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# 4. Development of Numerical Prediction Model of Refractory Corrosion for Glass Melting Tank

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A one-dimensional simulation model of the refractory corrosion was newly developed for the glass-melting tank in long-term prediction. The thermal radiation near the boundary of refractory in contact with molten glass plays an important role to predict a refractory corrosion rate. Although the Rosseland's approximation has been applied in lots of glass melting tank simulators to analyze the radiative heat transfer by the mathematical simplification, the validity of the approximation is not considered to be reliable near the boundary because of neglecting the radiation from boundary. We have obtained the refractory corrosion rate from the calculated temperature near the boundary using exponential integral radiation method combined with conduction. The prediction result is good agreement with the ordinary reference data of the actual tank refractory corrosion. The difference is larger than 20% for the prediction of the remainder refractory thickness calculated by the Rosseland's approximation compared with the exponential integral radiation method.

## 1. Introduction

The evaluation of refractory corrosion is important to predict a melting tank life and glass quality. The corrosion evaluation tests of refractory, called 'finger test' or 'pencil test', have been worked in past years[1]-[2]. Although some fundamental evaluation data can be obtained from such laboratory experiments, it is difficult to predict the long-term corrosion of melting tank refractory because the boundary temperature change is not considered along tank life in such experiments.

On the other hands, local and transient temperature distributions in glass melt can be obtained by numerical approach. The temperature evaluation of the boundary between molten glass and refractory is much important to determine the corrosion rate. Since glass is semitransparent, thermal radiation is the dominant heat transfer mechanism at high temperature in molten glass. The Rosseland's approximation is the most popular method to calculate the radiative heat transfer in glass melts[3]. Although the method is good agreement for optically thick medium such as a glass melts, the validity of the approximation is not considered to be reliable near the boundary because the radiation from the boundary is neglected in the approximation concept.

In this work, we develop a one-dimensional simulation model of the refractory corrosion for a melting tank in long-term prediction by means of higher accuracy treatment for radiative heat transfer. The exponential integral method which is a high accuracy expression for radiative heat transfer is introduced in order to evaluate the temperature on the glass-refractory boundary. The model predicts the corrosion rate at the flux line which is one of the critical parts in determining lifetime of a tank. Since it is unsuitable for manufacturing requirements to consider the all-physical mechanisms into the simulation model, we have achieved a simplest one-dimensional simulation model under considering the temperature of the side tank block above the flux line as the fixed temperature boundary

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condition, and solving the moving boundary heat transfer by refractory corrosion without thermal convection. The verification of this simulation model is confirmed by the comparative investigation with the ordinary reference data of refractory corrosion in melting tanks.

## 2. Model Description

The analytical model in this study is schematically represented in **Fig. 1**. The heat transfer and the moving boundary are taken into account. Thermal convection is not considered in the concave area caused by refractory corrosion. The simulation model is assumed to be a one-dimensional thermal radiation and conduction heat transfer model to simplify the several complex mechanisms of the refractory corrosion such as chemical reactions, the property change on the surface by desolated refractory, small-scale convection related to the surface tension of glass melts, multi-dimensional and three-phase boundary effects. The initial thickness of the refractory is 250 mm, and of the molten glass layer is 10 mm for the calculation stability. The refractory is made of a standard AZS in contact with clear float soda lime glass. The temperature dependence of thermal conductivity of the refractory[4] takes into account. Fixed temperature boundary condition is considered at the temperature of the side tank block above the flux line, and heat flux boundary condition is considered as a forced convection by air-cooling and radiation loss.

### 2.1 Heat transfer

The one-dimensional transient conductive heat transfer equation is represented as follows,

$$c\rho\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\dot{Q}_v \qquad [1]$$

where $c$, $\rho$, $T$, $t$, and $k$ stand for specific heat, density, temperature, time and thermal conductivity, respectively. $Q_v$ is radiative energy source term.

The radiative transfer equation for a one-dimensional plane parallel system and spectrally absorbing-emitting medium can be written as

$$\mu\frac{dI_\lambda}{dx}=\kappa_\lambda\left\{I_{b\lambda}\left(T(x)\right)-I_\lambda(x,\mu)\right\} \qquad [2]$$

where $\kappa_\lambda$ stand for the spectral absorption coefficient of the glass. $I_\lambda$ $(x, \mu)$ is the spectral radiative intensity, which is a function of position $x$, direction $\mu(=\cos\theta)$ and wavelength $\lambda$. $I_{b\lambda}$ $(T)$ is the spectral intensity of blackbody radiation given by Planck's function at absolute temperature $T$.

$\kappa_\lambda$ is related to $k_\lambda$ which is the imaginary part of complex refractive indices of glass, and expressed as follows,

$$\kappa_\lambda=\frac{4\pi k_\lambda}{\lambda} \qquad [3]$$

The refractive indices of the clear float soda lime glass reported by Rubin[5] are used in this simulation. The spectral dependency of absorption coefficient expressed by [3] is shown in **fig. 2**.

Since spectral calculation in according to equation [2] is much expensive for computational resource, the mean absorption coefficient, $\kappa$, is introduced in order to reduce computational time.

$$\frac{1}{\kappa}=\int_0^\infty\frac{1}{\kappa_\lambda}\frac{dI_{b\lambda}}{dT}d\lambda\Big/\int_0^\infty\frac{dI_{b\lambda}}{dT}d\lambda =\frac{\pi}{4\sigma T^3}\int_0^\infty\frac{1}{\kappa_\lambda}\frac{dI_{b\lambda}}{dT}d\lambda \qquad [4]$$

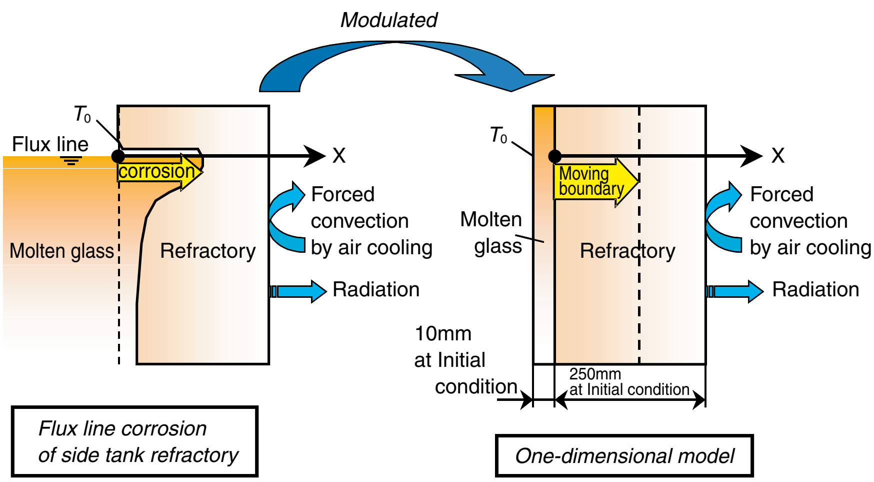


**Fig. 1 Schematic of the analytical model.**

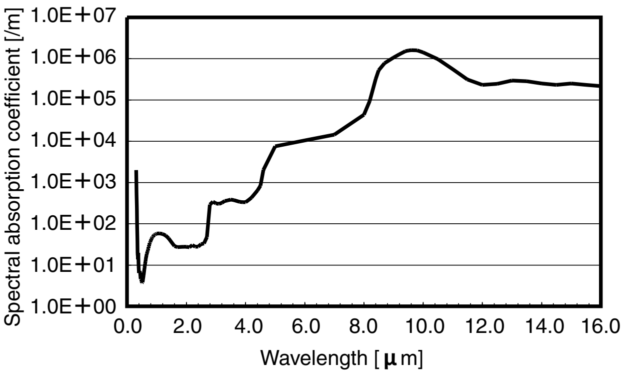


**Fig. 2 Spectral absorption coefficient for clear float soda. lime glass.**

The integration is executed from 0.31$\mu$m to 16.5$\mu$m because the blackbody emissive power can be considered larger than 99%.

The net radiative heat flux $q_i^R$ in element $i$ is obtained by introducing the mean absorption coefficient represented by [4] at the uniform temperature $T_i$,

$$q_i^R = 2\pi\Big\{E_3(\tau_i)\big[I_{i-1} - I_b(T_i)\big] - E_3(\tau_{i0} - \tau_i)\big[I_{i+1} - I_b(T_i)\big]\Big\} \qquad [5]$$

where $\tau_i$ ($=\overline{\kappa}\Delta x_i$) and $E_3(\tau_i)$ are optical thickness and exponential integral function[6], respectively. $I_{i-1}$ and $I_{i+1}$ are the raidative intensities from neighbor elements $i-1$ and $i+1$. The detail derivations of the equation [5] have been previously described by Modest[6], and are not repeated here.

### 2.2 Refractory corrosion model

The primary corrosion process is related to the solubility of the refractory in dependence on its temperature. **Figure 3** shows the refractory corrosion rate referred from[7]. The diffusion coefficient $D$ of refractory in molten glass is assumed to be Arrenius type expression.

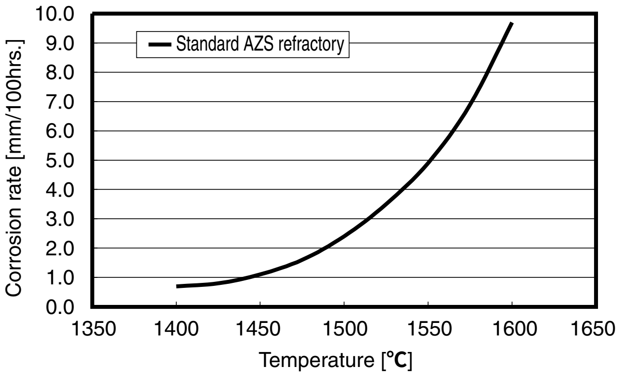


**Fig. 3 Refractory corrosion rate[7].**

$$D = A\exp(-\Delta E / RT) \qquad [6]$$

where $A$, $\Delta E$, $R$ and $T$ are the frequency factor for diffusion, activation energy, gas constant and absolute temperature, respectively.

The mass transfer flux $F$ can be written in the following expression.

$$\ln F = \ln \frac{A(c_\infty - c)}{\delta_c} - \left(\frac{\Delta E}{R}\right)\frac{1}{T} \qquad [7]$$

where $c$ and $\delta_c$ are concentration of the molten refractory in the glass melt and thickness of concentration boundary layer.

**Figure 4** shows the values of the mass transfer flux $F$ plotted in logarithmical form in the function of inversely temperature. The best-fit line is calculated by means of the least squares method, and expressed by a linear functional equation. From the equation, the distance of the moving boundary due to refractory corrosion can be obtained.

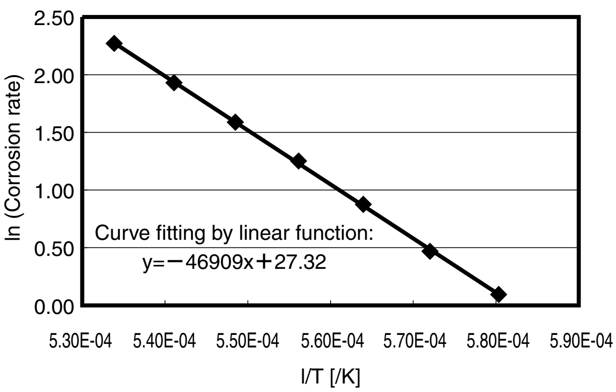


**Fig. 4 The mass transfer flux plotted in logarithmical form.**

## 3. Results and Discussion

**Figure 5** shows the calculation results of the refractory corrosion compared with the ordinary reference data[8] in melting tanks. The eight temperature conditions on side tank block of which initial thickness is 250mm are calculated. Until the remainder thickness of the refractory becomes around 100 mm, the corrosion rates keep on large rates in the higher temperature conditions. The refractory corrosion rate is small after the remainder thickness of the refractory becomes less than 50mm since the boundary temperature between the molten glass and the refractory becomes less than 1400°C as shown in **Fig. 6**. In the lower temperature conditions, the initial corrosion rates are small while the corrosion rates don't change like

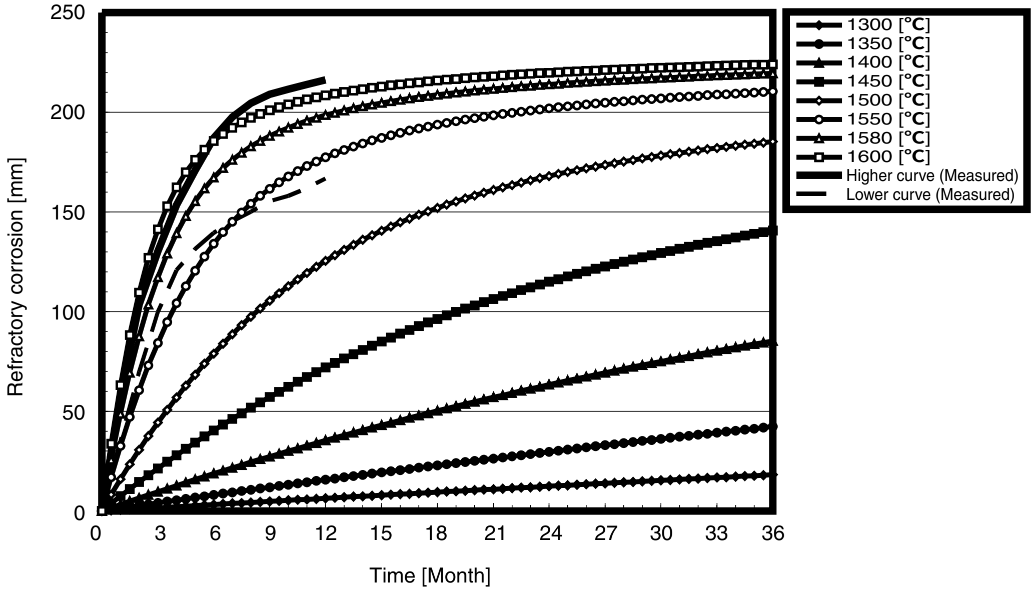


**Fig. 5 Comparison of the calculation results with reference data.**

the higher temperature conditions along time. The reference curves[8] are the summary values measured in a lot of melting tanks. The temperature at the point using this calculation is from 1560°C to 1600°C in the ordinary melting tanks for clear soda lime glass, and the prediction results are good agreement with the curves.

The corrosion prediction model is applied to evaluate the effect of the initial refractory thickness and patch block. **Figure 7** shows the calculation results of the remainder refractory thickness in three conditions: 250mm, 300mm initial thickness, and 250mm initial thickness with 50mm patch block when the remainder thickness is less than 30 mm. Fixed temperature boundary conditions are at 1580°C in three cases. The refractory of 250mm thickness reduces the refractory dissolution into glass melts compared with that of 300mm thickness. Larger remainder thickness of the side tank block is obtained by the patch block compared with the case of 300mm initial thickness although the total refractory thickness is the same.

**Figure 8** shows the remainder thickness of the refractory along time by using the exponential integral radiation method compared with Rosseland's approximation, respectively. The error gradually increases over 20% in the long-term prediction, and the difference of the thickness is up to 10.1mm. **Figure 9** shows the difference of the remainder thickness by decreased temperature of the tank to extend the tank life calculated by the exponential integral radiation method, and the difference between two methods. The difference between two methods is larger than that in case of 20°C decreased temperature after 24months. The difference between two methods is considered to be

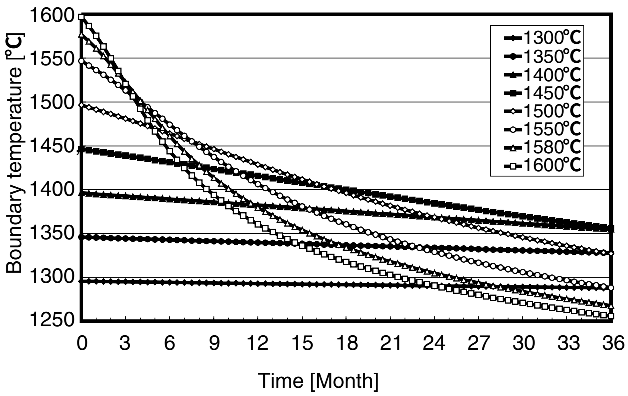


**Fig. 6 Boundary temperature changing along time in eight temperature conditions.**

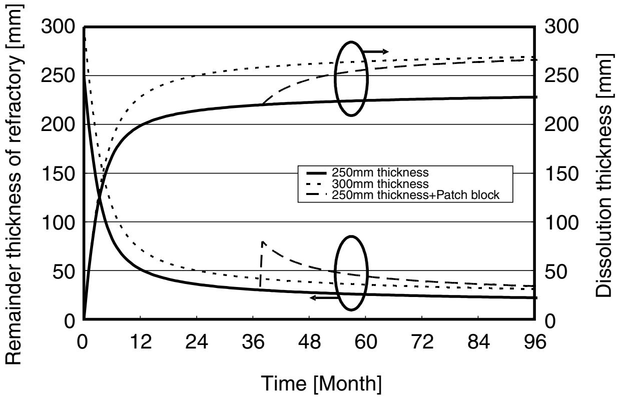


**Fig. 7 Difference of the refractory dissolution by the initial thickness and patch block.**

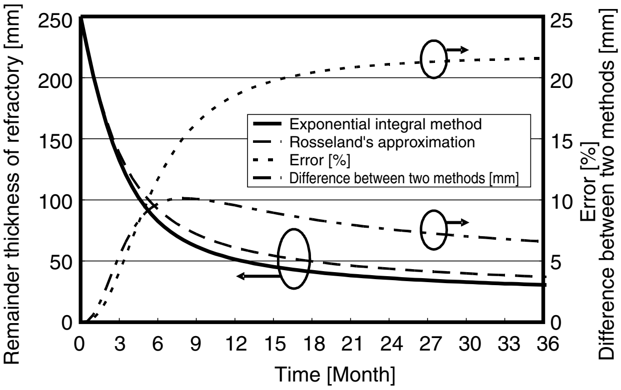


**Fig. 8 Prediction of the remainder thickness of refractory calculated by two methods.**

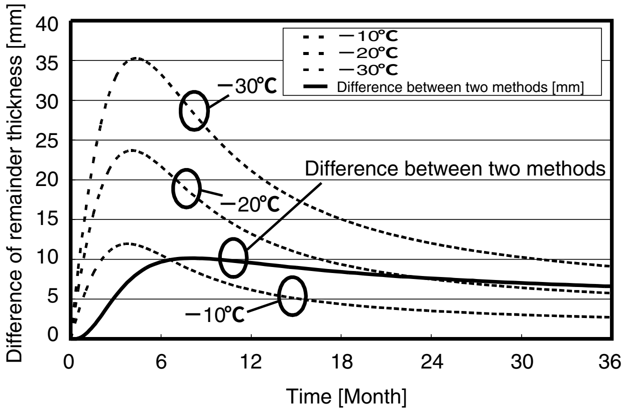


**Fig. 9 The difference of the remainder thickness by decreased temperature of the tank and between two methods.**

affected to predict the extending tank life by decreased temperature.

## 4. Conclusion

We presented a one-dimensional simulation model of the corrosion prediction for a melting tank refractory. The prediction result is good agreement with the reference corrosion rate. The simulation model can be applied to investigate the way of extending lifetime for a melting tank refractory. The difference between the exponential integral radiation method and Rosseland's approximation is larger than 20% for the remainder thickness of the refractory and equivalent in case of decreased tank temperature over 20℃ after 24 months.

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