. D. Peaslee, D. K. Panda and D. G. C. Robertson: Proc. of 76th Steelmaking Conference, (1993), 637.

6) D.-J. Min and R. J. Fruehan: *Metall. Trans. B*, **23** (1992), 29.

7) H. Jalkanen and L. Holappa: 5th Int. Conf. on Molten Slags Fluxes and Salts, The South African Institute of Mining and Metallurgy, (2004), 71.

8) R. Li and R. L. Harris: Pyrometallurgy'95 Conf. Proc., IMM, London, (1995), 107.

9) Y. Chung and A. W. Cramb: *Metall. Mater. Trans. B*, **31B** (2000), 957.

10) B. J. Keene: *Int. Mater. Rev.*, **38** (1993), 157.

11.) D. R. Poirier and H. Yin: *ISIJ Int.*, **38** (1998), 229.

12) N. Takiuchi, T. Taniguchi, N. Shinozaki and K. Mukai: *J. Jpn Inst. Met.*, **55** (1991), 44.

13) N. Takiuchi, T. Taniguchi, Y. Tanaka, N. Shinozaki and K. Mukai: *J. Jpn. Inst. Met.*, **55** (1991), 180.

14) K. Nakashima, K. Takihira, K. Mori and N. Shinozaki: *Mater. Trans., JIM*, **33** (1992), 918.

15) I. Jimbo and A. Cramb: *ISIJ Int.*, **32** (1992), 26.

16) H. Taimatsu, K. Nogi and K. Ogino: *J. High Temp. Soc. Jpn.*, **18** (1992), 14.

17) G. R. Belton: *Metall. Mater. Trans. B*, **7B** (1976), 235.

18) P. Sahoo, T. DebRoy and M. J. McNallan: *Metall. Trans. B*, **19B** (1988), 483.

19) G. K. Sigworth and J. F. Elliot: *Met. Sci.*, **3** (1974), 298.

20) A. Masui, K. Yamada and K. Takahashi: McMaster Symp., (1976), 1.

21) S. Asai and I. Muchi: *Trans. Iron Steel Inst. Jpn.*, **10** (1970), 250.

22) E. T. Turkdogan: Fundamentals of Steelmaking, The Institute of Materials, London, (1996), 221.

23) H. W. d. Hartog, P. J. Kreyger and H. Surinx: *Iron Steel Int.*, **46** (1973), 332.

24) D. J. Price: Process Engineering of Pyrometallurgy Symposium, IMM, London, (1974), 8.

25) B. Deo and R. Boom: Fundamentals of Steelmaking Metallurgy, Prentice Hall International, London, (1993), 176.

26) L. Holappa and P. A. Kostamo: *Scand. J. Metall.*, **3** (1974), 56.