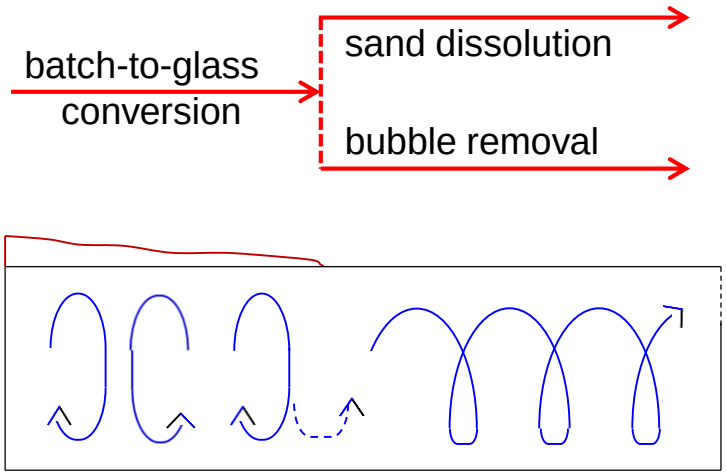
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Melt flow as a factor of glass melting

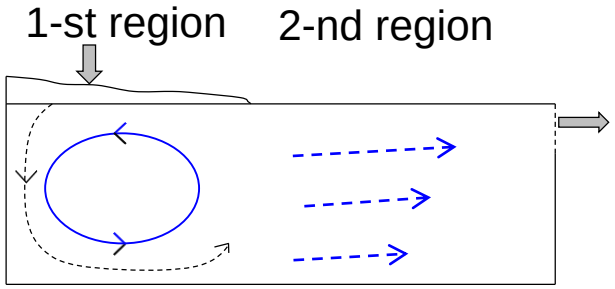
Lubomír Němec[1]
Marcela Jebavá[1]
Petra Cincibusová[1]
Pavel Budík[2]



Outline

- Three aspects of continual glass melting. Can a melting space work as a chemical reactor?

image of a simple melting space

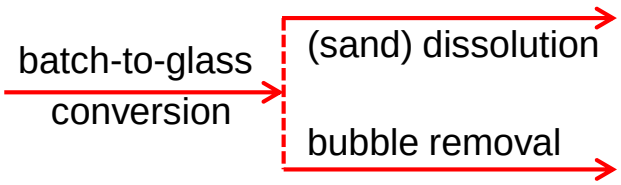


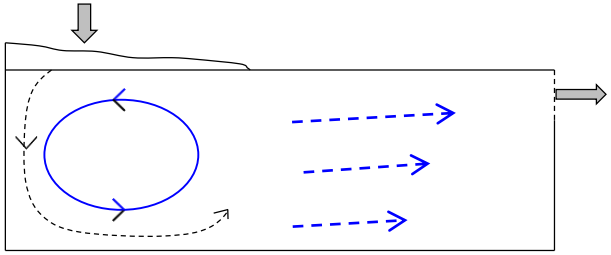
- Character of the melt flow and quantity u_i (2-nd region)
- Energetic model and its predictions (2-nd region)
- Principal results of homogenization (2-nd region)
- The structure and fundamental factors (1-st region)
- Overall characters o flows and results (1-st with 2-nd region)
- Problems, hesitations and expectations

Three aspects of continual glass melting

Three aspects characterize a glass melting chemical reactor:

1. Kinetics of phenomena described by kinetic equations ($\dot{r}$, τ_{ref}).
2. Phenomena ordering described by their serial and parallel courses, controlling phenomenon.





First region - kinetics Second region - kinetics and road

3. Road of the process – spatial map of phenomena. We need a quantity describing the road of the process:

Mass element needs kinetic time (τ_{Href}) and residence time (τ_G) to realize process. ($\tau_G \gg \tau_{Href}$).

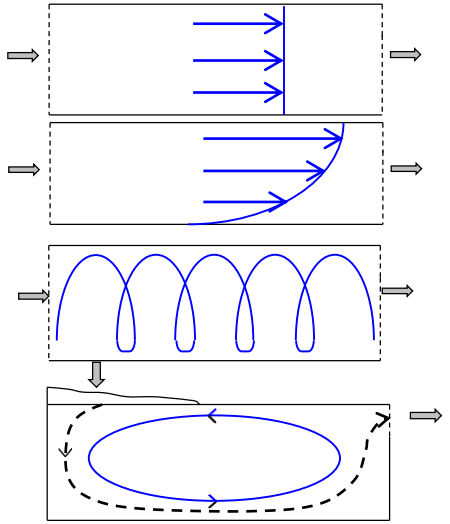
Rate of τ_{Href} to τ_G - space utilization – quantity expressing the road of the process (glass flow quality):

$$u_H = \frac{\tau_{Href}}{\tau_G};\ u_H \in \langle 0; 1 \rangle;\ \dot{M} = \frac{\rho V}{\tau_{Href}} u_H;\ H_M^L = \frac{\dot{H}^L \tau_{Href}}{\rho V} \frac{1}{u_H}$$

Kinetics and road (space utilization) are expressed separately and can be this way examined.

2-nd region: Character of the melt flow and quantity u_H

u_H is calculated by the parallel mathematical modelling of melt flow and melting phenomena.



piston flow: $u_D = u_F = 1$

isothermal uniform flow: $u_D = 0.445, u_F = 0.667$

transversal circulations: $u_D, u_F = 0.5 - 0.8$

longitudinal circulations: $u_D, u_F = 0.05 - 0.2$

(the space is divided into input and free level regions):

How does u_H reflect the character of the melt flow?

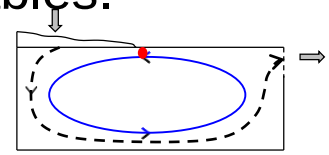
$$u_D = (1 - m_G)(1 - m_D);\ u_F = (1 - m_{virt}) \left(\frac{h_0}{h_{virt}}\right)^{1/3}$$

And how does u_H relate to fundamental quantities determining the character of melt flow? (Energetic model).

2-nd region: Energetic model and its predictions, u_H dependence on input quantities

Energetic model provides a macroscopic view on the character of melt flow and facilitates predictions of the beneficial melt flow.
Model defines the characteristic velocities of longitudinal and transversal circulations as a function of flow rate and energy variables.

$$v_{lc} = -C_1\left[(1-k_1)\left(H_M^T\dot{M} + \dot{H}^L\right) - (1-\xi)\dot{H}^L\right]$$

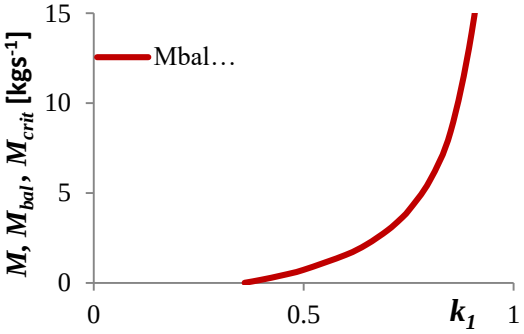


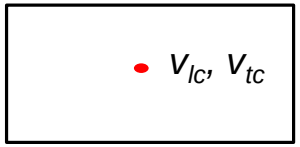
1-st 2-nd

v_{lc}: flow tension between 1-st and 2-nd region

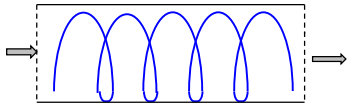
v_{lc} increases m_G, m_{virt}, $u_H = u_{Hbal} - K|v_{lc}|$
at v_{lc}=0, balanced state, unif. flow, $u_H = u_{Hbal}$(max)

$$\dot{M}_{bal} = \frac{\dot{H}^L(k_1-\xi)}{H_M^T(1-k_1)}$$





$$v_{tc} = C_3\left[(1-k_1)\left(\dot{M}H_M^T + \dot{H}^L\right) + (1-\xi)\dot{H}_{side}^L\right]$$

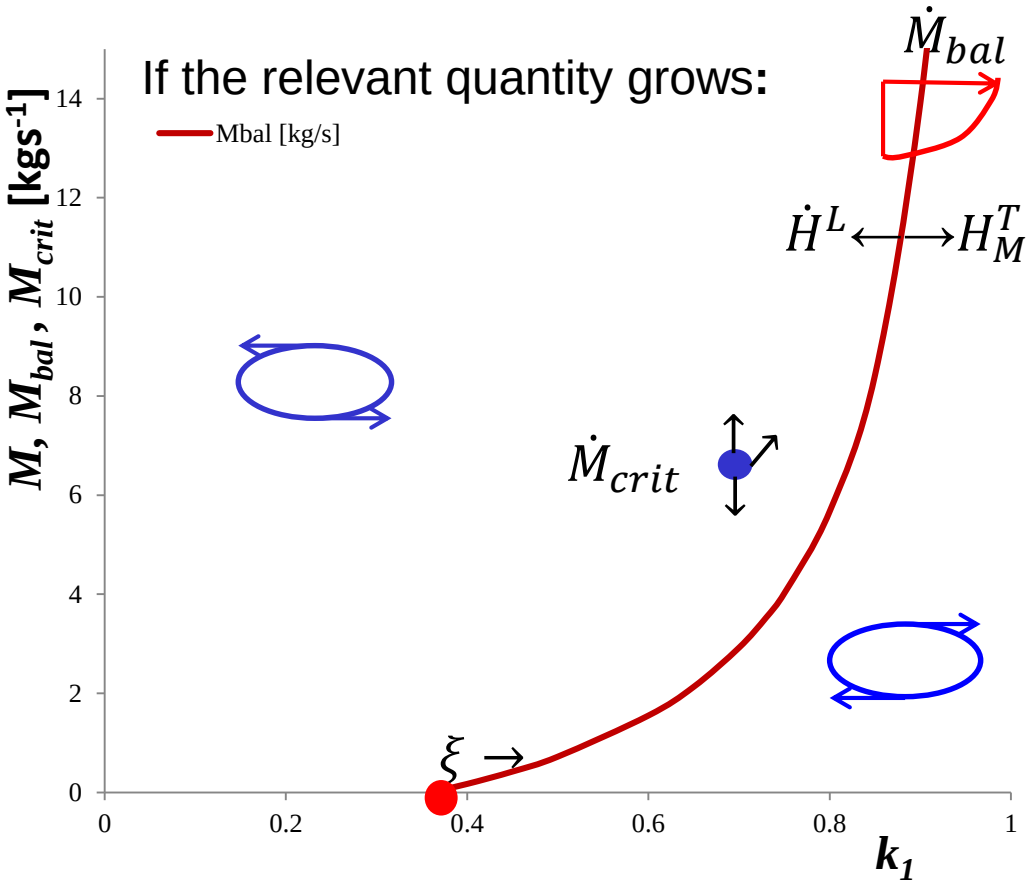


v_{tc} is efficient when v_{tc}/v_{lc}> 4 and spiral flow sets up, generally, u_H grows with v_{tc}

Suppression of longitudinal circulations is the principal step to achieve high space utilization; k_1 is the most significant quantity.

2-nd region: Energetic model and its predictions, the diagram of melt flows and position of $\dot{M}_{crit}$

Balanced energ. state ($v_{lc} = 0$): $\dot{M}_{bal} = \dfrac{\dot{H}^L(k_1 - \xi)}{H_M^T(1 - k_1)}$



When the values of $\dot{M}_{crit}$ and $\dot{M}_{bal}$ curve mutually approach, u_H and $\dot{M}_{crit}$ grow in the following step

Spiral flow: $v_{tc}/v_{lc} > 4$

Arrang. of energ. barriers: $u_H(long.) > u_H\ (trans.)$
Long. barriers do not support v_{lc}

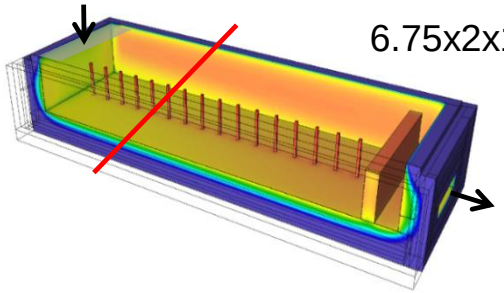
u: Left side: $k_1 \uparrow$, $\dot{H}^L \uparrow$, $H_M^T \downarrow$, $\xi \downarrow$, ;

Right side: opposite tendencies: $k_1 \downarrow$

2-nd region: Principal results of homogenization

Two heating arrangenets longitudinal and transversal barrier, T_{in}=1320°C, T_{ave}=1420°C

Inflow of primary cold melt containing sand particles, bubbles, best heating arrangement



6.75x2x1m

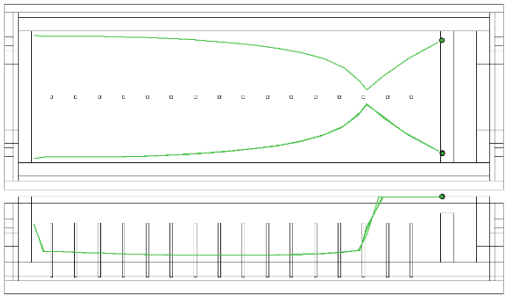
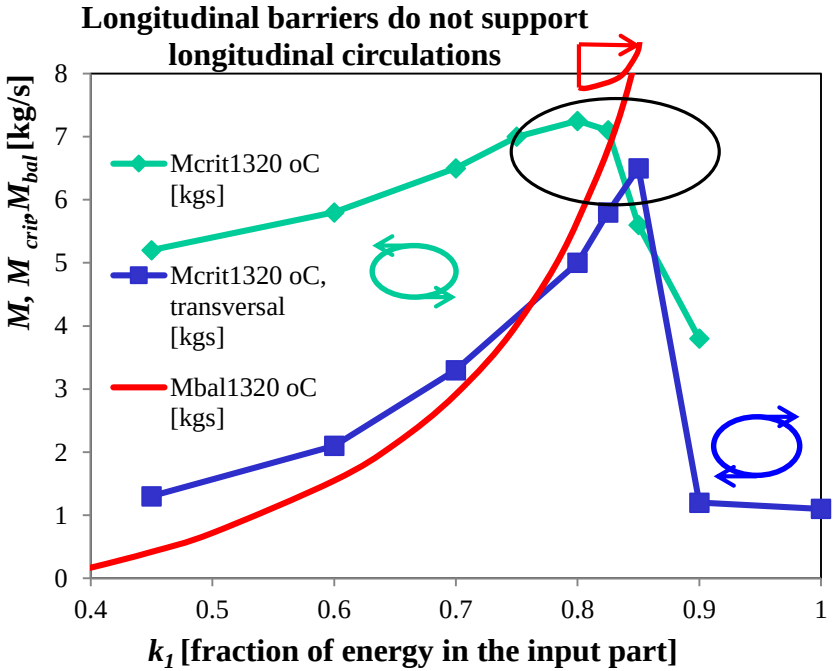
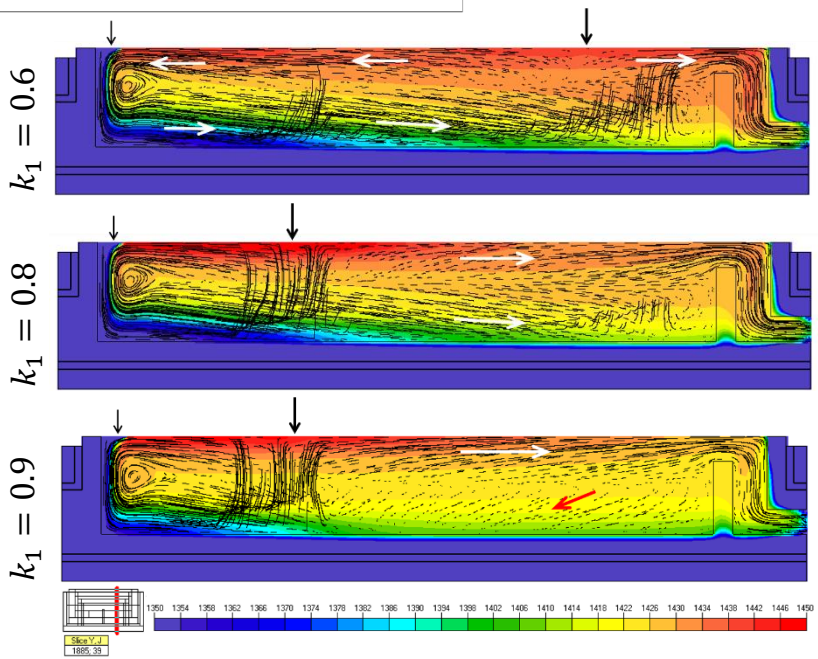


Fig. Trajectory of critical bubble which defines critical melting performance $\dot{M}_{crit}$



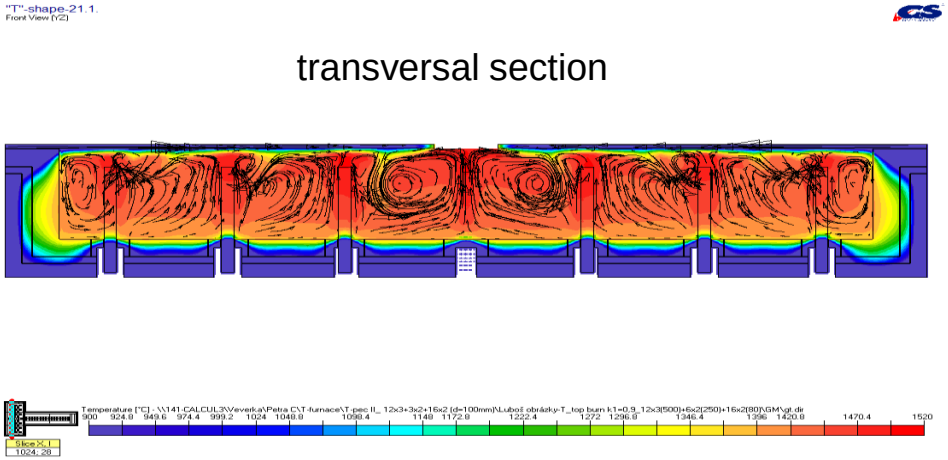


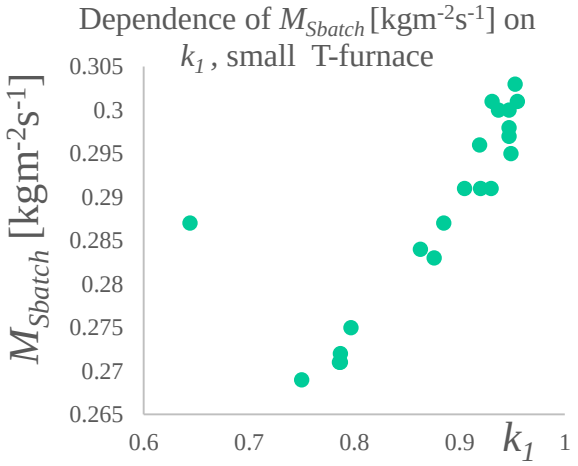
The melting performance at uniform-like flow increased several times ($u_H \rightarrow 0.5$), the values of the critical melting performance > 25 t/(m^{3}day).

Hrbek L. et al. JNCS (2017), (2018).

1-st region: The structure and fundamental goal

- The intended *first conversion region is attached* to the referred homogenization module (T-shape was prefered).This is now the input space for heating and conv.
- *The horizontal feeding of batch from both sidewalls* was selected.
- *The volumes of regions were considered approximately equivalent*, the capacities of both regions were assumed comparable under given conditions.
- The power supply to the 1-st region was planned to cover *the maximum assumed homogenization* performance (positioned close to $\dot{M}_{bal}(k_1)$ curve).
- The efficient absorption of heat by the batch was supported by the use of v*ertical electrodes and burners.*



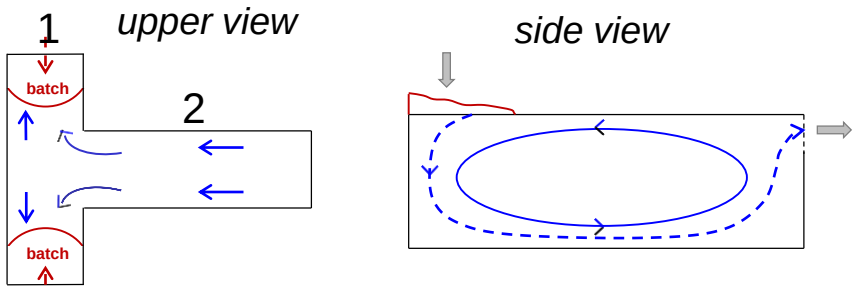


- The goal: to achieve the balanced state in the complete space under conditions when both regions attain their achievable melting capacity (batch conversion – melt homogenization)

1st and 2nd region: Character o flows and results

k_1 as factor affecting both space utilization and batch conversion by the melt flow character

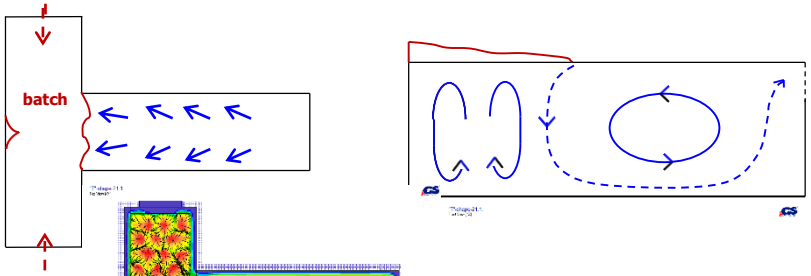
1. k_1 is small
$\dot{M}$ should be small



Energy under batch from both 1st and 2nd region, long. circul.

$$T_1 < T_2$$

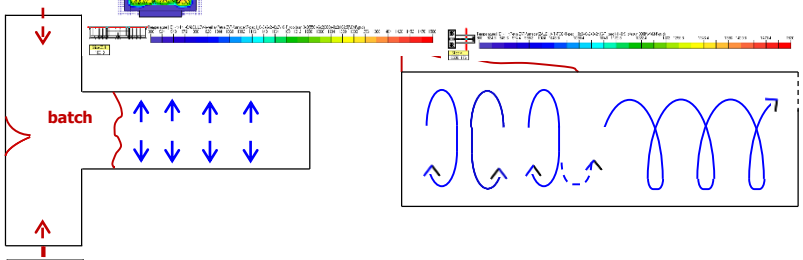
2. $k_1 > 0.7$
$\dot{M}$ grows



Smaller part of energy under batch from 2nd region, vertical circ. in 1-st region

$$T_1\ slightly < T_2$$

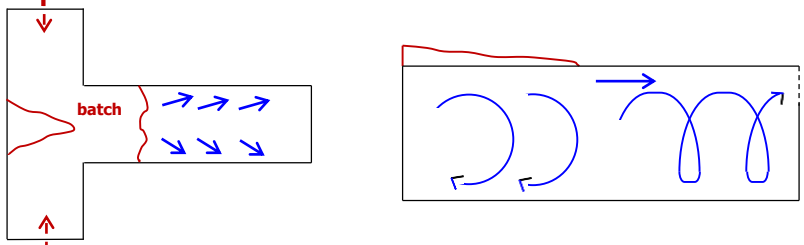
3. $k_1 \rightarrow k_1(\dot{M}_{bal})$



Energy under batch, small overheating, spiral flow in 2nd region → best conditions

$$T_1 \geq T_2$$

4. $k_1 > k_1(\dot{M}_{bal})$



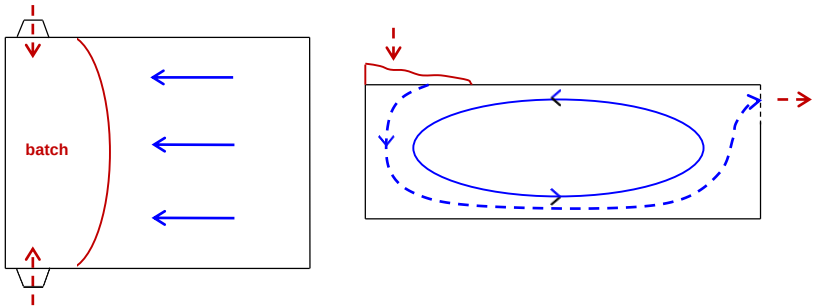
Overheating of the 1st region

$$T_1 > T_2$$

1-st and 2-nd region: Character o flows and results

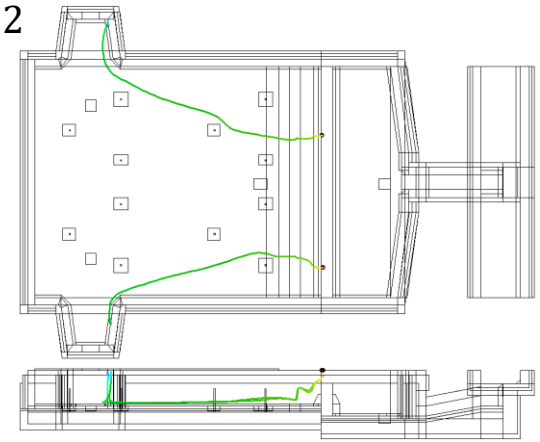
Two spaces with different flow character and consideration of results reality

container furnace



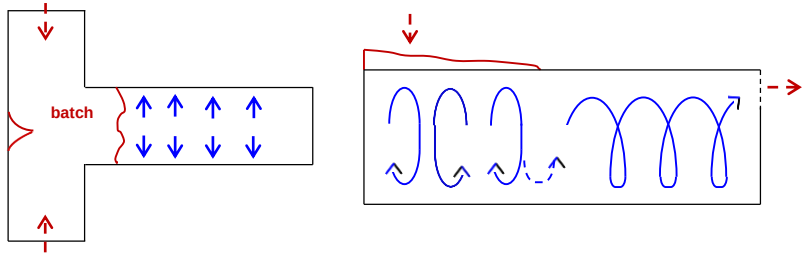
$T_{Gave} = 1387°C$
$V = 100\ m^3$
$\dot{M}_{crit} = 230\ t/day = 2.3\ t/(day\ m^3)$, $2.8\ t/(day\ m^2)$
$\dot{M}_{Sbatch} = 0.087\ kg/(m^2 s)$(spec. batch conversion rate)
$H_M^0 = 4411 kJ/kg$
$\dot{H}_{Joule}/\dot{H}_{tot} = 0.07$
$u_F = 0.048$
$k_1 = 0.52$

$$\dot{M}_{Sbatchl} = \frac{\alpha_l (t_1 - t_l)}{H_M^T}$$



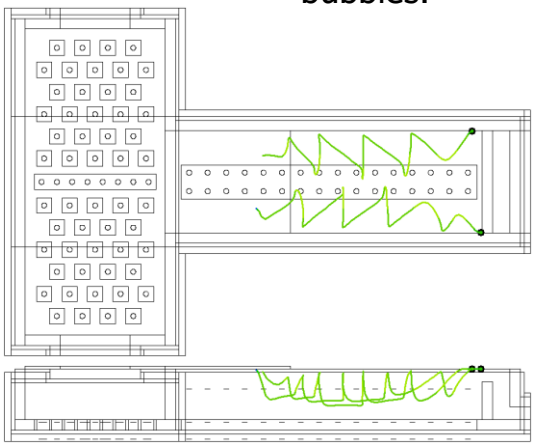
Container: α=90 $Wm^{-2}K^{-1}$
T-furnace: α=400 $Wm^{-2}K^{-1}$
If α=200 $Wm^{-2}K^{-1}$, then
V=40 m^3,
$\dot{M}_{crit}$= 11.5 *tons/* $(day\ m^3)$
$\dot{H}_{Joule}/\dot{H}_{tot} = 0.58$

T-furnace (maximal $\dot{M}_{crit}$, u_F*)*



$T_{Gave} = 1420°C$
$V = 30\ m^3$
$\dot{M}_{crit} = 460\ tons/day = 15.3\ tons/(day\ m^3)$
$\dot{M}_{Sbatch} = 0.289\ kg/(m^2 s)$
$H_M^0 = 2552\ kJ/kg$
$\dot{H}_{Joule}/\dot{H}_{tot} = 0.76$
$u_F = 0.149$
$k_1 = 0.92$

Trajectories of critical bubbles.



Problems and tasks

- Only batch conversion, sand dissolution and bubble removal were included.
- The model of batch conversion was used ignoring the structure of phase boundary between batch and melt. The values of $\dot{M}_{Sbatch}$ should be verified.
- No melting reserve in the second region is considered in present calculations (assessed around 10-20%).
- The overheating of the first region at higher k_1 should be restricted.
- The very low space utilization is achievable in the first region.
- In all-electric furnaces, lower values of batch conversion capacity are expected.
- The corrosion of RM in the first region was not assessed yet.
- Variables to control the real process are not completely specified (k_1, $\dot{H}_{Joule1}/\dot{H}_{comb1}\ldots$)

Thank you for your attention

This work has been supported by the Technology Agency of the Czech Republic in the project TH02020316 “*Advanced technologies in glass production*”.

The overheating of the first region

Two surfaces are at disposal in the furnace with combined heating.

If the batch conversion in the first region is controlled by heat transfer:

$$K_J \dot{M} H_M^T = S_{batchJ} \alpha_J \Delta t_J \qquad K_C \dot{M} H_M^T = S_{batchC}\, \alpha_C \Delta t_C, \qquad K_J + K_C = 1$$

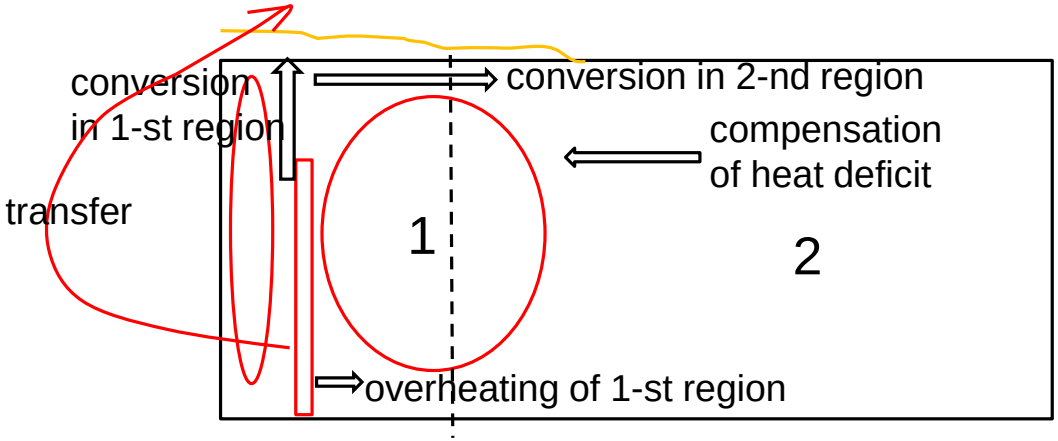
It is significant for conversion whether the surface is „saturated“ or „unsaturated“ for heat absorption. Saturated – batch extends, unsaturated – batch almost constant.

The lower surface appears saturated, and when increasing $\dot{M}$, the planned heat is not absorbed and batch proceeds in the 2-nd region:

$$K_J \left(\dot{M} + \Delta\dot{M}\right) H_M^T > S_{batchJ} \alpha_J \Delta t_J$$

The abundant energy partially heats the melt in the 1-st region and partially is transferred to 2-nd region by circulation.

Proposed solution: A fraction of Joule heat should be transferred to burners where the surface appears unsaturated. Equality is renewed on the lower surface, overheating is assumed to fade: $\left(K_J - \Delta K_J\right)\left(\dot{M} + \Delta\dot{M}\right) H_M^T = S_{batchJ} \alpha_J \Delta t_J$



The ratio of $\dot{H}_{Joule1} / \dot{H}_{comb1}$ appears a significant factor of batch conversion.