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Prediction of Droplet Generation and Blowing Parameters During basic Oxygen Steelmaking Processes

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***Abstract*—Droplet generation phenomenon and its dependence on process parameters have been determined using a predictive numerical model, which predict droplet generation rate based on the blowing number. Evaluation of blowing number is performed depending on lance dynamics, oxygen flow rate and surface tension. The developed model considers surface tension as a function of oxygen, carbon and sulphur content of bath and bath temperature. Bath temperature is predicted using the enthalpy change of oxidation reactions and change of specific heat in each component present in the bath. Predicted end blow carbon concentration and bath temperature correspond well with the experimental values obtained from steel plant. The effect of lance angle and lance height on droplet generation is also taken in account. It has been found that the rate of droplet generation in melt increases with increases of blowing number (NB) and jet momentum onto the metal bath. Bath temperature is found to be more dominating factor for droplet generation process compared to lance height.**

***Index Terms*— Droplet generation; Blowing number; Surface tension; Lance height; Jet momentum; Steel making.**

I. Introduction

In basic oxygen steelmaking process, impinging supersonic oxygen jet deforms as well as disintegrates the bath surface so that emulsified slag starts to form, which in turn helps in intensification of decarburization and other oxidation reactions by promoting the rigorous interaction among gas, slag, and molten steel [1 ,2]. The generation of carbon monoxide is taken place as a result of decarburization process and causes formation of bubbles [3, 4, and 5]. On the other hand, slag formation starts as a consequence of the oxidation of silicon, manganese and iron inside BOF converter [6, 7, and 8]. Oxygen is blowing into the converter at supersonic velocity (Mach number >2) through a water cooled lance. When the oxygen jet hits the metal bath, the generated metal droplets splits out from the bath into slag-metal-gas emulsion zone [9]. It is observed that the rate of the refining reaction is more at gas-metal-slag emulsion zone [10] and accordingly researchers have paid attention on investigating the kinetics of decarburization in emulsion phase and correlate the inferences with industrial data. Lin and Guthrie have investigated the behavior of emulsification caused by generated gas bubbles rising through oil/aqueous and oil/mercury analogues at low temperatures [11]. Cicutti et al. have analyzed the overall decarburization reaction including the emulsion behavior in

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BOS processes [12]. Decarburization reaction in the emulsion phase takes place due to the reduction of FeO, as FeO is directly react with carbon and other impurities present in the bath and forms oxides [13, 14]. Metal droplets, foamy slag and carbon monoxide bubbles mainly present in the emulsion zone. In BOS the droplet generation is a critical part of the process kinetics because it helps to contribute a large interfacial area during the blowing [15, 16]. Therefore, it enhances the mass transfer between metal droplet and slag due to availability of larger interfacial area.

Consequently, heat generation is also enhanced as heat is generated in the bath of BOF converter due to the exothermic reaction of all components present in melt [3]. Rate of droplet generation also influences the heat exchange between different zones of BOF converter [15, 17].

Metal droplets formation inside the BOF converter is governed by surface tension of liquid melt, which is a function of temperature, oxygen and sulphur content of liquid bath. A dimensionless number namely blowing number is introduced for describing the metal droplet generation phenomenon inside BOF converter, which is determined by considering jet velocity, surface tension and density of the melt [15]. Metal droplet generation also depends on flow rate of oxygen gas and jet impact velocity. The individual droplets are refined to lower the contents also found that the extent of decarburization depends on residence time of metal droplets. Meyer et al. also have suggested a relationship between the rate of droplet generation and mean residence time of droplets for top blowing steelmaking process [19]. Brooks et al. have developed a mathematical model to calculate the residence time of droplets in oxygen steelmaking processes [20]. Molloseau and Fruehan have found that metal droplets are "bloated" with CO gas, become less dense and spend longer time in the emulsion [21]. This implies that the residence time is more for bloated metal droplet and consequently the refining time is also more. Several mathematical model and experimental studies have been reported for understanding the role of droplet generation inside basic oxygen steelmaking processes in literature [18, 22-24]. Those models mainly consider the lance dynamic such as lance height and lance angle, where lance height changes continuously with respect to blowing time. Many researchers have not considered the inclination angle of lance inside the BOF converter for analyzing droplet generation phenomenon occurs during basic oxygen steel making process [25].On the other hand, although temperature of the bath has significant influence on droplet generation phenomenon, Subagyo et al. have described droplet generation process for low bath temperature using water model [24]. Recently it is found that the rate of droplet generation is about 8 to 10 kg/Nm^3 at high temperature [15]. Till date, in literature for modeling BOS process, it is assumed that the temperature of metal bath increases linearly and for calculation of bath temperature an empirical linear relation is considered [26, 27, 28]. The detail study of the behavior of droplet generation based on lance dynamic, surface tension and more realistically predicted temperature is necessary for understanding BOS process kinetics in more accurate fashion. The model of the present study actually considers the non-linear change in bath temperature and its prediction is performed considering its dependence on enthalpy of reaction and specific heat of each component. The main objective of this study is to predict the temperature profile, droplet generation, surface tension and blowing number.

II. THEORETICAL BACKGROUND, MODEL DETAIL AND INPUT PLANT DATA

According to Dogan et al. gas-metal phase is unstable as oxygen entered in the hot metal with high velocity [29]. Gravity and surface tension forces tend to stabilize the gas-metal interface in BOF converter. But inertial force destabilizes the gas-metal interface in dynamic condition. Due to the instability inside the converter, the droplets disintegrate and consequently there is an increase in interfacial area [28, 30, and 31]. Blowing number (N_B) based on Kelvin-Helmholtz instability criteria, as being suitable for modeling droplet generation which is suggested by Subagyo et al. [24]. On the basis of the Kelvin-Helmholtz instability criteria, the blowing number (N_B) has been used to quantify the influence of the generation of droplets on the kinetics of oxygen steelmaking. The Kelvin–Helmholtz instability can occur when there is velocity shear in a single continuous fluid. Blowing number is a function of surface tension, centerline velocity and density of gas and metal, where surface tension is depends on temperature, concentration of oxygen and Sulphur. From the given below equation it is clear that if the surface tension decreases then blowing number increases, when other parameter remains constant [24].

$$N_B = \frac{\rho_g U_G^2}{2\sqrt{\gamma g \rho_m}} \qquad 1$$

Where ρ_m and ρ_g are density of metal and gas respectively. NB is blowing number and g is gravitational force constant. Where U_G can be represented as jet centerline velocity at the metal surface [24]. The jet center line velocity obtained from equation (3), where, α is a constant and its value is taken as 0.44721.

$$U_G = \alpha U_J \qquad 2$$

$$\frac{1}{2}\rho_G U_G^2 = \rho_1 g x \qquad 3$$

Koria and Lange (1987), proposed a correlation of depth of penetration (x) and lance height (h) [32]. Depth of penetration in bath of BOF converter is predicted by the help of lance height, where lance height changes with respect to blowing time period. At the initial stage lance height is closer to the bath surface and then goes away with respect to time period. Lance height is again closer to the bath at the end of blowing. This model considers that the lance angle is 15°.

$$\frac{x}{h} = 4.469\left[\frac{0.7854 \times d_t^2 \times P_a\left(1.27\frac{P_0}{P_a}-1\right)\cos\alpha}{g\rho_1 h^3}\right] \qquad 4$$

Where d_t is the throat diameter of the nozzle in meter, Po is the supply pressure in bar and is taken as 8.106 bar and Pa is atmospheric pressure. Subagyo et al. (2003) have proposed a relation between the blowing number (N_B) and the rate of droplet generation (R_B) per unit volume of blown gas in the emulsion phase, which is given below [24].

$$\frac{R_B}{F_G} = \frac{(N_B)^{3.2}}{(2.6\times10^6+2\times10^{-4}(N_B)^{1.2})^{0.2}} \qquad 5$$

The temperature of bath increases non-linearly due to exothermic reaction during the blowing of oxygen into the BOF converter. The model has predicted bath temperature change with respect to blowing time by considering the enthalpy change associated with all the possible oxidation reactions and change of specific heat in each component present in bath. The bath temperature for each time step is calculated using equation (6) and equation (7). The enthalpy change of possible oxidation reactions and specific heat of each component present in the bath for the purpose prediction of temperature is taken from literature [33].

$$\Delta T = \frac{\Delta H_{SUM}}{C_{P,AVG}} \qquad 6$$

$$T_{i+1} = T_i + \Delta T \qquad 7$$

Where Ti is initial temperature of bath and Ti+1 is the new obtained temperature after each time step (i.e. 1 minute). ΔT is change of bath temperature in kelvin. Total heat content (ΔHsum) the bath of the steel melt for a time step is calculated by summing up the change in enthalpy associated with each possible reactions occurs during BOS process. The weighted average (based on mole fraction) of specific heat (Cp, avg) of each component present in molten bath as well as slag is considered with a correction factor for prediction of bath temperature after each time step.The bath temperature is updated after each time step by the addition of change in temperature with the previous temperature.

In this model surface tension is taken instead of interfacial tension because the model considers that there is no interaction between the slag and the metal phase due to high oxygen flow rate. According to Keene, surface tension prediction of liquid metal depends upon temperature of the bath, where temperature varies within the range of 1803 kelvin to 1873 kelvin [34]. After that Poirier and Yin (1998) have extended this relation as a function of concentration of oxygen and sulphur and ignored the interaction between sulphur and oxygen [35]. The correlation based on Gibbs-Langmuir adsorption isotherm, is given below:

$$\gamma = 1913 + 0.43[1826 - \mathrm{Ti+1}] + 67.75[\%C] - 0.107\mathrm{Ti+1}\ln[1 + \mathrm{Ksas}] - 0.153\mathrm{Ti+1}\ln[1 + \mathrm{Koao}] \qquad 8$$

$$\log K_0 = \frac{11370}{\mathrm{Ti+1}} - 4.09 \qquad 9$$

$$\log K_S = \frac{10013}{T_{i+1}} - 2.87 \qquad 10$$

$$\log f_o = e_o^o(mass\%\ O) + e_o^s(mass\%\ S) + e_o^c(mass\%\ C) \qquad 11$$

$$\log f_s = e_o^o(mass\%\ O) + e_o^s(mass\%\ S) + e_o^c\,(mass\%\ C) \qquad 12$$

Ko is the adsorption coefficients for oxygen on liquid iron alloy and Ks is the adsorption coefficients for sulphur on liquid iron alloy and values are taken from literature [31]. Where $a_o$the activity of oxygen and as is is the activity of Sulphur is calculated by using equation (11) & (12). The values of interaction parameters like e_o^o, e_o^c & e_o^s are obtained from literature [36]

Droplet generation and decarburization process are interdependent and accordingly to study droplet generation and emulsification of slag, variation of carbon and oxygen amount in bath is necessary. In this work, blown oxygen is distributed to each possible oxidation reaction as per the ratio of Gibbs free energy change associated with each probable oxide formation to the sum of changes in Gibbs free energy (ΔG) for of all the possible oxidation reactions similar to a literature reported approach for the same [37]. For that, temperature dependent Gibbs free energy change is considered and updated after each minute based on the changed temperature using following form of equation,

$$\Delta G = -x \pm yT \qquad 13$$

Where x and y are constant values of each possible oxide formation during basic oxygen steel making process taken from literature [33]. From mass balance, the oxides formed and the weight of each element remaining in bath is calculated and this in turn gives the steel composition of the bath. To update the value of ΔG for every reaction, following equation (equation no. 14) is considered.

$$\Delta G = \Delta G_0 + RT \ln K \qquad 14$$

Where K is equilibrium constant and R is real gas constant. As sulphur content in the bath is very low and removal of sulphur requires reducing condition, so the variation of sulphur and sulphur oxidation is not considered. The model assumed that the reaction of active element like oxygen, carbon and sulphur all are in equilibrium. Concentration of oxygen is approximated by considering equilibrium reaction of decarburization [33]. The model does not consider impact of reaction at emulsion zone and formation of fume but consider the droplet generation, when gas impinging on the liquid melts of BOF converter. The blowing number can be calculated as a function of bath temperature, oxygen, sulphur and carbon contents in the bath of BOS processes. Calculated blowing number in different cases is used to analyze the droplet generation under the given operating conditions for a 150 ton top blowing oxygen steelmaking process. The model is tested under four different cases of industrial data. But in this model the inclination angle is assumed to be 15°.Case-1, 2, 3 and 4 (industrial data) test under high temperature from 1873 K and 1963 K approximately. To study the effect of lance angle on droplet generation, different lance angles such as 5°, 10° and 15° , have been taken for only case 1. The blowing time period is 16 minute throughout the whole processes in different cases. Lance height throughout the system is varied from 0.9 to 1.25 meter. Input plant data of four different cases for a 150 ton BOF converter is summarized in Table I. Total volume of oxygen used for refining reaction is varied from 7000 to 8000 Nm3approximately throughout the system for all cases. Table II shows typical initial and end blow chemical compositions of BOS process for same four cases.

TABLE I. DATA FOR NUMERICAL CALCULATION

Parameters	Case-1	Case-2	Case-3	Case-4
Furnace capacity	155 ton	110 ton	155 ton	155 ton
Blowing Time	16 min	16 min	16 min	16 min
Oxygen flow rate	480 Nm^3/min	350 Nm^3/min	490 Nm^3/min	540 Nm^3/min
Supply pressure	8 atm	8 atm	8 atm	8 atm
Diameter of throat	0.024 meter	0.024 meter	0.024 meter	0.024 meter
Lance height	0.9-1.25 meter	0.9-1.25 meter	0.9-1.25 meter	0.9-1.25 meter
Initial hot metal temperature	1338℃	1386℃	1378℃	1364℃
Tapping temperature	1615-1625℃	1620-1627℃	1630-1638℃	1683-1687℃

III. RESULT AND DISCUSSION

Carbon content and bath temperature with respect to blowing time for four cases are presented in Fig. I and Fig. II respectively. Variation of carbon concentration is found, varied from around

4.5 to 0.05 wt. % with respect to blowing period as evident in Fig. I. Bath temperature is varied almost from 1600 to 1900 kelvin .Carbon concentration, dissolved oxygen content and bath temperature required for the calculation of surface tension, which in turn helps to predict the rate of droplet generation. Blowing number (NB) is the function of surface tension, density of liquid metal and jet centerline velocity and calculated values of blowing number with respect to blowing time is given Fig. III. Initially lance height is closer to the bath of hot metal and varies from 0.9 m to 1.25 m throughout the blowing period. At the end of the blown again lance height is closer to bath surface. When lance height is closer to bath surface, transfer of jet momentum increases from gas to liquid, so that blowing number increases. Fig. III presents the change of blowing number (NB) with lance height (h) throughout the blowing period in different case of steelmaking. From the above figure it is found that the variation of blowing number (NB) with lance height is 4 to 6. Blowing number (NB) is maximum at the initial stage and final stage as lance is closer to the bath surface of liquid melt.

TABLE II. TYPICAL INITIAL AND FINAL CHEMICAL COMPOSITIONS OF BOS PROCESS FOR DIFFERENT CASE OF STEEL

Initial composition	Case-1	Case-2	Case-3	Case-4	Final composition	Case-1	Case-2	Case-3	Case-4
%C	4.22	4.85	4.26	4.9	%C	0.05	0.07	0.05	0.05
%Mn	0.07	0.06	0.07	0.06	%Mn	NA	NA	NA	NA
%P	0.105	0.150	0.115	0.151	%P	0.021	0.025	0.028	0.036
%S	0.045	0.075	0.046	0.074	%S	0.049	0.06	0.056	0.052
%Si	0.66	0.46	0.75	0.55	%Si	NA	NA	NA	NA

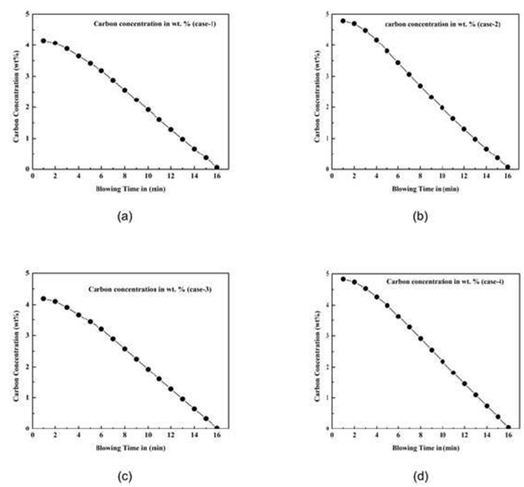

Fig 1. represent the concentration of carbon in each stage

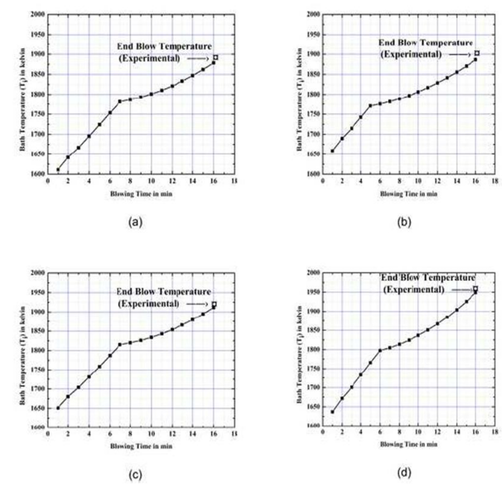

Fig 2. Represent the bath temperature at each stage

Surface tension is a function of oxygen, carbon, sulphur and temperature of molten liquid. Practically it is difficult to calculate the surface tension at a temperature range of 1873 K to 1973 K. Fig. IV (a) presents the change in surface tension (γ) from 1.592 N/m to 0.929 N/m with respect to time period. Surface tension of hot melt decreases, when bath temperature increases inside the bath of BOF converter. In case-2 variation of surface tension (γ) from 1.566 N/m to 0.853 N/m shown in Fig. IV(b), where temperature changes from 1659 K to 1887 K. Surface tension of liquid melt increases due to the increases of oxygen and sulphur concentration. Fig. V(c) presents the change of surface tension (γ) from 1.509 N/m to 0.87 N/m by considering the oxygen and sulphur concentration. From equation (8) it is found that surface tension decreases with increase in activity of oxygen (a_O). Change in surface tension (γ) varies from 1.803 N/m to 1.053 N/m presented in Fig. IV (d). It is found that surface tension (γ) varies in the range of 1.8 to 0.8 N/m in all cases within the temperature range 1873 K to 1973 K.

From the above study it is inferred that if the concentration of oxygen increases then surface tension decreases, that means rate of droplet generation increases with increase in blowing number at initial and final stage. Carbon content in liquid metal is calculated from 1.6 to 0.05 wt. % at the end stage of the blow (i.e. around last 5 minutes of blow), where blowing number increases with lance height. Variation of blowing number with respect to bath carbon content at the end stage of the blowing period for different lance height is

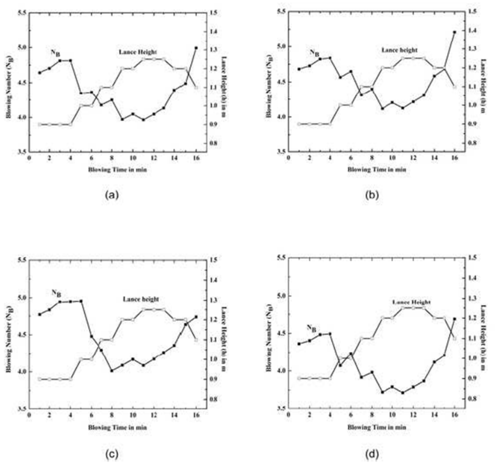

Fig 3. Represent the bath blowing number with respect to time period

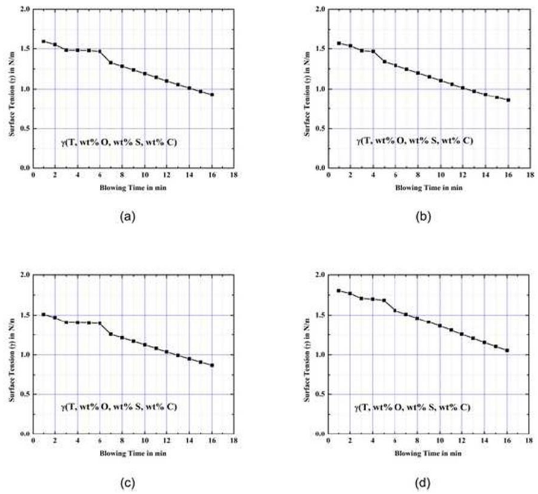

Fig 4. Represent the surface tension with respect to time period

presented in Fig. V. It is observed that blowing number (NB) varies from 3.5 to 6 for the variation of bath carbon content from 1.0 wt. % to 0.05 wt. %. Therefore, it is obvious that blowing number is lower for lower bath carbon content. It is also evident for all the cases presented here that blowing number decreases if lance height increases.

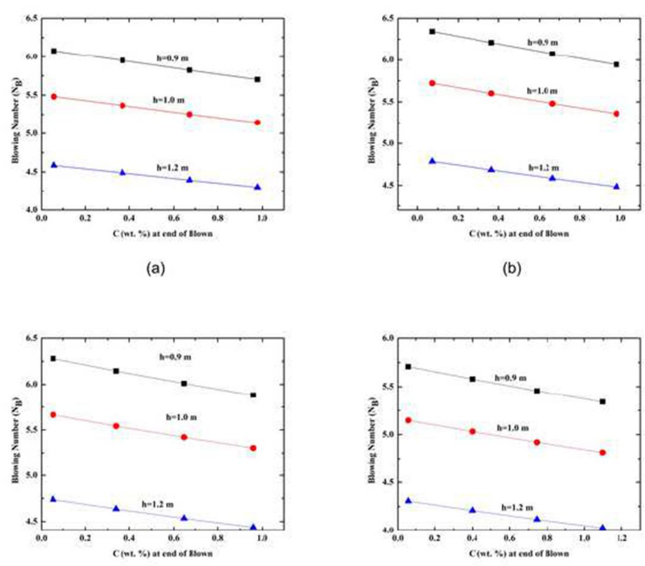

Fig 5. Represent the blowing number with respect to time period at different lance height

Rate of droplet generation depends on blowing number (NB), surface tension (γ), temperature (T) and lance height (h). Rate of droplet generation is predicted for high temperature in four different cases considered in this study. Variation of droplet generation rate per unit volume of blown gas with respect blowing number is presented in Fig. VI. It is found that rate of droplet generation decreases with decreases in blowing number and varies from around 5.5 to 10.5 Kg/Nm3 throughout the blowing processes. The variation of rate of droplet generation with respect to blowing time for different lance angles (5°, 10° and 15°) for representative

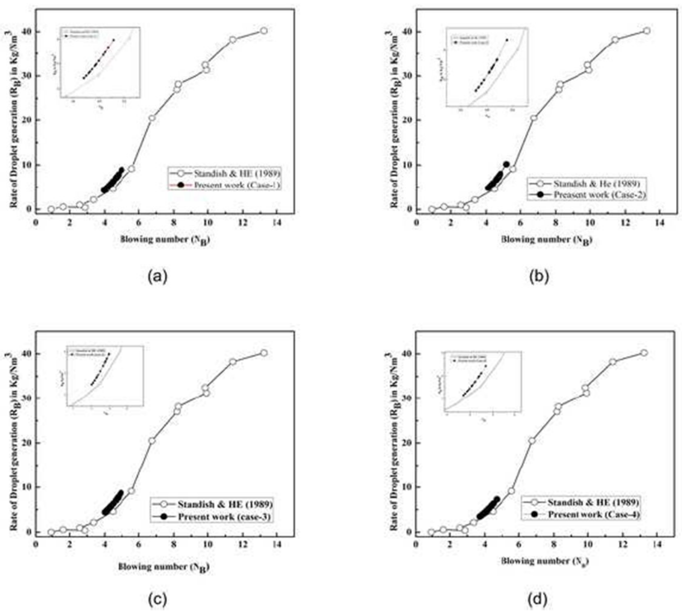

Fig 6. Represent the rate of droplet generation with respect to blowing parameter

case 1 has been presented in Fig. VII. The rate of droplet generation is found to be less for higher lance angle if other process parameters remain constant. This may be attributed to the fact that lower lance angle causes higher depth of penetration and higher jet centerline velocity. The contour plots for droplet generation rate with respect to lance height and bath temperature for all the cases studied here is shown in Fig. VIII. It is observed that bath temperature is more dominating factor for droplet generation process compared to lance height. Higher bath temperature corresponds to higher rate of droplet generation even the lance height is not minimum at that point (Fig. VIII (a), Fig. VIII (b) and Fig. VIII (d)). For the case 3, a little deviation in such trend is observed (Fig. VIII(c)).

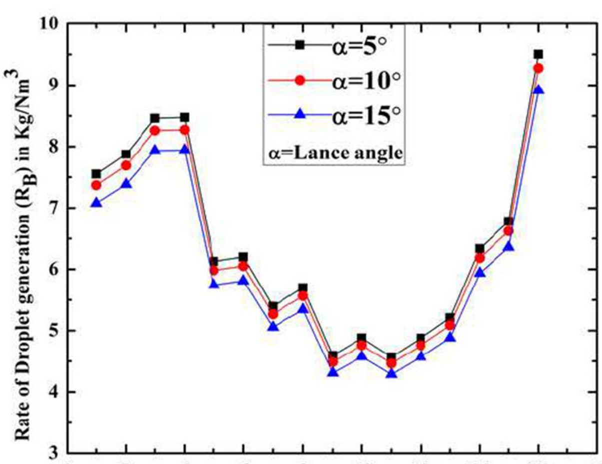

Fig 7. Represent the rate of droplet generation with respect to blowing parameter at different lance angle

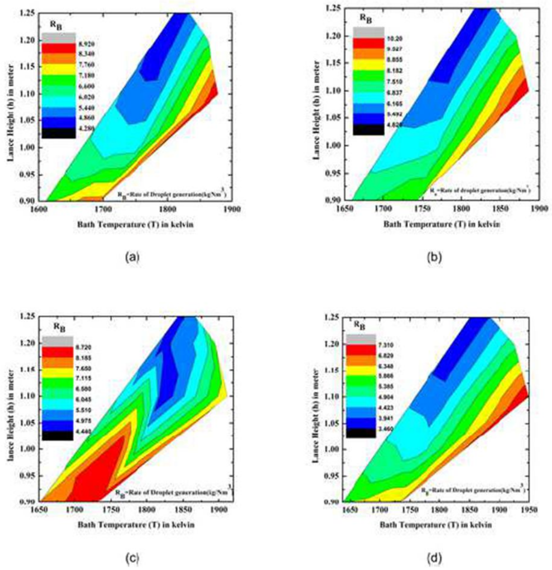

Fig 8. Represent the bath temperature with respect to lance height

IV. CONCLUSION

Droplet generation prediction and blowing number calculation for different cases of steelmaking via BOF converter has been carried out and also compared with industrial data collected from steel plant. Flux addition is not considered to develop the model for prediction of droplet generation. In different cases of steelmaking it was concluded that blowing number increases with decrease in lance height, as decrease of lance height causes increases the intensity of jet momentum. Also due to decrease in surface tension the blowing number increases in the initial and final stage of blowing at constant lance height. Surface tension is a function of temperature, oxygen content, sulphur content and carbon content, decreases with increasing of oxygen content and temperature. Surface tension is also decreased with the decrease in carbon concentration.
Therefore, droplet generation in BOF converter reaches to maximum value at the end of the blowing processes when surface tension is minimum. Rate of droplet generation is found to be maximum of 10.5 Kg/Nm3 in case of basic oxygen steel making process with blowing number ranging from 3.5 to 5.5. The compendium of this study can be extended to correlate the kinetics of oxidation reactions with droplet generation phenomenon for basic oxygen steel making process.

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