# Effect of Temperature on Slag Foaming

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Slag foaming has become important not only for the modern electric arc furnace but also for basic oxygen steelmaking and new ironmaking processes, such as bath smelting. In the electric arc furnace, foaming practices are widely used to shield the refractories from the arc and to protect metal from the atmosphere. Slag foaming is also used to stabilize the arc in the modern electric arc furnace. The control of the foaming height is required for steady-state operation in the bath-smelting process.

Several investigations on slag foaming have been previously carried out. Cooper and Kitchener[1] measured the foam lives of $CaO$-$SiO_2$ slags as a function of $CaO/SiO_2$ ratio, concentration of $P_2O_5$, and temperature. The foam life increased with decreasing temperature and decreasing $CaO/SiO_2$ ratio. Cooper and Kitchener's results indicate that the apparent activation energy for foaming is much higher than that for viscous flow. Swisher and McCabe[2] have also measured the foam life of $CaO$-$SiO_2$ slags. Their experimental results indicate that the foam lives increase with decreasing basicity and temperature. Hara and Ogino[3] studied the effect of slag composition, surface active additives, and gas composition on the foaming behavior of $FeO$-$SiO_2$-$CaO$ slags. The foam height increases sharply when the ratio O/Si is decreased below 3.5. Hara and Ogino considered that melt viscosity does not have a role in the foaming behavior of the slags. However, they found that surface tension plays an important role on foam lives.

In previous work,[4,5] the foaming index, $\Sigma$, and foam life, $\tau$, were introduced to describe the experimental results. These parameters are defined as

$$\Sigma = \frac{h}{V_g} \qquad [1]$$

$$\tau = \frac{-t}{\ln \dfrac{h}{h_0}} \qquad [2]$$

where $h$ is the foam height, $V_g$ is the superficial gas velocity, and $t$ is the time required to reduce the foam height from $h_0$ to a specified $h$ position when gas injection is stopped.

The foaming index is the average gas traveling time through the foamed layer and the dimension of time. The foaming index is dependent on the physical properties of slag, such as viscosity, surface tension, and density. It is also a function of the bubble size. For an ideal foam (i.e., first law drainage rate and constant void fraction), the foaming index is equal to average foam life. By dimensional analysis, Zhang[6] has obtained the following relation:

$$\Sigma = 1.83 \frac{\mu^{1.2}}{\sigma^{0.2} d^{0.9}} \qquad [3]$$

where $\rho$ is the density of the slag, $\sigma$ is the surface tension, $v$ is the viscosity, and $d$ is the bubble size. Using Eq. [3], it is possible to predict the foaming index for a slag at a given bubble size. Similar equations have also been derived by Jiang and Fruehan[7] for bath-smelting slags, such as $CaO$-$SiO_2$-$Al_2O_3$-$FeO$, in their experimental setup.

The data in the literature indicate that the effect of temperature on the foaming behavior of slags used in ironmaking and steelmaking operations has not been investigated in detail. In particular, most of the work done by Ito and Fruehan[4,5] was done at temperatures less than 1723 K, whereas 1823 to 1923 K is more typical of steelmaking processes. Therefore, the effect of temperature on slag foaming was studied. Also, there is some controversy as to the effect of slag depth on foaming. Equations [1] and [2] indicate that the foam height is independent of slag depth as long as there is a sufficient amount of slag to form foam. Some interpretations of foaming suggest it depends on slag volume. Therefore, experiments were conducted as a function of slag weight.

A schematic of the experimental apparatus is shown in Figure 1. A molybdenum disilicide resistance furnace was used in the experiments. The hot zone of the furnace was 10 cm. The slag was contained in an alumina crucible (i.d. = 41 mm, $H$ = 300 mm). The argon gas was introduced into the molten slag through an alumina tube (i.d. = 1.57 mm). The tube was placed approximately 0.5 cm above the bottom of the crucible. When foam height reached a steady-state level, the foam-gas interface was detected by two molybdenum wire probes (0.76-mm diameter). The molybdenum wires were protected by alumina tubes. The
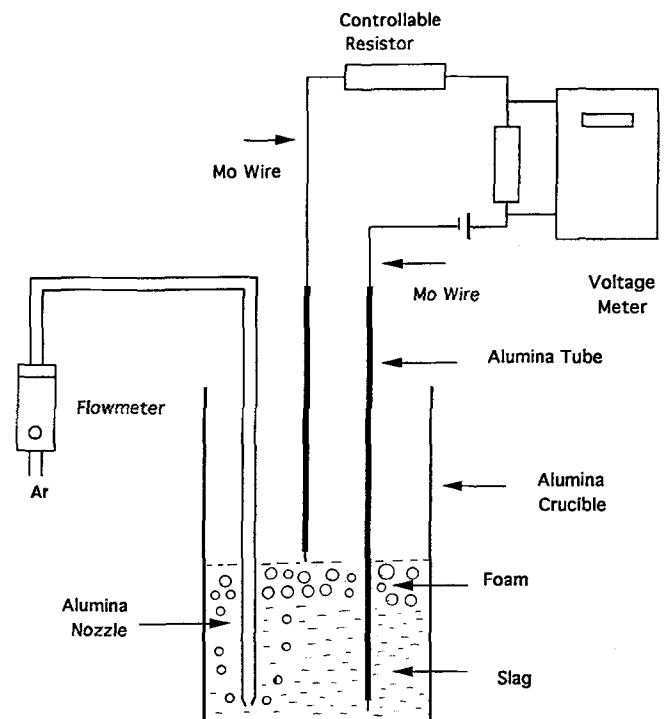


Fig. 1—Schematic of the experimental apparatus.

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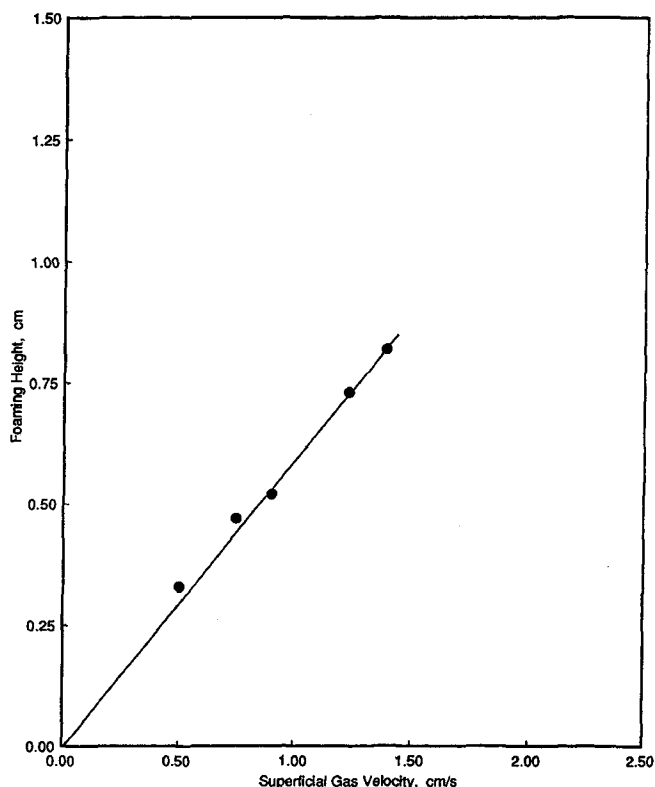
Fig. 2—The relation between foam height and gas flow rate for a 48 pct CaO-32 pct SiO₂-10 pct Al₂O₃-10 pct FeO slag at 1873 K.
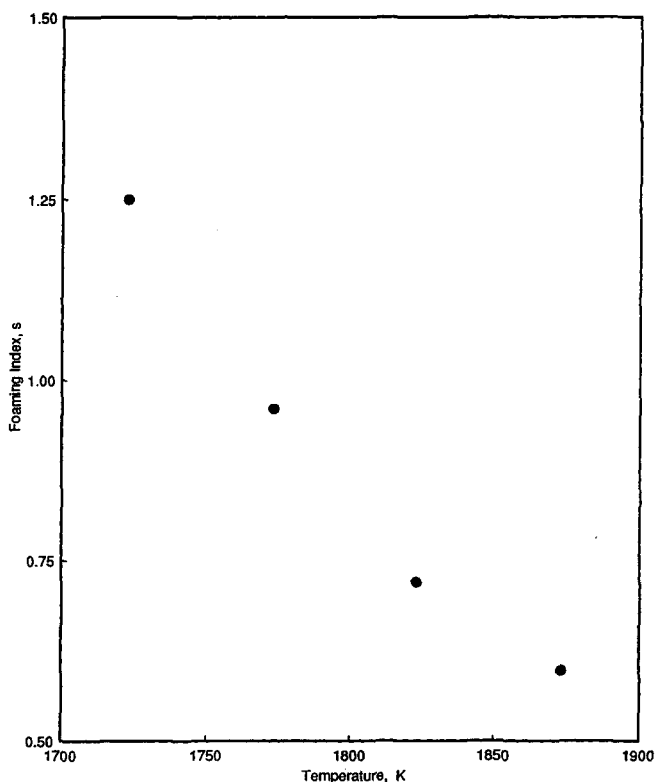


Fig. 3—Effect of temperature on foaming index for a slag containing 48 pct CaO, 32 pct SiO₂, 10 pct Al₂O₃, and 10 pct FeO.
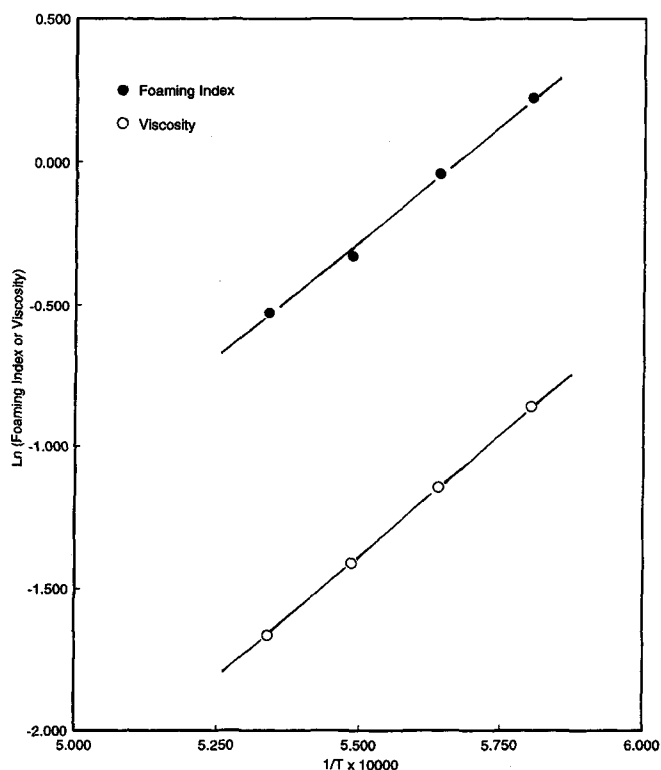


Fig. 4—The temperature dependency of foaming index (s) and viscosity (Pa·s) for a 48 pct CaO-32 pct SiO₂-10 pct Al₂O₃-10 pct FeO.

wires form a circuit with a dry battery. The foaming height was measured as the difference between the top of the foam surface and the liquid slag surface at rest. A series of measurements were made at various gas flow rates in order to obtain an accurate value of the foaming index.

The slag was prepared by mixing the desired amounts of reagent grade CaO, Al₂O₃, and SiO₂. The slag was premelted in an alumina crucible at 1873 K using an induction furnace with a graphite susceptor. Iron oxide (FeO) was made by reducing Fe₃O₄ in a CO-CO₂ gas mixture at 1273 K.

For most experiments, 160 g, which corresponds to a slag depth of 4.2 cm at 1873 K, was used. The slag was put in an alumina crucible and placed in the hot zone of the furnace. When temperature was reached and stabilized, a desired amount of FeO was added to the slag. The sample was heated under an argon atmosphere. After the experiment, the sample was quenched and analyzed.

The foam height as a function of superficial gas velocity for a slag containing 48 pct CaO, 32 pct SiO₂, 10 pct Al₂O₃, and 10 pct FeO at 1773 K is shown in Figure 2. The foam height increases linearly with increasing superficial gas velocity. The foaming index is obtained from the slope of the line shown in Figure 2. Similar experiments were also carried out at different temperatures, and the results are shown in Figure 3. As shown in Figure 3, the foaming index decreases with increasing temperature.

The temperature dependence of the foaming index and viscosity for a slag containing 48 pct CaO, 32 pct SiO₂, 10 pct FeO, and 10 pct Al₂O₃ is shown in Figure 4. Urbain's model[8] is used to calculate the viscosity of the slags under consideration. From the data given in Figure 4, the tem-

perature dependence of the foaming index is obtained as

$$\Sigma = 1.78 \times 10^{-5} \exp\left[\frac{16{,}797}{T}\right] \qquad [4]$$

Equation [4] is valid for the slag and experimental conditions used in this investigation. From Eq. [4], the apparent activation energy for the decay of the foam is obtained to be 139.6 kJ/mole. From the slope of the line for the viscosity, the activation energy for the viscous flow is 144.7 kJ/mole, which is slightly higher than that for the foam decay but within the experimental uncertainty of the two properties.

Experiments were carried out to investigate the effect of slag volume on the foaming index. In these experiments, only the amount of slag used was changed but all the variables were kept constant. A slag containing 40 pct $SiO_2$, 40 pct CaO, 10 pct $Al_2O_3$, and 10 pct FeO was used. Due to the limitations of the experimental apparatus, the maximum amount of slag used was 205 g. It was found that the foam index was 2.1, 2.23, and 2.36 s at 1723 K for 80, 140, and 205 g of slag, respectively. The experimental results indicate that the foaming index is almost independent of the amount of slag. The small increase in the foaming index might be due to the gas holdup in the slag. The relation, Eq. [3], developed by Zhang[6] indicates that the foaming index is independent of the amount of slag used. Using their correlations, the foaming for the same slag is calculated to be 2.07 s at 1723 K, which is in agreement with the present results. It must be noted that more substantial experiments are required to demonstrate the effect of slag height on foaming index.

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# Effect of Gas Type and Pressure on Slag Foaming

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In previous publications,[1,2] experimental results on the effect of the bubble size and the effect of the carbonaceous particles on slag foaming have been reported. It was found that the foam index is inversely proportional to the average bubble diameter. The foam index ($\Sigma$) is defined as

$$\Sigma = \frac{H_f}{v_s} \qquad [1]$$

where $H_f$ is the foam height and $v_s$ is the superficial gas velocity, which is the ratio of the volumetric gas flow rate to the cross-sectional area of the container. A general correlation obtained by dimensional analysis can be used to predict the foam index for the liquid slag as a function of its physical properties. The foam index was found to be approximately proportional to the liquid slag viscosity, inversely proportional to the slag density and the average bubble diameter, but relatively independent of the slag surface tension. When carbonaceous particles such as coke or coal char are present in the liquid slag, the foam stability of the slag will be significantly reduced. It was reported that the foam index of the liquid slag with the presence of carbonaceous particles depends on the surface coverage of the liquid slag, *i.e.*, the ratio of the total cross-sectional area of the particles to the liquid slag surface area. For a CaO-$SiO_2$-$CaF_2$-($Al_2O_3$) slag with an initial foam index of 2 or 4 seconds without carbonaceous particles at 1500 °C, the foam was totally suppressed when the slag surface was covered 15 ~ 20 pct by carbonaceous particles. It was also concluded from the X-ray observations that the antifoam effect of coke or coal char particles is primarily due to the nonwetting nature of the carbonaceous material with the liquid slag.

On the other hand, the effect of the gas phase on slag foaming has not been well examined, and information concerning that effect is very limited. Several studies indicated that the slag foamability was affected by the use of different types of gas for bubbling. These results were reviewed by Ogino *et al.*[3] However, in most of the cases, the slag could react with the gas phase. For example, the foam height of slags containing FeO was found to increase when the bubbling gas was used in the order of air, Ar, $N_2$-7 pct CO. Ogino *et al.* speculated that this was due to the decrease in the bubble size as a result of the Marangoni effect induced by chemical reaction.

In this work, the gases used did not react with the liquid slag. The slag was composed of CaO, $SiO_2$, $CaF_2$, and $Al_2O_3$ and was melted in the alumina crucible (diameter = 41 mm). The temperature was controlled at 1400 °C or

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