A SIMPLE MODEL OF REFINING IN GLASS MELTING FURNACE WITH VERTICAL FLOW AND COVERED LEVEL

LUBOMÍR NĚMEC, JAROSLAV LUBAS

Institute of the Chemistry of Glass and Ceramic Materials, Czechoslovak Academy of Sciences, Sokolska 38, 120 00 Prague 2

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The simple model presented takes into account the possible accumulation of a refining agent under the glass batch in the melting rooms with vertical flow. The relations describing an increase of the refining agent concentration in the glass melt have been derived from the mass balance of the refining agent and the calculations have been performed showing the influence of the main factors on the process. The necessary experimental data have been collected and the effect of the refining agent accumulation on the refining behaviour has been demonstrated.

INTRODUCTION

Although the complex mathematical models of glass melting furnaces seem to outline the future development of glass melting, the simple models describing only the fundamental features of the equipment are needed too. These models are able to evaluate very quickly intentions of designer or technologist without complex calculations and especially without obtaining a great many experimental data.

This work presents a simple model of single bubble behaviour in the all electric glass melting furnace with covered glass level and vertical flow.

When glass is refined in these furnaces, the accumulation of a refining agent under the glass batch may occur. The accumulation effect is caused by refining agent reabsorption (sulphates, chlorides etc.) or by reabsorption of its efficient component (oxide refining agents) transported here by bubbles from the refining regions. The mentioned phenomenon is schematically demonstrated in Fig. 1. For refining, especially the downflowing glass melt is significant, carrying down the bubbles. These are rapidly growing at refining temperatures and later start to rise to the glass batch. The refined glass melt is usually pulled out from the bottom, the upwards flowing glass melt having thus only inferior significance for the refining. In Fig. 1, there is illustrated one circulation roll where refining is realized between A and B.

Refining is assumed to be completely realized as far as in the region A where one part of the refining agent diffuses into the bubbles whereas another part may be accumulated on the bubble surfaces in gall layer [1]. These bubbles are subsequently rising to the region B with lower temperature where reabsorption of the refining agent occurs and the concentration of the refining agent or dissolved refining gas is growing. The refining agent may even exclude from the melt and penetrate out of the furnace as was observed [2]. This effect brings about differences between the optimum refining agent concentration determined by the laboratory crucible melts and those needed for the actual melting furnace. In addition, the refining agent accumulation should be taken into account when determining the actual concentration of a refining agent for the purpose of the mathematical modeling.

The following simplifying presumptions have been accepted to derive the model:

1. At zero time, there is no refining agent in the furnace, the concentration of the refining agent in the entering glass batch being constant.
2. The effect of the refining agent precipitation and reabsorption is occurring only in regions A and B, respectively. The refining is executed between A and B.
3. No refining agent is evaporated through the glass batch.
4. The bubbles are downflowing and rising by the same mean velocity over the cross section of flow, the average refining time $\tau_R$ being constant with time.

5. The glass melt is flowing from B to A and through C by the same mean velocity, the circulation time $\tau_C$ being constant. The ratio $\tau_C/\tau_R$ and $\tau_R/\tau_C$ is the whole number.

**THEORETICAL**

**Oxide refining agents**

The oxide refining agent are sufficiently soluble in the glass melt, therefore no refining agent precipitation can be expected in A and B. However, oxygen transported by bubbles is shifting the equilibrium between both valencies to the higher one. Eventually, the equilibrium between both forms sets corresponding to temperature in B and pure oxygen atmosphere. The superfluous transported oxygen is penetrating through the glass batch.

The fundamental equation has the form:

$$
\frac{4}{b} M_{(a+b)}^+ + 2O_2^- = \frac{4}{b} M^+ + O_2
$$

(1)

For the mass balance of dissolved oxygen in region B holds:

If $\tau_C/\tau_R = n \geq 1$, then the oxygen concentration in B during i-th bubble circulation is given by:

$$
c_{Bi} = \frac{\dot{V}_0 c_{0} + \dot{V} (1 - K_{R,i-1}) c_{B,i-1}}{V}
$$

(2)

If $\tau_R/\tau_C = 1/n > 1$, then for the oxygen concentration may be written:

$$
c_{Bi} = \frac{\dot{V}_0 c_{0} + \dot{V} (1 - K_{R,i-1}) c_{B,i-1}}{V}
$$

(3)

where $c_{Bi}$ is 0 for $i < 0$.

The amount of the refining agent transported by bubbles from A to B or precipitated in A is equal to:

$$
c_{Bi} = \frac{\dot{V}_0 c_{0} + \dot{V} (1 - K_{R,i-1}) c_{B,i-1}}{V}
$$

(6)

where $i$ in eqs (2–6) designates the i-th circulation circle with the period of $\tau_C$. The value of $c_{Bi}$ may grow up to the maximum value given by the saturated oxygen concentration in B, however, this value need not to be reached (being dependent from the values of $1 - K_{R,i}$). If the maximum value of $c_{Bi}$ is reached ($c_{Bi} = c_{SB}$), the respective superfluous oxygen penetrating through the glass batch is given by:

$$
in_{Bi} = \dot{V}_0 (c_0 - K_{R,i-1} c_{SB})
$$

(7)

The value of $c_{Bi}$ in the steady state plays the decisive role for the refining between B and A.

**The refining agents having limited solubility in glass**

Sulphates as well as halides are only partially soluble in the commercial glasses. If solubility in the given region is surpassed, the refining agent precipitation may occur namely on the surfaces; at higher temperatures, the thermal decomposition of sulphates or evaporation of halides occurs. Therefore, the first part of the refining agent diffuses in A into the bubbles and the second one is excluded on the bubble surfaces in form of a gall layer. In addition a part of the refining agent may be excluded on the walls as well as bottom of the furnace. The refining agent transported by bubbles is reabsorbed in B, where its concentration grows and solubility may be eventually surpassed. In this case, the superfluous refining agent is precipitated on the interphase boundaries or under the glass bath. For the mass balance of the refining agent, one may write:

If $\tau_C/\tau_R = n \geq 1$, then $c_{Bi}$ in the i-th bubble circulation circle is given by:

$$
c_{Bi} = \frac{\dot{V}_0 c_{0} + \dot{V} (1 - K_{R,i-1}) c_{B,i-1}}{V}
$$

(8)

If, on the contrary, $\tau_R/\tau_C = 1/n > 1$, then $c_{Bi}$ in i-th glass circulation circle is given by:

$$
c_{Bi} = \frac{\dot{V}_0 c_{0} + \dot{V} (1 - K_{R,i-1}) c_{B,i-1}}{V}
$$

(9)

where $c_{Bi}$ is 0 for $i < 0$ and $K_{R,i}, K_{A,i}$ is 1 for $i < 0$.

The amount of the refining agent transported by bubbles from A to B or precipitated in A is equal to
Table I

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Ref. agent concentration [kg.m⁻³]</th>
<th>Number of bubbles followed</th>
<th>k [m.s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1427</td>
<td>3.29</td>
<td>estimation</td>
<td>1.00x10⁻⁹</td>
</tr>
<tr>
<td>1427</td>
<td>13.16</td>
<td>estimation</td>
<td>1.00x10⁻⁹</td>
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<td>1580</td>
<td>3.29</td>
<td>8</td>
<td>2.20x10⁻⁸</td>
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<tr>
<td>1580</td>
<td>13.16</td>
<td>18</td>
<td>1.30x10⁻⁷</td>
</tr>
</tbody>
</table>

zero so long as \( c_{Bi} < c_{SA}(K_{Bi}, K_{Ai} = 1) \). At higher values of \( c_{Bi} \), the maximum amount of the excluded refining agent is characterized by:

\[
2 - K_{R,i-1} - K_{A,i-1} = \frac{c_{Bi} - c_{SA}}{c_{Bi,i-1}} \tag{10}
\]

Equation (10) indicates the decrease of the refining agent concentration in \( A \) to the value of its solubility. In fact, however, the portion of the refining agent transported by bubbles or excluded in \( A \) is unknown, therefore at least one of the coefficients \( K_{R,i} \) and \( K_{A,i} \) must be estimated. The maximum refining agent concentration in \( B \) may reach the solubility in \( B \) - \( c_{SB} \) and the respective superfluous amount of transported refining agent is precipitated in \( B \). This amount in the steady state is given by:

\[
\dot{n}_{Bi} = \dot{V}_0 c_0 - \dot{V}(1 - K_{R,i-1}) c_{SB} - \dot{V}_0 (K_{R,i-1} + K_{A,i-1} - 1) c_0. \tag{11}
\]

For the refining accomplishing between \( B \) and \( A \), the bubble of initial radius \( a_0 \) is considered to be carried down from \( B \) to \( A \) by the glassmelt. In \( A \), the bubble rising velocity has the same absolute value as is the downflowing velocity of glass. In the following moment, the growing bubble stars to rise to \( B \) where refining is completed. If the distance between \( A \) and \( B \) is designated by \( h \), we have:

\[
h = v_{GLASS} \tau R - \int_0^\tau \frac{2g \rho(T)}{\eta(T)} \left( a_0 + \int_0^\tau k(T) \, d\tau \right)^2 \, d\tau \tag{12}
\]

\[
v_{GLASS} = \frac{2g \rho(T_A)}{\eta(T_A)} \left( a_0 + \int_0^\tau k(T) \, d\tau \right)^2 \tag{13}
\]

where \( T = T(\tau) \). Both equations are solved using iteration method. Because of the monotonous temperature increase between \( B \) and \( A \), as well the experimental values of bubble growth rates may be applied in eqs. (12–13).

EXPERIMENTAL

For the application of derived equations in the case of borosilicate glass refined by NaCl, several experimental values are necessary.

The concentration and temperature dependence of the average bubble growth rate.

For this purpose, the method of photographing of glass melt with bubbles at high temperatures has been applied. From the dependencies between bubble radii and time, the average values of bubble growth rate have been obtained. The results of measurement are in Table I.

The estimation of saturated concentration of NaCl in the borosilicate glass.

The saturated NaCl concentracion has been obtained by mixing of NaCl melt and the borosilicate glass melt in the silica glass crucible at two temperatures only. The value of \( c_S \) at 1400°C determined by the subsequent chemical analysis was 3.78 kg.m⁻³, the value at 1 450°C was 2.44 kg.m⁻³. At higher temperatures, another experimental arrangement is necessary (bubbling of glass by NaCl vapour). This arrangement was not at disposal.

The analyzed concentration of NaCl in outputting glass \( c_C \) was 2.22 kg.m⁻³.

DISCUSSION

To demonstrate the significance of derived equations, several model calculations have been performed.

The course of \( c_{Bi} \) growth calculated from (8) and (9) respectively for \( K_A = 1, K_R \leq 1 \) is presented in Fig. 2, whereas the case of \( K_A \leq 1, K_R = 1 \) is in Fig. 3. As is obvious from Fig. 2, the refining agent precipitation in region \( B \) occurs at values \( K_R \leq 0.8 \).
A Simple Model of Refining ...

Fig. 4. The time dependence of $c_{Bi}$. Meaning of symbols, see Fig. 1 and Fig. 2. 

This application. The data used for the calculations have following values:

$\tau_R = \tau_C = 2000\; s$; $c_o = 3.29\; kg.m^{-3}$; $c_{SA} = 2.0\; kg.m^{-3}$; $c_{SB} = 4.0\; kg.m^{-3}$; $K_A = 0.99$; $K_R = 0.7$; 1. $V_0 = 1.64 \times 10^{-5}\; m^3.s^{-1}$; $\dot{V} = 6.32 \times 10^{-4}\; m^3.s^{-1}$; 2. $V_0 = 1.64 \times 10^{-5}\; m^3.s^{-1}$; $\dot{V} = 3.16 \times 10^{-5}\; m^3.s^{-1}$; 3. $V_0 = 1.64 \times 10^{-5}\; m^3.s^{-1}$; $\dot{V} = 6.32 \times 10^{-5}\; m^3.s^{-1}$

The temperature as well the concentration dependence of the bubble growth rate is assumed to be exponential. The experimental values of $k$ obtained at higher temperatures (see Table I) have been used for the derivation of the following relation:

$$k = 8.188 \times 10^{-12}\exp(19.23c_B)$$

$$\cdot \exp\left(-32700c_B+12080\right)\; [m.s^{-1}]$$

The results of the $c_{Bi}$ calculation are in Fig. 5. If $K_A$ is assumed to be 1 (curve 1), the precipitation of

Table II

<table>
<thead>
<tr>
<th>$K_R$</th>
<th>$c_B$ [kg.m$^{-3}$]</th>
<th>$c_C$ [kg.m$^{-3}$]</th>
<th>$\dot{m}_A$ [kg.s$^{-1}$]</th>
<th>$\dot{m}_B$ [kg.s$^{-1}$]</th>
</tr>
</thead>
<tbody>
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<td>1.0</td>
<td>3.29</td>
<td>3.29</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>3.65</td>
<td>3.29</td>
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<td>0</td>
</tr>
<tr>
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<td>4.00</td>
<td>3.29</td>
<td>0</td>
<td>1.49x10$^{-6}$</td>
</tr>
<tr>
<td>0.7</td>
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<td>4.00</td>
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<td>0</td>
<td>1.47x10$^{-5}$</td>
</tr>
<tr>
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<td>4.00</td>
<td>3.29</td>
<td>0</td>
<td>2.13x10$^{-5}$</td>
</tr>
</tbody>
</table>

Table III

<table>
<thead>
<tr>
<th>$K_A$</th>
<th>$c_B$ [kg.m$^{-3}$]</th>
<th>$c_C$ [kg.m$^{-3}$]</th>
<th>$\dot{m}_A$ [kg.s$^{-1}$]</th>
<th>$\dot{m}_B$ [kg.s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>3.29</td>
<td>3.29</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.99</td>
<td>3.20</td>
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<tr>
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<tr>
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<td>1.61x10$^{-5}$</td>
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<tr>
<td>0.85</td>
<td>2.36</td>
<td>2.00</td>
<td>2.23x10$^{-5}$</td>
<td>0</td>
</tr>
</tbody>
</table>

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The final values of the refining agent concentrations and the rates of refining agent precipitation.

\[ K_A = 0.99; \quad K_R = 0.70; \quad \tau_R = \tau_C = 2000 \text{ s}; \quad c_0 = 3.29 \text{ kg.m}^{-3}; \quad c_{SA} = 2.0 \text{ kg.m}^{-3}; \quad c_{SB} = 4.0 \text{ kg.m}^{-3} \]

<table>
<thead>
<tr>
<th>( \dot{V}_0 ) ([\text{m}^3.\text{s}^{-1}])</th>
<th>( \dot{V} ) ([\text{m}^3.\text{s}^{-1}])</th>
<th>( c_B ) ([\text{kg.m}^{-3}])</th>
<th>( c_C ) ([\text{kg.m}^{-3}])</th>
<th>( \dot{m}_A ) ([\text{kg.s}^{-1}])</th>
<th>( \dot{m}_B ) ([\text{kg.s}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 1.64 \times 10^{-5} )</td>
<td>( 6.32 \times 10^{-4} )</td>
<td>3.03</td>
<td>2.09</td>
<td>( 1.92 \times 10^{-5} )</td>
<td>0</td>
</tr>
<tr>
<td>( 1.64 \times 10^{-5} )</td>
<td>( 3.16 \times 10^{-4} )</td>
<td>3.72</td>
<td>2.57</td>
<td>( 1.78 \times 10^{-5} )</td>
<td>0</td>
</tr>
<tr>
<td>( 1.64 \times 10^{-5} )</td>
<td>( 6.32 \times 10^{-5} )</td>
<td>4.00</td>
<td>2.76</td>
<td>( 2.50 \times 10^{-5} )</td>
<td>6.16 \times 10^{-6}</td>
</tr>
</tbody>
</table>

Fig. 5. The time dependence of \( c_B \) for the given furnace. Meaning of symbols, see Fig. 1 and Fig. 2. \( V_0 = 1.64 \times 10^{-5} \text{ m}^3.\text{s}^{-1}; \quad \dot{V} = 6.32 \times 10^{-5} \text{ m}^3.\text{s}^{-1}; \quad \tau_R = \tau_C = 2000 \text{ s}; \quad 1. \quad c_0 = 3.0 \text{ kg.m}^{-3}; \quad c_C = 2.22 \text{ kg.m}^{-3}; \quad K_R = 0.587; \quad K_A = 1; \quad 2. \quad c_0 = 3.0 \text{ kg.m}^{-3}; \quad c_C = 2.22 \text{ kg.m}^{-3}; \quad K_R = 1; \quad K_A = 0.992; \quad 3. \quad c_0 = c_{SB} = 3.78 \text{ kg.m}^{-3}; \quad K_R = 1; \quad K_A = 0.98 \]

NaCl for given \( c_C \) (analyzed in glass products) occurs in \( B \) for \( K_R = 0.587 \) (\( c_B = c_{SB} \)) and consequently the concentration of refining agent, \( c_B \), between \( B \) and \( A \) can not be further raised by increasing \( c_0 \). Only when \( K_A < 1 \), the increase of \( c_0 \) may cause also increase in \( c_B \) (curves 2–3). The values of \( c_B \) have been applied for the calculation of the maximum downflowing glass velocity being proportional to the maximum glass output of the furnace (eqs. 12–13). Since for this case \( K_R < 1 \) (\( K_R = 0.587 \)) and the glass refining can not be optimized by the increase of the refining agent concentration, \( c_0 \), the new vertical temperature gradient has been proposed to accelerate refining. The values of \( V_{\text{GLASSMAX}} \) as well as both temperature curves are in Fig. 6. As is obvious from this figure, the new temperature gradient increases the glass output about 1.8 times.

**CONCLUSION**

As is obvious from the presented results, the mass balance of a refining agent in the glass melting rooms with vertical flow and covered level is needed to improve refining. The presented model is able to include the fact of increase of the refining agent concentration under the glass batch leading to the refining agent precipitation from the glassmelt and to its penetrating through the refractory walls of a melting room. When preparing the complex mathematical models of glass melting process, this mass balance of a refining agents is necessary too. The more detailed data of the refining agent solubility and bubble behaviour are needed. The regular control of the refining agent concentration in the outputting glass may help to reveal in time the refining agent precipitation inside of a glass melting room.
Fig. 2. The time dependence of $C_{Bi}$. $V_0$ - volume glass flow inward or outward of the circulation roll, $V$ - total volume glass flow in the circulation roll between the regions A and B, $\tau_R$, $\tau_C$, $c_0$, $c_{SA}$, $c_{SB}$ - see Fig. 1. $K_A$ - the portion of refining agent precipitated in region A during the i-th circulation cycle, $1 - K_R$ - the portion of refining agent precipitated in region B during the i-th circulation cycle. $K_A = 1$; $V_0 = 1.64 \times 10^{-5} \text{m}^3 \cdot \text{s}^{-1}$; $V = 6.32 \times 10^{-5} \text{m}^3 \cdot \text{s}^{-1}$; $\tau_R = \tau_C = 2000 \text{ s}$; $c_0 = 3.29 \text{ kg.m}^{-3}$; $c_{SA} = 2.0 \text{ kg.m}^{-3}$; $c_{SB} = 4.0 \text{ kg.m}^{-3}$.

Fig. 3. The time dependence of $C_{Bi}$. Meaning of symbols, see Fig. 1 and Fig. 2. $K_R = 1$; $V_0 = 1.64 \times 10^{-5} \text{m}^3 \cdot \text{s}^{-1}$; $V = 6.32 \times 10^{-5} \text{m}^3 \cdot \text{s}^{-1}$; $\tau_R = \tau_C = 2000 \text{ s}$; $c_0 = 3.29 \text{ kg.m}^{-3}$; $c_{SA} = 2.0 \text{ kg.m}^{-3}$; $c_{SB} = 4.0 \text{ kg.m}^{-3}$

The influence of ratio $V_0/V$ on the $C_{Bi}$ growth is obvious from Fig. 4. The appropriate numerical values are in Tab.II, III and IV, respectively.

Following conclusions may be drawn from the results of model calculations:
If $c_C < c_0$, precipitation of the refining agent occurs.
If $c_C = c_0$, no precipitation occurs.
If there is precipitation only in B, then: $c_B > c_0$; $K_R < 1$; $c_C < c_0$.
For the precipitation only in A:
$c_B < c_0$; $K_A < 1$; $c_C < c_0$.

Generally, the decrease of $K_R$ increases the value of $c_B$ whereas the decrease of $K_A$ decreases this value. The decrease of ratio $V/V_0$ supports the refining agent precipitation in place B (see Fig. 4).

As an example of model application, the necessary data have been obtained for the glass furnace melting the borosilicate glass refined by the sodium chloride. Because of lack of sufficiently accurate experimental data, only qualitative conclusions may be drawn from...
Fig. 6. The dependence of $V_{\text{GLASS} \max}$ in downflowing glass melt on the refining agent concentration $c_B$, (Fig. 5) and the vertical temperature gradient in the centre of the furnace, $z$ – the vertical distance from the glass batch surface, 1. original vertical temperature gradient, 2. new temperature gradient.

List of Symbols

- $A, B, C$: see Fig. 1.
- $\tau_C$: average circulation time of glass melt [s]
- $\tau_R$: average circulation time of bubbles [s]
- $c_C$: output refining agent concentration [kg.m$^{-3}$]
- $c_0$: input refining agent concentration [kg.m$^{-3}$]
- $c_{\text{Bi}}$: refining agent concentration under the glass batch (region B) in the $i$-th circulation cycle [kg.m$^{-3}$]
- $c_{\text{SA}}, c_{\text{SB}}$: saturated refining concentration in the region A and B respectively, see Fig. 1 [kg.m$^{-3}$]
- $\dot{V}_0$: volume glass input or output [m$^3$.s$^{-1}$]
- $\dot{V}$: total volume glass flow in one circulation roll [m$^3$.s$^{-1}$]
- $1-K_{\text{Ai}}$: portion of the refining agent conc. precipitated in the region A in the $i$-th circ. cycle
- $1-K_{\text{Bi}}$: portion of the refining agent conc. transported by bubbles from A to B in the $i$-th circ. cycle
- $m_{\text{AI}}, m_{\text{BI}}$: mass velocity of the refining agent precipitation in A and B, respectively [kg.s$^{-1}$]
- $h$: refining height – see Fig. 1. [m]
- $v_{\text{GLASS}}$: average downstream glass velocity in one circulation roll [m.s$^{-1}$]
- $\tau_R$: refining time [s]
- $\rho$: glass density [kg.m$^{-3}$]
- $\eta$: glass viscosity [Pa.s]
- $a_0$: initial bubble diameter [m]
- $T$: temperature [K]
- $k$: average bubble growth rate [m.s$^{-1}$]
- $M_{O_2}$: molecular mass of oxygen [kg.mol$^{-1}$]
- $c_{\text{Bi}}$: total concentration of the refining ion in the region B [%]
- $\rho_{\text{ex}}$: external pressure [kPa]
- $M_M$: molecular mass of the refining ion [kg.mol$^{-1}$]
- $K_{\text{eq}}$: equilibrium constant of the reaction (1) involving the oxygen ion activity [mol.l$^{-1}$]
- $c_{\text{Bi}}$: total concentration of the ref. ion in the region B [mol.l$^{-1}$]
- $c_{\text{Btot}}$: input total concentration of the ref. ion in the region B [mol.l$^{-1}$]

References


Submitted in English by the authors
JEDNODUCHÝ MODEL ČERENÍ VE SKLÁŘSKÉ TAVÍCÍ PECI S VERTIKÁLNÍM PRŮCHODEM SKLOVINY A ZAKRYTOU HLADINOU

Lubomír Nemec, Jaroslav Lubas

Ústav chemie skelných a keramických materiálů ČSAV, Sokolská 38, 120 00 Praha 2

V práci je uveřejněn jednoduchý jednorozměrný model čerení v tavičním prostoru s vertikálním průchodem skloviny a zakrytou hladinou, beroucí v úvahu efekt akumulace červicí látky pod vrstvou kmene na hladině. Při odvozování vztahů popisujících rozložení červicí látky ve sklovině se vycházelo z hmotové bilance této látky v jednom cirkulačním válci skloviny. Publikované výpočty ukazují vliv proudu a množství cefiva vyloučeného na povrch bublin a v červicí oblasti na koncentraci červicí látky pod vrstvou vsazky. Experimentální data pro borosilikátní sklovinu umožnila odhadnout vliv akumulačního efektu na průběh čerení ve zvoleném tavičním prostoru.


Obr. 2. Časová závislost cB. V – objemový tok průtoku průtoku červicí skloviny, V – celkový objemový tok skloviny cirkulačním válcem mezi místy B a A, τc, c0, CSA, CSB viz legenda k obr. 1. 1 – KA – podl čerudiva vyloučeného v oblasti A během jednoho cirkulačního cyklu, 1 – KB – podl čerudiva vyloučeného v oblasti B během jednoho cirkulačního cyklu. KA = 1; V0 = 1.64x10^-5 m^3.s^-1; V = 6.32x10^-5 m^3.s^-1; τc = 2000 s; c0 = 3.29 kg.m^-3; CSA = 2.0 kg.m^-3; CSB = 4.0 kg.m^-3.

Obr. 3. Časová závislost cB. Význam veličin viz legendy k obr 1 a 2. KR = 0.587; KA = 1; V0 = 6.32x10^-5 m^3.s^-1; τc = 2000 s; c0 = 3.29 kg.m^-3; CSA = 2.0 kg.m^-3; CSB = 4.0 kg.m^-3.

Obr. 4. Časová závislost cB pro danou pec. Význam veličin viz legendy k obr. 1 a 2. KR = 0.587; KA = 1; V0 = 6.32x10^-5 m^3.s^-1; V = 6.32x10^-4 m^3.s^-1; τc = 2000 s; c0 = 3.0 kg.m^-3; cC = 2.22 kg.m^-3; KR = 1; KA = 1; 2. c0 = 3.0 kg.m^-3; cC = 2.22 kg.m^-3; KR = 1; KA = 0.992; 3. c0 = CSA = 3.75 kg.m^-3; KR = 1; KA = 0.98.

Obr. 5. Závislost maximum sestupné rychlosti υMAX na koncentraci čerudící látky cB (viz obr. 5) a vertikální teplotní gradient v centru peci. z – vertikální uzávěrnost od povrchu vsazky, 1 – původní vertikální gradient, 2 – nový teplotní gradient.