Behavior of Slag Foaming Caused by Blowing Gas in Molten Slags

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The relationship between the height of foaming slag and blowing gas flow rate has been investigated at different temperature and with additives such as coal, coke, graphite and CaO, in order to understand the foaming phenomenon in most metallurgical processes comprehensively. On the basis of experimental results, the regressed foam behavior equations \( \Delta h = b \cdot V^m \) were obtained. Those correlation coefficients were in range from 0.995 to 0.999. It means that the foam behavior equation can be used to describe foaming ability of the slag foaming caused by blowing gas quantitatively. The foaming index \( \Sigma \) is only a limited case for of the foam behavior equation and can be used only at high temperature and without additives for the foaming phenomenon caused by blowing gas. It was found also that the large carbonaceous particles could decrease the height of foaming slag, however the fine carbonaceous and CaO powder could increase it. The basicity of the slag affects the height of foaming slag.

KEY WORDS: slag foaming; additive; foaming index \( \Sigma \); foam behavior equation; molten slag.

1. Introduction

Generally, it is accepted that the main factors to determine the stability and life of slag foaming are viscosity, surface tension and the viscoelastic characteristics of slag films. And also electrical double layers with exist on film surface.\(^1\)–\(^3\) Fruehan and his collaborators have first introduced a foaming index \( S \) into metallurgical processes to describe the foaming phenomenon quantitatively, which is relative to bubble size, surface tension and viscosity introduced by the experimental results with dimensional analysis.\(^4\),\(^5\) They concluded that the slag foaming increases with increasing viscosity and decreasing surface tension. In comparing with the changing, the suspension of second-phase solid particles plays a more important part in the slag foaming. Gudenau and his collaborators have found that metallurgical slag foaming can be divided into two groups, spherical foam caused by blowing gas and polyedric foam originated from reactions of reduction or decomposition.\(^6\),\(^7\) The height of slag foaming caused by blowing gas can be remained stable at a blowing gas flow rate. But the height of slag foaming originated from reactions of reduction or decomposition increases with time to the maximum value and then falls down.\(^9\) The foaming index \( \Sigma \) can not be used to describe the foaming phenomenon quantitatively for the foam originated from reactions. The purpose of present study is to fine the relationship between the foaming height and blowing gas flow rate in different molten slag of the metallurgical process. Yoon and Shin have studied the influence of the coke size (4, 1.6 and 0.8 mm) on the foaming slag containing the FeO in blowing gas.\(^9\) The larger the coke size, the lower the foam height. However, in this case the two kinds foams in the slag.

The effect of temperature and additives on the foam height and the suitable condition of the foaming index \( \Sigma \) in the condition of slag foaming caused by blowing gas will be discussed along with experiment results.

2. Experimental Apparatus and Experiment

The experiments were carried out in a Tamman furnace shown in Fig. 1. This furnace was constructed with a constant temperature zone of 130 mm height and the temperature accuracy of this zone is \( \pm 10^\circ C \), in which an alumina...
The composition of slag (made of chemical agent by analytical purity) is indicated in Table 1. The sample 1\textsuperscript{st} slag was used in smelting reduction\textsuperscript{10}; The sample 2\textsuperscript{nd} and 5\textsuperscript{th} slags were basic slag for the second-refining and electric arc furnace respectively.\textsuperscript{11} The basicity (mass\%(CaO)/(mass\%SiO\textsubscript{2}) of the slags in the experiment varied from 0.5 to 2.6.

The slag was held in a graphite crucible of $\varnothing$40 mm and 120 mm height. In order to prevent graphite crucible from reacting with oxide, the crucible was lined with a flake of molybdenum of 0.10 mm thickness. During the experiment, Ar or high purity N\textsubscript{2} was blown from the bottom of the furnace. 

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Table 1. Composition of synthetic slags (mass %).

| Molten slag | CaO | SiO\textsubscript{2} | MgO | Al\textsubscript{2}O\textsubscript{3} | CaF\textsubscript{2} | Basicity (R) |
|-------------|-----|----------------|-----|-----------------|-----------------|-------------|
| 1\textsuperscript{st} | 30.0 | 60.0 | 10.0 | 0.5 |
| 2\textsuperscript{nd} | 37.2 | 33.8 | 18.0 | 11.0 | 1.1 |
| 3\textsuperscript{rd} | 41.2 | 25.8 | 8.0 | 15.0 | 1.6 |
| 4\textsuperscript{th} | 48.7 | 24.3 | 7.0 | 20.0 | 2.0 |
| 5\textsuperscript{th} | 47.7 | 18.3 | 9.0 | 10.0 | 15.0 | 2.6 |

Table 2. Foam behavior equations and foaming index $\Sigma$ of synthetic slags.

| Sample | Temp. | Additive | Experimental foam behavior equation | Correlative coefficient | Revised foam behavior equation | Relative error | Foaming index $\Sigma$ |
|--------|-------|----------|-----------------------------------|------------------------|--------------------------------|---------------|----------------------|
| 1\textsuperscript{st} | 1600 | no | $\Delta h = 0.521 V^{0.566}$ | 0.999 | $\Delta h = 0.521 V^{1.000}$ | 5.5 % | 0.521 |
| 1\textsuperscript{st} | 1550 | no | $\Delta h = 0.754 V^{0.956}$ | 0.999 | $\Delta h = 0.754 V^{1.000}$ | 6.1 % | 0.754 |
| 2\textsuperscript{nd} | 1500 | no | $\Delta h = 0.387 V^{1.045}$ | 0.999 | $\Delta h = 0.387 V^{1.000}$ | 6.3 % | 0.387 |
| 3\textsuperscript{rd} | 1500 | no | $\Delta h = 1.073 V^{1.01}$ | 0.999 | $\Delta h = 1.073 V^{1.000}$ | 2.9 % | 1.073 |
| 4\textsuperscript{th} | 1500 | no | $\Delta h = 0.681 V^{0.975}$ | 0.999 | $\Delta h = 0.681 V^{1.000}$ | 3.8 % | 0.681 |
| 4\textsuperscript{th} | 1450 | no | $\Delta h = 0.902 V^{1.045}$ | 0.995 | $\Delta h = 0.902 V^{1.000}$ | 6.9 % | 0.902 |
| 5\textsuperscript{th} | 1500 | no | $\Delta h = 1.170 V^{1.01}$ | 0.999 | $\Delta h = 1.170 V^{1.000}$ | 2.4 % | 1.170 |

4. Discussion

4.1. The Suitability to Foaming Index $\Sigma$

The foaming index $\Sigma$ means the foaming ability of the slag in the foam caused by blowing gas. Comparing to the foaming index $\Sigma$ in the Table 2, the foaming ability of the slag in the different processes at temperature 1500°C was arranged in the order as following: sample 5\textsuperscript{th} slag>sample 3\textsuperscript{rd} slag>sample 4\textsuperscript{th} slag>sample 2\textsuperscript{nd} slag. This result is in correspondence with the practice in the metallurgical process.

If the index $m$ in foam behavior equation is not 1, therefore foam factor $b$ will not be a constant. The foaming ability of the slag foaming caused by blowing gas should be described by foam behavior equation quantitatively, but not by the foaming index $\Sigma$.

The temperature effect on the $\Delta h$ of sample 1\textsuperscript{st} slag has been shown in Fig. 3. As revealed in this figure, the lower temperature, the higher the $\Delta h$ at same $V$. At relatively high temperature (1 600 and 1 550°C), the linearity is quite good. However, at lower temperature (1 450 and 1 500°C), the linearity is not so good. The $b$ in the foam behavior equa-
tation is not a constant. Such results appear for sample 2\textsuperscript{st} and sample 4\textsuperscript{th} slags at different temperature too. As indicated above, there is a transcritical temperature $T_{tr}$ for different slag. If the temperature is higher than the $T_{tr}$, the foaming index $S$ can be used to describe the foaming ability of the slag. The lower the $T_{tr}$ is, the wider the temperature range is achieved for the foaming index $S$ to be used. This $T_{tr}$ is related to composition and physicochemical properties of slag.

The composition of the sample 1\textsuperscript{st} slag came from a slag in the Ref. 5\textsuperscript{th}). In fact, the relationship between the $D_{h}$ and $V$ are not all in linearity, though all the data were regressed as linearity in that paper. The foaming index $S$ was also used to describe the foaming ability by some researchers. From the results of the experiment, the conclusion was reached that the foaming ability of the slag caused by blowing gas could be described by the foam behavior equation. Only in the condition, that the index $m$ in foam behavior equation is 1, the foaming index $S$ can be used. Practically, the foaming index $S$ is only a limited case for the foam behavior equation.

4.2. The Influence of Temperature and Additives

The effect of different coke size on the $D_{h}$ of sample 3\textsuperscript{rd} slag at 1500°C has been displayed in Fig. 4. The linearity without any additive is good, while the linearity with an additive is not good. In Fig. 4, the $D_{h}$ increases with fine powder coke (76 and 105 \textmu m) and decreases with grain coke (1 and 3 mm). The finer the coke powder, the higher the $D_{h}$. On the other hand, the larger the coarse coke grain, the lower the $D_{h}$. These results were attained by adding coke in the sample 1\textsuperscript{st} slag at 1550°C and sample 5\textsuperscript{th} slag at 1500°C. In the smelting reduction process of the thick slag layer, it is very important to keep slag height stably without abnormal slag foaming. The slag foaming can be controlled by adding carbonaceous material.

Comparing Fig. 4 with Fig. 5, it is found that promotion of the $D_{h}$ by adding fine powder coal is more significant than by adding fine powder coke, while inhibition of the $D_{h}$ by coarse grain coal is effectively less than by coarse grain coke. The reason is that there is the volatile matter in the coal. At high temperature, the heat decomposition of the volatile in the coal takes place, then, much of gas will be produced in the slag. The coarse grain coal has the effect on controlling the slag foaming, but the volatile matter could decrease this effect. In the experiments adding coal in sample 1\textsuperscript{st} slag at 1550°C and sample 4\textsuperscript{th} slag at 1450°C, the results are similar to those in Fig. 5.

The experiment of adding graphite in different size was also carried out in sample 3\textsuperscript{rd} slag at 1500°C. The influence of the graphite on the height of slag foaming is as same as the coke and coal. The fine powder graphite increases the $D_{h}$, but the coarse grain decreases the $D_{h}$. The degree of the influence from the graphite lies between that from the coke and coal. The graphite, coke and coal are different in the C content, volatility and structure, which have influence on the height of slag foaming. The reason of that is not clear currently and should be studied in the future.

The effect of adding CaO powder on the $D_{h}$ is analogous to that of adding fine powder coke. The result of sample 4\textsuperscript{th} slag at 1450°C was shown in Fig. 6. Such results were observed in the experiments for sample 1\textsuperscript{st} slag at 1550°C and sample 2\textsuperscript{nd} slag at 1500°C. The increase of $D_{h}$ relates not only to adding amount but also to the basicity of the slag.

After adding the fine powders of CaO and carbonaceous material in the molten slag, these powders may be adhered on the bubble surface and increase the viscoelastic characteristics of slag films. In this condition the gathering microbubbles will be hindered, so that $D_{h}$ increase. The added coarse grain carbonaceous material can control the slag foaming. The reasons, firstly, that the coarse coke has many pores to adhere microbubbles and gather big bubble, which results in discharging bubble,\textsuperscript{12} and, secondly, that in added coarse grain coke can increase the heat capacity of the slag and may prevent viscosity from decreasing.\textsuperscript{63}
5. Conclusion

(1) The linear relationship between $\Delta h$ of the molten slag and $V$ exists only under relatively high temperature. In this condition, the foaming index $\Sigma$ can be used to describe foaming ability of the molten slag quantitatively. Under lower temperature and with additive in the slag there is no linear relationship between them.

(2) The foam behavior equation is in the power-law form and can be used to describe foaming ability of the slag foaming caused by blowing gas. In fact, the foaming index $\Sigma$ is only a limited case for of the foam behavior equation.

(3) Some fine powders added in the molten slag may be adhered by the bubble face and increase the viscoelastic characteristics of slag films. It means that the gathering microlubes in the slag will be hindered and $\Delta h$ increases. But the added coarse grain carbonaceous material can suppress the slag foaming.

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