Foaming Behavior of CaO–SiO₂–FeO–MgO<sub>satd</sub>–X (X=Al₂O₃, MnO, P₂O₅, and CaF₂) Slags at High Temperatures

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The foaming index was measured for CaO–SiO₂–FeO–Al₂O₃ and CaO–SiO₂–FeO–MgO<sub>satd</sub>–X (X=Al₂O₃, MnO, P₂O₅, and CaF₂) slags to understand the foaming behavior. The foaming index of the CaO–SiO₂–FeO–10Al₂O₃ slags (C/S=0.93 and 1.2) decreases with increasing content of FeO up to 20 % and is almost constant for FeO content through 20 to 40 %. The viscosity of slags could be considered as the major contributor to foaming behavior. The addition of Al₂O₃ into the silicate slags results in an increase of foaming index due to an increase of slag viscosity; this could be explained by the structural role of Al₂O₃ in aluminosilicate slags. In the MgO-saturated and Al₂O₃-containing slags, FeO behaves as an acidic oxide, because slag melts would be more basic than MgO-saturated and non-Al₂O₃ slags, where FeO behaves as a basic oxide, due to Al₂O₃ enhances the dissolution of MgO into the slags. The addition of MnO into the MgO-saturated slags decreases foaming index, simply due to a decrease of slag viscosity. However, the addition of CaF₂ and P₂O₅ into the slags results in the complex foaming behavior of slags; this is probably due to the Marangoni effect. The relationships between foaming index and the physical properties of slags can be obtained from the dimensional analysis as follows:

\[
\Sigma = 214 \frac{\mu}{\sqrt{\rho \sigma}} \quad \text{(for the CaO-based slags)}
\]

\[
\Sigma = 999 \frac{\mu}{\sqrt{\rho \sigma}} \quad \text{(for the MgO-saturated slags)}
\]

The foam height is predicted as a function of decarburization rate from the molten iron and the contribution of slag foaming in EAF process was discussed as a function of decarburization rate.

KEY WORDS: foaming index; viscosity; Marangoni effect; dimensional analysis; foam height; EAF.

1. Introduction

Slag foaming phenomena in metallurgical processes have been investigated to develop an innovative processes and to reduce energy consumption, particularly in the smelting reduction and steelmaking processes. Recently, the foaming phenomena in the modern electric arc furnace (EAF) have drawn attention from researchers, because foam-controlling technology in EAF process plays an important role in protection of metal bath from atmosphere as well as in saving of electric energy by enhancing post combustion rate.

Slag foaming in steelmaking condition has been investigated for several decades.¹–¹⁶ Cooper and Kitchener described the stability of slag foam in terms of “foam life”, which was defined as the time to decay of a certain volume of slag foam under the static conditions.¹ The experimental results for the CaO–SiO₂–P₂O₅ slags indicated that foaming was absent in the CaO–SiO₂ binary system but foam stability markedly increased with increasing content of P₂O₅, and decreasing temperature and slag basicity. They explained these results based on surface elasticity, however, it was restricted only to the acidic melts of highly viscous slags. Swisher and McCabe made an experimental study to understand the possible mechanisms for the stability of slag foam in the CaO–SiO₂–Cr₂O₃ melts.³¹ By comparing foam stability and surface tension of the slags, it was suggested that the Marangoni elasticity effect would be probably the largest contributor to foam stability. Hara et al. also discussed the relationship between surface tension and foam life; decrease of surface tension resulted in an increase of foam life.⁴ It was reported that increase of P₂O₅, Na₂O, and CaF₂ contents in the CaO–SiO₂–FeO slags contributed to increase in foam life due to Marangoni effect. However, the addition of 10 % MgO had no effect on foam stability.

On the other hand, Ito and Fruehan adopted a dynamic measurement of the foam stability in terms of “foaming index”, which is equal to the retention or traveling time of the gas in the slag.⁵,⁶ The foaming index of the CaO–SiO₂–FeO slags increased with increasing content of MgO and P₂O₅, while it was slightly decreased by addition of S and CaF₂. An empirical equation to predict the foaming index for CaO–SiO₂–FeO slag was suggested as follows by the di-
mensional analysis:
\[
\sum = 570 \frac{\mu}{\sqrt{\rho \sigma}} \quad \cdots (1)
\]

where \( \mu, \sigma, \rho \) are respectively viscosity, surface tension, and density of the slag. The similar equation for the foaming index as a function of the physical properties of bath smelting slags (CaO–SiO_2–FeO and CaO–SiO_2–FeO–MgO–Al_2O_3) was suggested with the proportional coefficient of 115 by Jiang and Fruehan. In spite of the same dependence of foaming index on physical properties of the slag, the difference of the coefficient indicated that foaming characteristic of slags would be dependent on slag system investigated and the structure of molten slags.

In viewpoint of application to the commercial steelmaking processes, the dissolution of MgO from refractory should be considered. However, the previous studies were restricted to the CaO-based slags with small amount of MgO. Recently, Jung and Fruehan measured the foaming index of MgO-saturated BOF slags. They reported that foaming index of CaO–SiO_2–FeO–MgO slags decreased with increasing content of FeO up to about 20% and was almost constant to 32% FeO. This trend of foaming index was mainly attributed to that of viscosity of slags. However, the effect of various additives on foaming index in the MgO-saturated slags is still insufficient.

Therefore, in the present study, the foaming behavior of CaO–SiO_2–FeO–Al_2O_3 slags was simply considered; thereafter the effect of addition of Al_2O_3, MnO, P_2O_5, and CaF_2 on foaming characteristic of CaO–SiO_2–FeO–MgO slags (EAF slags) was investigated.

2. Experimental

A schematic diagram of the experimental apparatus is shown in Fig. 1. An electric resistance furnace was used with R-type thermocouple to establish an isothermal condition. The slag sample was held in the MgO crucible (45-mm ID, 50-mm OD, 150-mm Height) for MgO saturation. The argon gas was introduced into the molten slag through an alumina nozzle (2-mm ID, 4-mm OD). The foam height was defined as the increment of the slag surface level from the original slag level detected by the electric probe made of a platinum wire. The stable foam height was measured after 10 min from bubbling, which was determined by preliminary experiment. Also, the temperature gradient in the furnace was measured as a function of height from the bottom of the crucible; thus it was confirmed that the temperature profile in the crucible was fixed as 1783 K in the present experiments.

The master slag of CaO–SiO_2–30FeO–MgO–X (X = Al_2O_3, MnO, P_2O_5, and CaF_2) (C/S = 1.2) were made in the MgO crucible for 8 hr to make saturation.

3. Results and Discussion

3.1. Bubble Formation in EAF Process

The foaming index has been known to be dependent on bubble diameter as well as on physical properties of molten slags. In the smelting reduction and BOF processes, bubbles were generally formed by slag/metal reaction; that is, the reaction between FeO in slag and carbon in iron melt as follows:

\[
\text{FeO(slag)} + \text{C} = \text{Fe(l)} + \text{CO(g)} \quad \cdots (2)
\]

The diameter of CO bubbles formed by Eq. (2) has been reported to be about less than 1 mm. Because of significant effect of fine bubbles on foam stability, the bubble diameter should be taken into account in the calculation of foam height in the smelter and BOF; thus, Zhang and Fruehan proposed the following equation from the dimensional analysis:

\[
\sum = 115 \frac{\mu^{1.2}}{\sigma^{0.2} \rho D_{0.9}} \quad \cdots (3)
\]

On the other hand, in the EAF process, the combustion of injected carbon is predominant mechanism of bubble formation, although the reduction of FeO in slag by injected carbon would occur. Yi and Rhee measured bubble diameter generated both by Ar injection and FeO reduction by injected fine cokes in the CaO–SiO_2–FeO slag. The maximum diameter of bubbles was about 13–15 mm and the average value was about 7–9 mm, although very small bubbles with the diameter less than 1 mm were also observed. By comparing their experimental results with the relationship between bubble diameter and flow rate reported by Davidson and Harrison, they suggested that bubble diameter in the gas injection systems such as EAF process would be dominantly affected by the equilibrium between inertia and buoyancy forces rather than physical properties of slags such as surface tension, which is important in the slag/metal reaction regarding detachment of bubbles from metal/slag interface.

Consequently, bubble diameter is generally known as a function of gas flow rate, combustion rate, and slag compo-
From the foregoing review about bubble diameter, it could be assumed that the dependence of bubble diameter on slag composition would not be serious in EAF process.

### 3.2. Effect of FeO and Al\(_2\)O\(_3\) Content on Foaming Index

The foaming index of the CaO–SiO\(_2\)–FeO–10Al\(_2\)O\(_3\) slags (C/S=0.93 and 1.1) is shown in Fig. 2 as a function of FeO content. It is indicated that foaming index decreases with increasing content of FeO up to about 20% and is almost constant for FeO content through 20 to 40%. This trend is also observed for bath smelting slags measured by Fruehan et al. At the same content of FeO in the slags, the foaming index decreases with increasing slag basicity; however, the effect of basicity on foaming index decreases with increasing FeO content. It is of interest that foaming index of the CaO–SiO\(_2\)–FeO–10Al\(_2\)O\(_3\) slags is about two times higher than those of other slags previously reported.

The tendency in Fig. 2 can be explained on the basis of viscosity of slags as shown in Fig. 3. The viscosities of both present and previous slag systems decrease with increasing content of FeO. In Fig. 3, the viscosities of the slags were estimated using Urbain’s model. Mills suggested that the discrepancies between the experimental values and the predicted values are of the order of ±15%, which are similar to the experimental uncertainties for the viscosity measurements. From the result in Fig. 3, it is believed that the decrease of viscosity is the major contributor to foam instability of slags. In addition, the viscosity of the CaO–SiO\(_2\)–FeO–10Al\(_2\)O\(_3\) slags is estimated to be higher than those of the CaO–SiO\(_2\)–FeO–MgO\(_{\text{satd}}\) and CaO–SiO\(_2\)–FeO–15Al\(_2\)O\(_3\)–10MgO slags. It has been known that addition of Al\(_2\)O\(_3\) into the CaO–SiO\(_2\)–FeO slags results in an increase of slag viscosity, because of the formation of aluminate tetrahedra, [AlO\(_4\)\(^-\)]. The network unit of [AlO\(_4\)\(^-\)]\(^2+\)Ca\(^{2+}\)[AlO\(_4\)\(^-\)] would be more stable than single [AlO\(_4\)\(^-\)] structural unit. Therefore, this aluminate tetrahedra enhances the degree of polymerization of slags by compensating the extra negative charge with consumption of Ca\(^{2+}\) cations. This structural analysis provides that the effect of Al\(_2\)O\(_3\) on foaming index shown in Fig. 2 can be explained by the structural role of Al\(_2\)O\(_3\) in aluminosilicate slags.

The effect of FeO content on foaming index of the CaO–SiO\(_2\)–FeO–Al\(_2\)O\(_3\)–MgO\(_{\text{satd}}\) slags is shown in Fig. 4. Unlike as in the case of non-MgO slags, the foaming index slightly increases with increasing content of FeO. Because the slag melts become more basic than non-MgO slags by MgO saturation, FeO probably behaves as an acidic oxide in this melts containing Al\(_2\)O\(_3\). This trend is opposite from the case of CaO–SiO\(_2\)–FeO–MgO\(_{\text{satd}}\) slags, where FeO behaves as a basic oxide. In the CaO–SiO\(_2\)–FeO–Al\(_2\)O\(_3\)–MgO\(_{\text{satd}}\) slags, Al\(_2\)O\(_3\) still contribute to increase the viscosity of slags based on the structural role as explained above. Recently, Park reported that Al\(_2\)O\(_3\) enhances the solubility of MgO in the CaO–SiO\(_2\)–FeO–Al\(_2\)O\(_3\)–MgO\(_{\text{satd}}\) slags. Hence, the solubility of MgO for saturation...
tion would be higher than that of non-Al$_2$O$_3$ slags at a fixed CaO/SiO$_2$ ratio; thus slag melts would be more basic than non-Al$_2$O$_3$ slags. Consequently, FeO probably behaves as an acidic oxide in the MgO-saturated and Al$_2$O$_3$-containing slags. Also, it is generally known that Fe$^{3+}$/Fe$^{2+}$ ratio increases with increasing total content of iron oxide in the slags when slag basicity (CaO/SiO$_2$ ratio) is less than 1.5.\(^{18,25}\)

3.3. Effect of CaF$_2$ Content on Foaming Index

Figure 5 exhibits the relationship between the foaming index and the content of CaF$_2$ in the MgO-saturated slags with those of previous work.\(^5,8\) The foaming index decreases with increasing content of CaF$_2$ up to about 5\%, which is similar to the result of CaO–SiO$_2$–FeO–CaF$_2$ slags measured by Ito and Fruehan. This is probably due to a decrease in slag viscosity by reacting F$^-$/H$^+$ ion with silicate polyanions. However, the foaming index increases with increasing CaF$_2$ content at higher than 5\% CaF$_2$. In the results of Roth et al.,\(^8\) the maximum value of foaming index was observed as a function of CaF$_2$ content in the ladle slags. They suggested that this unexpected tendency at low content of CaF$_2$ probably resulted from the Marangoni effect, which would be caused by surface adsorption of surface-active component such as CaF$_2$. Hara et al. reported that Marangoni effect would be maximized when CaF$_2$ added about 10\% into the CaO–SiO$_2$–FeO slags.\(^4\)

As shown in Fig. 5, the foaming behavior in the present slag system is opposite from that of ladle slags, where very low content of SiO$_2$; thus it is some questionable, if the explanation by Roth et al. could be available in the present slag system. It has been reported that the effect of CaF$_2$ on the depolymerization of slag network is observed as a function of CaF$_2$ content in the ladle slags.\(^26,27\) At higher than this critical CaF$_2$ content, CaF$_2$ probably dilute the basic oxide such as CaO and MgO in the MgO-saturated basic slags, which result in an increase of slag viscosity. However, a more detailed investigation for the structural role of CaF$_2$ in the basic melts is required.

3.4. Effect of MnO Content on Foaming Index

Figure 6 exhibits the relationship between foaming index and MnO content in the CaO–SiO$_2$–30FeO–MgO$_{slag}$ slags with those of previous work for comparison.\(^8\) The foaming index slightly decreases with increasing content of MnO in the slags, which is similar to those of highly basic slags measured by Roth et al. These trends are primarily due to a decrease in slag viscosity, an increase of the surface tension and the density of the slags by addition of MnO, which generally behaves as a basic oxide. In addition, the foaming index of the present slag system is about 3 times higher than those of literature, because of low basicity (CaO/SiO$_2$ ratio) of the present slag.

3.5. Effect of P$_2$O$_5$ Content on Foaming Index

Figure 7 exhibits the foaming index as a function of P$_2$O$_5$ content in the CaO–SiO$_2$–30FeO–MgO$_{slag}$ slags (CaO/SiO$_2$=1.2) with those of previous work for the purpose of comparison.\(^1,5\) The foaming index exhibits a maximum value at about 3\% of P$_2$O$_5$ in the slag; this is probably due to Marangoni effect as in the case of CaF$_2$ addition into the ladle slags, which has been suggested by Roth et al.\(^8\) However, because P$_2$O$_5$ is more surface-active than CaF$_2$, the Marangoni effect caused by P$_2$O$_5$ would be larger than that by CaF$_2$. Hara et al. estimated that surface adsorption of 1–2\% P$_2$O$_5$ on bubbles would be approximately equivalent to that of 10\% CaF$_2$ in the CaO–SiO$_2$–FeO slags for the maximum Marangoni effect.\(^4\) The foaming index at the composition higher than 3\% P$_2$O$_5$ decreases with P$_2$O$_5$ content, which result from a decrease in Marangoni effect due to a saturation of bubble surface by excess adsorption of P$_2$O$_5$. Marangoni effect appears due to the concentration gradient of surface-active substances on bubble surface. Thus, this effect would disappear when the bubble surface is saturated with the surface-active substances, because of no concentration gradient, which is the deriving force for
the Marangoni effect. This is probably the reason why the foaming index decreases at the composition higher than 3% $P_2O_5$.

3.6. Effect of Slag Basicity on Foaming Index

Figure 8 exhibits the dependence of foaming index of the CaO–SiO$_2$–FeO–MgO$_{satd}$–X (X=Al$_2$O$_3$, MnO, $P_2O_5$, and CaF$_2$) slags at 1783 K on the modified basicity index ($[CaO/FeO+MnO+CaF_2+MgO]/[SiO_2+P_2O_5]$) in molar basis and on the content of Al$_2$O$_3$. The foaming index decreases with increasing basicity index up to about 2.0, which is similar to the basicity dependence of slag viscosity. Generally, the viscosity of slags decreases with increasing slag basicity and vice versa in surface tension. Therefore, high viscosity and low surface tension is expected to favor the stability of slag foam.

However, the foaming index increases with increasing basicity when basicity index is higher than about 2.0. Ito and Fruehan reported that increases of foaming index for CaO–SiO$_2$–FeO–Al$_2$O$_3$ slags would result from the precipitation of solid particles such as 2CaO · SiO$_2$ at higher CaO content, and the particles significantly increased foam stability. The similar explanation can be seen in the Cooper and Kitchener's work. Jung and Fruehan suggested that if the slag is high enough in MgO content as in the present MgO-saturated slags, magnesiowüstite (FeO·MgO) may be the phase which crystallize first. Therefore, the increase in foaming index may be due to the role of the particles, which increase the viscosity of slags. In addition, the increase of foaming index with Al$_2$O$_3$ content is observed, because Al$_2$O$_3$ in aluminosilicate melts behaves as a network former by consuming cations in order to compensate extra negative charge as explained in Sec. 3.1.

3.7. Dimensional Analysis for the Foaming Index

It is expected that foaming index can be related to the physical properties of slags. The technique of dimensional analysis was applied in order to find the relationship describing the foaming index as a function of the slag properties. Jiang and Fruehan previously carried out a dimensional analysis for the foaming index of the bath-smelting slags. In the present study, the similar method has been taken to find the quantitive relationship between foaming index and slag properties.

It can be assumed that foaming index is a function of all the variables and dimensional constants, which may affect foaming index.

$$
\Sigma = f(\rho, \mu, \sigma, g) \quad \text{(4)}
$$

where $\rho$, $\mu$, $\sigma$, and $g$ are respectively density, viscosity, surface tension of slags, and gravity. In Eq. (4), there are 5 variables and 3 fundamental dimensions; therefore, two dimensionless groups are to be obtained. Through dimensional analysis, the final forms are obtained as follows:

$$
\Pi_1 = \frac{\Sigma \mu \mu}{\sigma} \quad \text{(5)}
$$

$$
\Pi_2 = \frac{\rho \sigma^3}{\mu^3 g} \quad \text{(6)}
$$

Here, $\Pi_1$ is related to bubble life in the foam layer and $\Pi_2$ (Morton number) is related to bubble velocity or mobility in the foam. Therefore, the dependence of foaming index on the physical properties of slags can be found by obtaining the relationship between these two dimensionless groups ($\Pi_1$, $\Pi_2$). To accomplish this, the physical properties of slags should be obtained first. In the present study,
density and surface tension of multi-component slags were calculated by using an additive method.\(^7,17\) Also, viscosity of slags was calculated on the basis of Urbain’s model.\(^21\)

Figure 9 exhibits the relationship between two dimensionless groups (\(\Pi_1, \Pi_2\)) with those of bath-smelting slags by Jiang and Fruehan for comparison.\(^7\) The following relationships were obtained for the case of CaO–SiO\(_2\)–FeO–10Al\(_2\)O\(_3\) and CaO–SiO\(_2\)–30FeO–MgO\(_{sat}\)–X (X/\(100\)) slags, respectively.

\[
\log \frac{P_2}{H_{11005}} = 2.0 \log \frac{P_1}{H_{11001}} - 5.7 \\
\log \frac{P_2}{H_{11005}} = 1.8 \log \frac{P_1}{H_{11001}} - 7.0
\]

From these results, the final relation for each case is obtained as follows, respectively:

\[
\Sigma = 214 \frac{\mu}{\sqrt{\rho \sigma}} \quad \text{(for the CaO-based slags)} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (9)
\]

\[
\Sigma = 999 \frac{\mu}{\sqrt{\rho \sigma}} \quad \text{(for the MgO-saturated slags)} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (10)
\]

This analysis gives the same dependence of foaming index on slag properties as that derived by Jiang and Fruehan, except that a coefficient of 115 (Eq. (1)) was previously obtained.\(^7\) The difference between the coefficients is believed to be due to the difference in the slag properties used for each analysis. Equations (9) and (10) also indicate that viscosity is more important than surface tension in determining the foaming index.

4. Slag Foaming in EAF Process

In the present study, if the combustion rate and gas flow rate are given at a fixed temperature and oxygen potential, the foam height and the amount of energy saving in EAF can be calculated based on the dimensional analysis derived in the present study.

Based on the estimated foaming index, the foam height \(h\) in the furnace can be calculated using Eq. (11) derived by Ito and Fruehan.\(^6\)

\[
h = h_0 + \sum \mu \sqrt{\rho \sigma} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (11)
\]

where \(h_0\) is a height before foaming begins and \(\mu \sqrt{\rho \sigma}\) is the superficial gas velocity calculated using the combustion rate of injected carbon \((\text{dC/dt})\). The reaction mechanism and rate of carbon combustion is as follows:\(^28\)

\[
\begin{align*}
\text{C(s)} + \frac{1}{2} \text{O}_2(g) &= \text{CO}(g) \quad \Delta H = 67150 \text{ cal/mol} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (12) \\
\text{FeO}^{\text{slag}} + \text{C(s)} &= \text{Fe}(l) + \text{CO}(g) \\
J_C^{\text{red}} &= 1.67 \times 10^{-7} \text{ (mass\%FeO)} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (13) \\
\text{CO}_2(g) + \text{C(s)} &= 2\text{CO}(g) \\
J_C^{\text{boud}} &= 6.35 \exp(-19500/T) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (14)
\end{align*}
\]

where \(J_C^{\text{com}}, J_C^{\text{red}}, \) and \(J_C^{\text{boud}}\) are the mole flux of carbon (mol/cm\(^2\) sec) in combustion reaction, reduction reaction, and Boudouard reaction, respectively. The rate of Eq. (14) has been known to be controlled by the rate of CO\(_2\) evolution in Eqs. (12) and (13). Then, the foam height is calculated using the superficial gas velocity.

Figure 10 exhibits the foam height as a function of combustion rate. The foam height linearly increases with increasing rate of decarburization. The slope is a function of foam stability and means the foaming index estimated in this study. Therefore the foam height about 71.9 cm is predicted using the superficial gas velocity about 35.5 cm/sec, which was calculated by the reaction between carbon and oxygen, and the foaming index about 2.03 under conditions given in Table 1.

The electric energy saving in EAF process can be achieved by controlling slag foaming; that is, the slag foaming increases post-combustion ratio (PCR), concentration of combustion heat on molten iron, and arc efficiency. The energy of post-combustion reaction is as follows:

\[
\text{CO(g)} + \frac{1}{2} \text{O}_2(g) = \text{CO}_2(g), \quad \Delta H = -67150 \text{ cal/mol} \ldots \ldots (15)
\]
The amount of energy saving is dependent on PCR. Figure 11 exhibits the relationship between the foam height and the amount of energy saving with the industrial process data. The amount of energy saving linearly increases with the foam height and the slope is a function of post-combustion. Therefore it is deduced that the amount of energy saving increase with increasing rate of decarburization, foam height, and PCR.

5. Conclusions

The foaming index was measured for CaO–SiO2–FeO–Al2O3 and CaO–SiO2–FeO–MgO satu–X (X=Al2O3, MnO, P2O5, and CaF2) slags to understand the foaming behavior. The results of this study can be summarized as follows:

1) The foaming index of the CaO–SiO2–FeO–Al2O3 slags (C/S=0.93 and 1.2) decreases with increasing content of FeO up to 20% and is almost constant for FeO content through 20 to 40%. The viscosity of slags could be considered as the major contributor to foaming behavior.

2) The addition of Al2O3 into the silicate slags results in an increase of foaming index due to an increase of slag viscosity; this could be explained by the structural role of Al2O3 in aluminosilicate slags.

3) In the MgO-saturated and Al2O3-containing slags, FeO behaves as an acidic oxide, because slag melts would be more basic than MgO-saturated and non-Al2O3 slags, where FeO behaves as a basic oxide, due to Al2O3 enhances the dissolution of MgO into the slags.

4) The addition of MnO into the MgO-saturated slags decreases foaming index, simply due to a decrease of slag viscosity. However, the addition of CaF2 and P2O5 into the slags results in the complex foaming behavior of slags; this is probably due to the Marangoni effect.

5) The relationships between foaming index and the physical properties of slags can be obtained from the dimensional analysis as follows:

\[ \Sigma = 214 \frac{\mu}{\sqrt{\rho \sigma}} \]  
(for the CaO-based slags)

\[ \Sigma = 999 \frac{\mu}{\sqrt{\rho \sigma}} \]  
(for the MgO-saturated slags)

6) The foam height is predicted as a function of decarburization rate from the molten iron under the industrial EAF operating conditions and the amount of electric energy saving can be estimated from the foam height estimated in the present study.

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