

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

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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 assumptions 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.

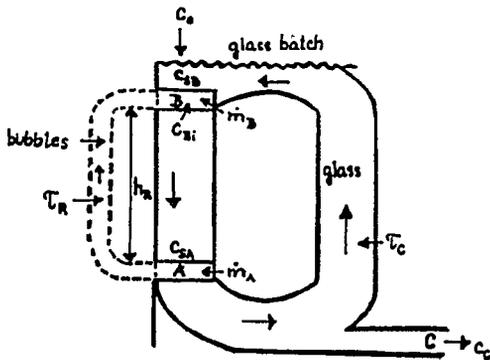


Fig. 1. Schematic figure of a refining agent transport by bubbles and glass melt and its mass balance in one circulation roll. A – refining region, B – region of refining agent precipitation, C – exit of glass melt, c_{SA} , c_{SB} – the saturation concentration of a refining agent in the region A and B, respectively, c_0 , c_C – input and output concentrations of a refining agent, respectively, c_{Bi} – refining agent concentration in the region B during the i -th circulation cycle, τ_C – the average circulation time of glass melt in the circulation roll, τ_R – the average circulation time of bubbles.

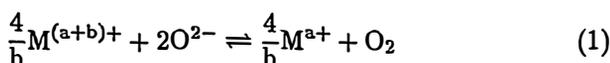
4. The bubbles are downflowing and rising by the same mean velocity over the cross section of flow, the average refining time τ_R being constant with time.
5. The glass melt is flowing from B to A and through C by the same mean velocity, the circulation time τ_C being constant. The ratio τ_C/τ_R and τ_R/τ_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:



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:

$$c_{B_i} = \frac{\dot{V}_0 c_0 + \dot{V}(1 - K_{R,i-1}) c_{B,i-1}}{\dot{V}} + \frac{(\dot{V} - \dot{V}_0) K_{R,i-n} c_{B,i-n}}{\dot{V}} \quad (2)$$

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

$$c_{B_i} = \frac{\dot{V}_0 c_0 + \dot{V}(1 - K_{R,i-\frac{1}{n}}) c_{B,i-\frac{1}{n}}}{\dot{V}} + \frac{(\dot{V} - \dot{V}_0) K_{R,i-1} c_{B,i-1}}{\dot{V}} \quad (3)$$

where $c_{B_i} = 0$ for $i < 0$.

The values of $1 - K_{R,i}$ give the portion of oxygen concentration excluded from the glass melt in A owing to refining. The maximum portion of excluded oxygen in A corresponds to the c_{B_i} decrease up to the value of oxygen saturation concentration at appropriate temperature in A, c_{SA} :

$$(1 - K_{R,i-1})_{\max} = \frac{c_{B,i-1} - c_{SA,i-1}}{c_{B,i-1}} \quad (4)$$

where:

$$c_{SA,i-1} = \frac{2.5 \times 10^{-3} b M_{O_2} c_{B_{tot\%,i-1}} \rho p_{ex}^{b/4}}{M_M (K'_{eq}{}^{b/4} + p_{ex}^{b/4})} \quad (5)$$

and

$$c_{B_{tot\%,i-1}} = \frac{100 \dot{V}_0 c_{0tot} + (\dot{V} - \dot{V}_0) c_{B_{tot,i-1}}}{\dot{V}} \quad (6)$$

where i in eqs (2-6) designates the i -th circulation circle with the period of τ_C . The value of c_{B_i} 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_{B_i} is reached ($c_{B_i} = c_{SB}$), the respective superfluous oxygen penetrating through the glass batch is given by:

$$\dot{m}_{B_i} = \dot{V}_0 (c_0 - K_{R,i-1} c_{SB}) \quad (7)$$

The value of c_{B_i} 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 batch. For the mass balance of the refining agent, one may write:

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

$$c_{B_i} = \frac{\dot{V}_0 c_0 + \dot{V}(1 - K_{R,i-1}) c_{B,i-1}}{\dot{V}} + \frac{(\dot{V} - \dot{V}_0) K_{R,i-n} + K_{A,i-b} - 1}{\dot{V}} c_{B,i-n} \quad (8)$$

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

$$c_{B_i} = \frac{\dot{V}_0 c_0 + \dot{V}(1 - K_{R,i-\frac{1}{n}}) c_{B,i-\frac{1}{n}}}{\dot{V}} + \frac{(\dot{V} - \dot{V}_0) (K_{R,i-1} + K_{A,i-1} - 1) c_{B,i-1}}{\dot{V}} \quad (9)$$

where $c_{B_i} = 0$ for $i < 0$ and $K_{R,i}, K_{A,i} = 1$ 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

The average values of bubble growth rate in the borosilicate glass

Temperature [°C]	Ref. agent concentration [kg.m ⁻³]	Number of bubbles followed	k [m.s ⁻¹]
1427	3.29	estimation	1.00×10^{-9}
1427	13.16	estimation	1.00×10^{-9}
1580	3.29	8	2.20×10^{-8}
1580	13.16	18	1.30×10^{-7}

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

$$2 - K_{R,i-1} - K_{A,i-1} = \frac{c_{B,i-1} - c_{SA}}{c_{B,i-1}} \quad (10)$$

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:

$$\begin{aligned} \dot{m}_{B_i} &= \dot{V}_0 c_0 - \dot{V}(1 - K_{R,i-1}) c_{SB} \\ &\quad - \dot{V}(K_{R,i-1} + K_{A,i-1} - 1) c_0. \end{aligned} \quad (11)$$

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 glass melt. 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 starts to rise to B where refining is completed. If the distance between A and B is designated by h , we have:

$$\begin{aligned} h &= v_{GLASS} \tau_R - \int_0^{\tau_R} \frac{2g\rho(T)}{9\eta(T)} \\ &\quad \times \left(a_0 + \int_0^{\tau_R} k(T) d\tau \right)^2 d\tau \end{aligned} \quad (12)$$

$$v_{GLASS} = \frac{2g\rho(T_A)}{9\eta(T_A)} \left(a_0 + \int_0^{\tau_R} k(T) d\tau \right)^2 \quad (13)$$

where $T = T(z)$. 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 concentration 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 1450°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_{B_i} 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 $K_R \leq 0.8$.

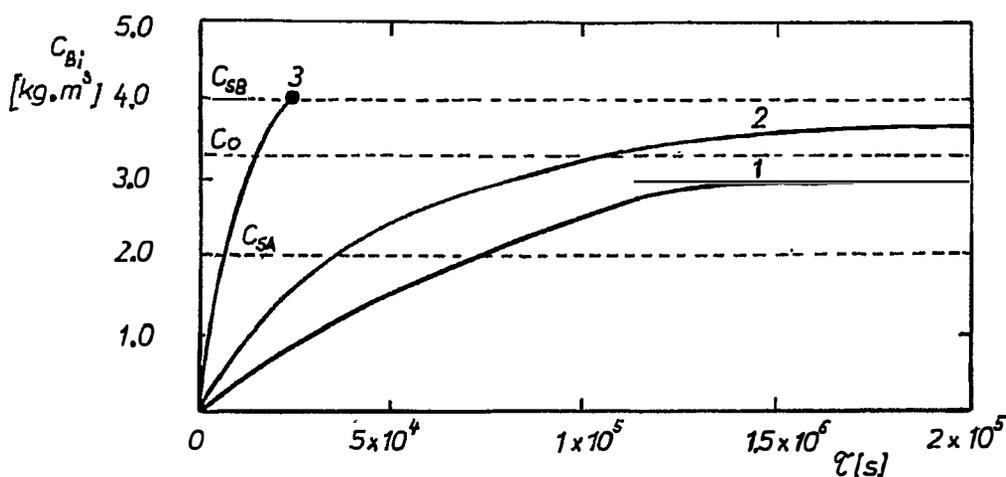


Fig. 4. The time dependence of c_{Bi} . Meaning of symbols, see Fig. 1 and Fig. 2. $\tau_R = \tau_C = 2000$ s; $c_0 = 3.29$ kg.m⁻³; $c_{SA} = 2.0$ kg.m⁻³; $c_{SB} = 4.0$ kg.m⁻³; $K_A = 0.99$; $K_R = 0.7$; 1. $\dot{V}_0 = 1.64 \times 10^{-5}$ m³.s⁻¹; $\dot{V} = 6.32 \times 10^{-4}$ m³.s⁻¹; 2. $\dot{V}_0 = 1.64 \times 10^{-5}$ m³.s⁻¹; $\dot{V} = 3.16 \times 10^{-4}$ m³.s⁻¹; 3. $\dot{V}_0 = 1.64 \times 10^{-5}$ m³.s⁻¹; $\dot{V} = 6.32 \times 10^{-5}$ m³.s⁻¹

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

$$\tau_R = \tau_C = 2000 \text{ s}; \dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}; \dot{V} = 6.32 \times 10^{-4} \text{ m}^3 \cdot \text{s}^{-1}; c_0 = 3.0 \text{ kg} \cdot \text{m}^{-3}.$$

For the temperature dependence of NaCl solubility, the Arrhenius type of dependence has been supposed. Using the experimental data, the temperature dependence of the NaCl solubility in the glass melt has the form:

$$c_S = 1.105 \times 10^{-6} \exp\left(\frac{25172}{T}\right) \quad [\text{kg} \cdot \text{m}^{-3}]$$

Table II

The final values of the refining agent concentrations and the rates of their precipitation. $K_A = 1$; $\dot{V}_0 = 1.64 \times 10^{-5}$ m³.s⁻¹; $\dot{V} = 6.32 \times 10^{-5}$ m³.s⁻¹; $\tau_R = \tau_C = 2000$ s; $c_0 = 3.29$ kg.m⁻³; $c_{SA} = 2.0$ kg.m⁻³; $c_{SB} = 4.0$ kg.m⁻³

K_R	c_B [kg.m ⁻³]	c_C [kg.m ⁻³]	\dot{m}_A [kg.s ⁻¹]	\dot{m}_B [kg.s ⁻¹]
1.0	3.29	3.29	0	0
0.9	3.65	3.29	0	0
0.8	4.00	3.29	0	1.49×10^{-6}
0.7	4.00	3.29	0	8.08×10^{-6}
0.6	4.00	3.29	0	1.47×10^{-5}
0.5	4.00	3.29	0	2.13×10^{-5}

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:

$$k = 8.188 \times 10^{-12} \exp(19.23c_B) \cdot \exp\left(\frac{-32700c_B + 12080}{T}\right) \quad [\text{m} \cdot \text{s}^{-1}]$$

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 III

The final values of the refining agent concentrations and the rates of their precipitation. $K_A = 1$; $\dot{V}_0 = 1.64 \times 10^{-5}$ m³.s⁻¹; $\dot{V} = 6.32 \times 10^{-5}$ m³.s⁻¹; $\tau_R = \tau_C = 2000$ s; $c_0 = 3.29$ kg.m⁻³; $c_{SA} = 2.0$ kg.m⁻³; $c_{SB} = 4.0$ kg.m⁻³

K_A	c_B [kg.m ⁻³]	c_C [kg.m ⁻³]	\dot{m}_A [kg.s ⁻¹]	\dot{m}_B [kg.s ⁻¹]
1.00	3.29	3.29	0	0
0.99	3.20	3.17	2.02×10^{-6}	0
0.95	2.88	2.73	9.10×10^{-6}	0
0.90	2.56	2.30	1.61×10^{-5}	0
0.85	2.36	2.00	2.23×10^{-5}	0

Table IV

The final values of the refining agent concentrations and the rates of refining agent precipitation.
 $K_A = 0.99$; $K_R = 0.70$; $\tau_R = \tau_C = 2000$ s; $c_0 = 3.29$ kg.m⁻³; $c_{SA} = 2.0$ kg.m⁻³; $c_{SB} = 4.0$ kg.m⁻³

\dot{V}_0 [m ³ .s ⁻¹]	\dot{V} [m ³ .s ⁻¹]	c_B [kg.m ⁻³]	c_C [kg.m ⁻³]	\dot{m}_A [kg.s ⁻¹]	\dot{m}_B [kg.s ⁻¹]
1.64×10^{-5}	6.32×10^{-4}	3.03	2.09	1.92×10^{-5}	0
1.64×10^{-5}	3.16×10^{-4}	3.72	2.57	1.78×10^{-5}	0
1.64×10^{-5}	6.32×10^{-5}	4.00	2.76	2.50×10^{-6}	6.16×10^{-6}

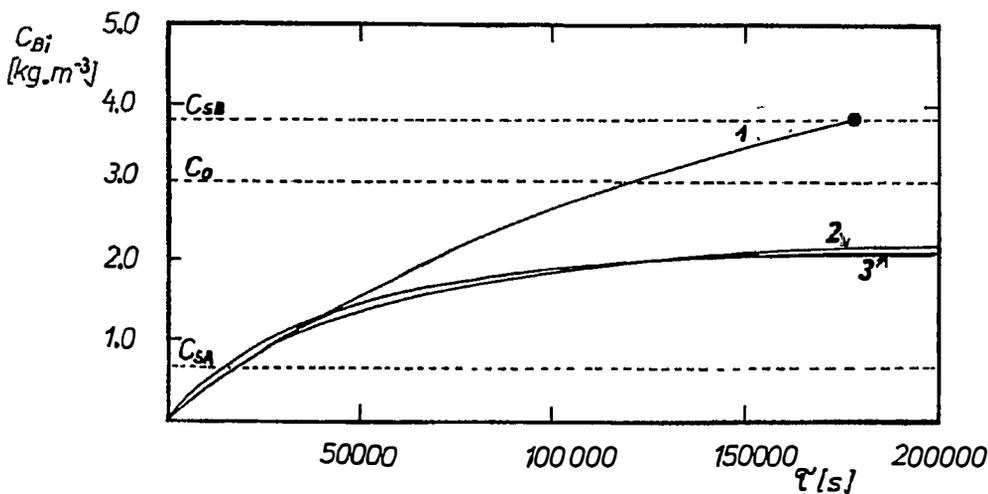


Fig. 5. The time dependence of c_{Bi} for the given furnace. Meaning of symbols, see Fig. 1 and Fig. 2. $\dot{V}_0 = 1.64 \times 10^{-5}$ m³.s⁻¹; $\dot{V} = 6.32 \times 10^{-5}$ m³.s⁻¹; $\tau_R = \tau_C = 2000$ s; 1. $c_0 = 3.0$ kg.m⁻³; $c_C = 2.22$ kg.m⁻³; $K_R = 0.587$; $K_A = 1$; 2. $c_0 = 3.0$ kg.m⁻³; $c_C = 2.22$ kg.m⁻³; $K_R = 1$; $K_A = 0.992$; 3. $c_0 = c_{SB} = 3.78$ kg.m⁻³; $K_R = 1$; $K_A = 0.98$

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 $V_{GLASSMAX}$ 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.

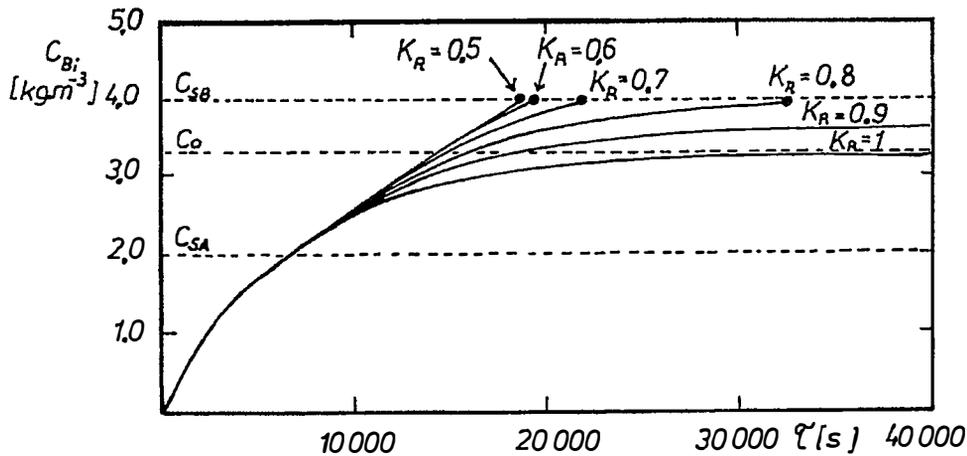


Fig. 2. The time dependence of c_{Bi} . \dot{V}_0 - volume glass flow inward or outward of the circulation roll, \dot{V} - total volume glass flow in the circulation roll between the regions A and B, τ_R , τ_C , c_0 , c_{SA} , c_{SB} - see Fig. 1, $1 - K_A$ - the portion of refining agent precipitated 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. $K_A = 1$; $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 6.32 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\tau_R = \tau_C = 2000 \text{ s}$; $c_0 = 3.29 \text{ kg} \cdot \text{m}^{-3}$; $c_{SA} = 2.0 \text{ kg} \cdot \text{m}^{-3}$; $c_{SB} = 4.0 \text{ kg} \cdot \text{m}^{-3}$.

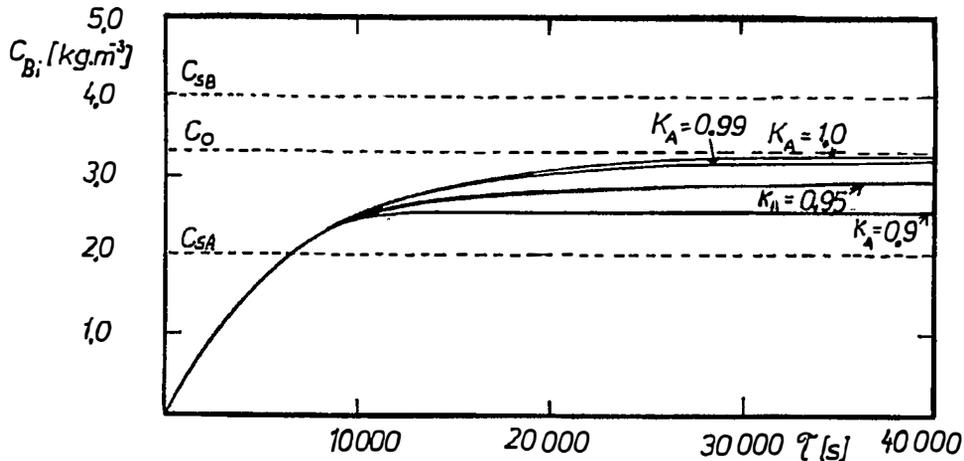


Fig. 3. The time dependence of c_{Bi} . Meaning of symbols, see Fig. 1 and Fig. 2. $K_R = 1$; $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 6.32 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\tau_R = \tau_C = 2000 \text{ s}$; $c_0 = 3.29 \text{ kg} \cdot \text{m}^{-3}$; $c_{SA} = 2.0 \text{ kg} \cdot \text{m}^{-3}$; $c_{SB} = 4.0 \text{ kg} \cdot \text{m}^{-3}$.

The influence of ratio \dot{V}_0/\dot{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 \dot{V}/\dot{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

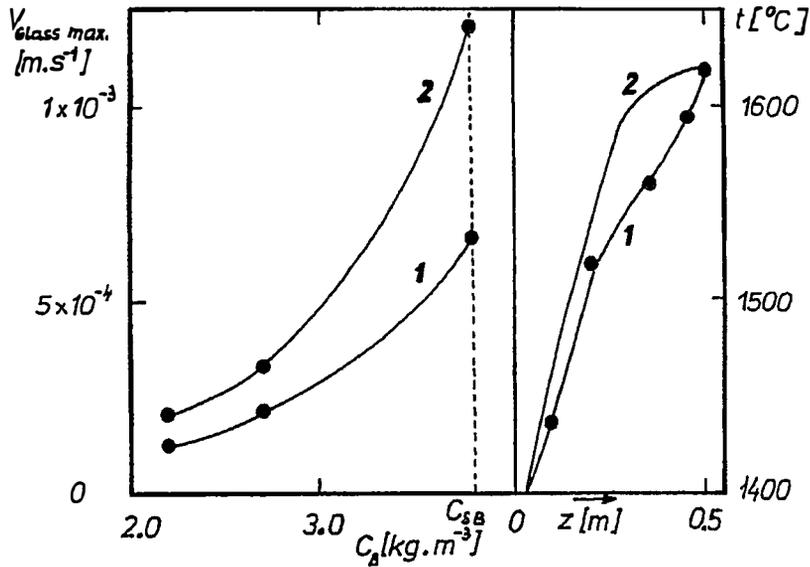


Fig. 6. The dependence of $v_{GLASSMAX}$ in downflowing glass melt on the refining agent concentration c_B , (Fig. 5) and the vertical temperature gradient in the centre of the furnace. z - the vertical distance from the glass batch surface, 1. original vertical temperature gradient, 2. new temperature gradient.

List of Symbols

A, B, C see Fig. 1.

τ_C average circulation time of glass melt [s]

τ_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_{Bi} refining agent concentration under the glass batch (region B) in the i -th circulation i cycle [kg.m⁻³]

c_{SA}, c_{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 [m³.s⁻¹]

\dot{V} total volume glass flow in one circulation roll [m³.s⁻¹]

$1-K_{Ai}$ portion of the refining agent conc. precipitated in the region A in the i -th circ. cycle

$1-K_{Ri}$ portion of the refining agent conc. transported by bubbles from A to B in the i -th circ. cycle

\dot{m}_A, \dot{m}_B mass velocity of the refining agent precipitation in A and B, respectively [kg.s⁻¹]

h refining height - see Fig. 1. [m]

v_{GLASS} average downstream glass velocity in one circulation roll [m.s⁻¹]

τ_R refining time [s]

ρ glass density [kg.m⁻³]

η 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]

$c_{Btot\%}$ total concentration of the refining ion in the region B [%]

p_{ex} external pressure [kPa]

M_M molecular mass of the refining ion [kg.mol⁻¹]

K'_{eq} equilibrium constant of the reaction (1) involving the oxygen ion activity [mol.l⁻¹]

c_{0tot} input total concentration of the ref.ion [mol.l⁻¹]

c_{Btot} input concentration of the ref.ion in the region B [mol.l⁻¹]

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Submitted in English by the authors

JEDNODUCHÝ MODEL ČEŘENÍ VE SKLÁŘSKÉ TAVICÍ PECI S VERTIKÁLNÍM PRŮCHODEM SKLOVINY A ZAKRYTOU HLADINOU

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V práci je uveřejněn jednoduchý jednorozměrný model čeření v tavicím prostoru s vertikálním průchodem skloviny a zakrytou hladinou, beroucí v úvahu efekt akumulace čeřící látky pod vrstvou kmene na hladině. Při odvozování vztahů popisujících rozložení koncentrace čeřící látky ve sklovině se vycházelo z hmotové bilance této látky v jednom cirkulačním válci skloviny. Publikované výpočty ukazují vliv průtoku a množství čeřiva vyloučeného na povrchu bublin a v čeřící oblasti na koncentraci čeřící látky pod vrstvou vsázky. Experimentální data pro borosilikátovou sklovinu umožnila odhadnout vliv akumulčního efektu na průběh čeření ve zvoleném tavicím prostoru.

Obr. 1. Schématické znázornění transportu čeřící látky bublinami a sklovinou a hmotová bilance čeřící látky v jednom cirkulačním válci. A – čeřící oblast, B – oblast vylučování čeřiva, C – výstup skloviny, c_{SA} , c_{SB} , – nasycené koncentrace čeřiva v místě A a B, c_0 , c_C – vstupující a vystupující koncentrace čeřiva, τ_C – průměrná doba oběhu skloviny v rotačním útvaru, τ_R – průměrná cirkulační doba bublin z místa B do A a zpět.

Obr. 2. Časová závislost c_{Bi} . \dot{V}_0 – objemový tok přitékající nebo vytékající skloviny, \dot{V} – celkový objemový tok skloviny cirkulačním válcem mezi místy B a A, τ_R , τ_C , c_0 , c_{SA} , c_{SB} viz legenda k obr. 1, $1 - K_A$ – podíl čeřiva vyloučeného v oblasti A během jednoho cirkulačního cyklu, $1 - K_R$ – podíl čeřiva vyloučeného v oblasti B během jednoho cirkulačního cyklu. $K_A = 1$; $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 6.32 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\tau_R = \tau_C = 2000 \text{ s}$; $c_0 = 3.29 \text{ kg} \cdot \text{m}^{-3}$; $c_{SA} = 2.0 \text{ kg} \cdot \text{m}^{-3}$; $c_{SB} = 4.0 \text{ kg} \cdot \text{m}^{-3}$.

Obr. 3. Časová závislost c_{Bi} . Význam veličin viz legendy k obr. 1 a 2. $K_R = 1$; $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 6.32 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\tau_R = \tau_C = 2000 \text{ s}$; $c_0 = 3.29 \text{ kg} \cdot \text{m}^{-3}$; $c_{SA} = 2.0 \text{ kg} \cdot \text{m}^{-3}$; $c_{SB} = 4.0 \text{ kg} \cdot \text{m}^{-3}$.

Obr. 4. Časová závislost c_{Bi} . Význam veličin viz legendy k obr. 1 a 2. $\tau_R = \tau_C = 2000 \text{ s}$; $c_0 = 3.29 \text{ kg} \cdot \text{m}^{-3}$; $c_{SA} = 2.0 \text{ kg} \cdot \text{m}^{-3}$; $c_{SB} = 4.0 \text{ kg} \cdot \text{m}^{-3}$; $K_A = 0.99$; $K_R = 0.7$ 1. $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 6.32 \times 10^{-4} \text{ m}^3 \cdot \text{s}^{-1}$; 2. $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 3.16 \times 10^{-4} \text{ m}^3 \cdot \text{s}^{-1}$; 3. $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 6.32 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$.

Obr. 5. Časová závislost c_{Bi} pro danou pec. Význam veličin viz legendy k obr. 1 a 2. $\dot{V}_0 = 1.64 \times 10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$; $\dot{V} = 6.32 \times 10^{-4} \text{ m}^3 \cdot \text{s}^{-1}$; $\tau_R = \tau_C = 2000 \text{ s}$; 1. $c_0 = 3.0 \text{ kg} \cdot \text{m}^{-3}$; $c_C = 2.22 \text{ kg} \cdot \text{m}^{-3}$; $K_R = 0.587$; $K_A = 1$; 2. $c_0 = 3.0 \text{ kg} \cdot \text{m}^{-3}$; $c_C = 2.22 \text{ kg} \cdot \text{m}^{-3}$; $K_R = 1$; $K_A = 0.992$; 3. $c_0 = c_{SB} = 3.78 \text{ kg} \cdot \text{m}^{-3}$; $K_R = 1$; $K_A = 0.98$.

Obr. 6. Závislost maximální sestupné rychlosti $v_{GLASS MAX}$ na koncentraci čeřící látky c_B (viz obr. 5) a vertikální teplotní gradient v centru pece. z – vertikální vzdálenost od povrchu vsázky, 1 – původní vertikální gradient, 2 – nový teplotní gradient.