The Czech Academy of Sciences

UNIVERSITY OF CHEMISTRY AND TECHNOLOGY PRAGUE

The impact of energy distribution on the glass melting performance of the melting channel examined by mathematical modelling

Author:	Ing. Lukáš Hrbek
Supervisor:	prof. Ing. Lubomír Němec, DrSc.
Advisor:	Ing. Marcela Jebavá, Ph.D

Aim of simulation

- Segmented melting
  - Each segment specialized on particular process
  - High surface => high heat losses

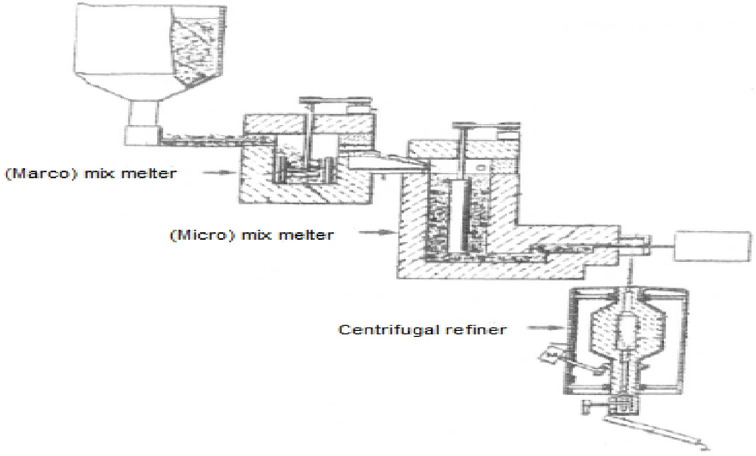
Heating/ preheating

Homogenization module

Cooling

Batch/ cullet

- Module
  - Simplify segmented melting
  - Processes of sand dissolving and bubble removal simultaneously



Description of melting process

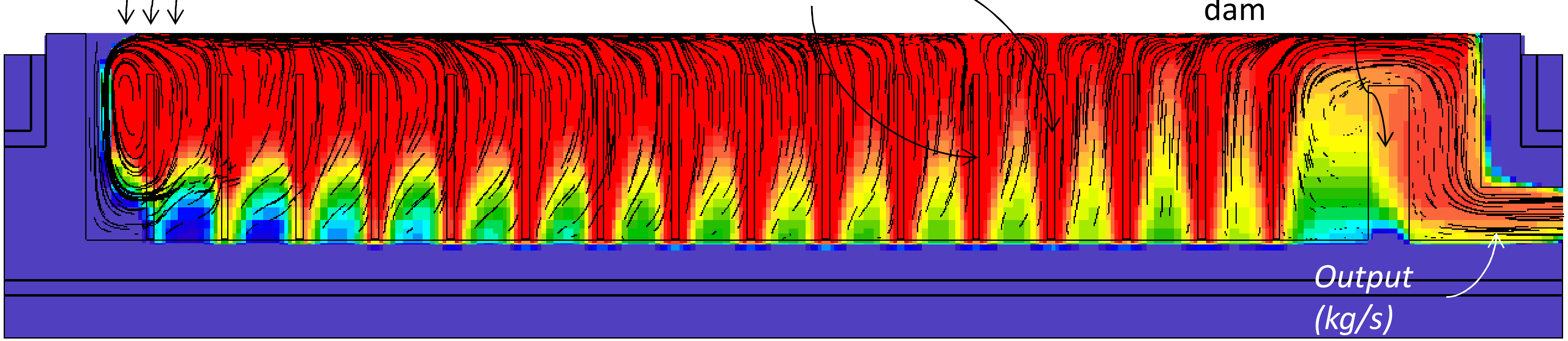
- **Utilization of melting space <0;1>** $u = \frac{\tau_H}{\tau_G}$
  - Time needed for realizing the relevant homogenization process, $\boldsymbol{\tau_H}$
  - Aplication of utilization aims at replacing the 3D picture of melt flow and melting phenomena by an simple integral quantity.
- The mean residence time τ_G involves the volume melting performance:
  - Space volume **V** (m^3) $\tau_G = \frac{V}{\dot{V}}$
  - Volume flow rate (volume melting performance) $\dot{\boldsymbol{V}}$ (m^3 s^{-1})
- **Specific energy consumption involving *u*** (J kg^{-1}) $H_M^0 = H_M^T + \frac{\dot{H}^L \cdot \tau_H}{\rho V} \frac{1}{u}$
  - Theor. spec. energy for heating, phase transf., reactions $\boldsymbol{H_M^T}$ (J kg^{-1})
  - Total heat flux by interfaces $\dot{\boldsymbol{H}}^{\boldsymbol{L}}$ (J s^{-1})
- **Melting performance involving *u*** (m^{3}s^{-1}) $\dot{M} = \frac{V}{\tau_H} \cdot u$

Energy consumption and melting performance are function of the utilization and therefore, their values depend on the character of the melt flow.

We found that the most effective character of melt flow appear uniform and helical flow.

Initial module setting

Dimensions of the module	1 x 2 x 6.77 m^3
Transverse refractory dam (melting phenomena terminated)	6.225 m
16 electrodes - *6 electrodes* - *10 electrodes*	60 cm or 30 cm *first part* *second part*
Initial glass melt temperature	1320 °C (1220 °C)
Stabilized average melt temperature after calculations	1420 °C
10 000 bubbles	0.1 mm
10 000 sand particles	0.5 mm



Input of molten raw glass (kg/s)

Electrodes

Transverse refractory dam

Output (kg/s)

Types of flow, energetic model

- The character of melt flow is determined by its throughput flow and by natural melt convection.
- The character of natural convection is determined by the longitudinal, transversal and vertical energy distribution in the melt.
- The longitudinal energy distribution plays crucial role for the overall character of flow and glass melting. The characteristic velocity component can be defined with the assistance od the driving force of the longitudinal circulations:

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

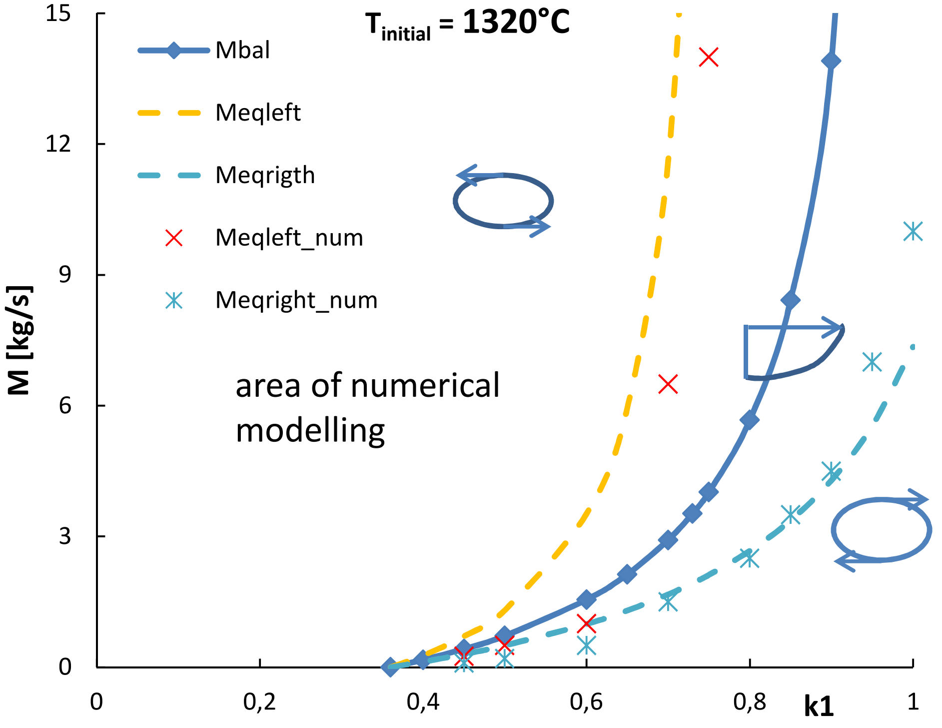
- C_1 is a constant (obtainable from numerical solution). v_{lc} is defined on the longitudinal axis of the melt level and in the centre of length of longitudinal circculation. ξ *is* fraction of heat losses in the input part, k_1 fraction of heat in the input part.

- If the energy distribution between input and following part of the space is balanced, v_{lc}= 0 and the resulting flow rate is given by:

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

- The curve $\dot{M}_{bal}(k_1)$ demarcates the region of the counterclockwise melt circulations left and clockwise circulations right of the curve in the coordinates $\dot{M}$ and k_1
- The asumed flow along the curve $\dot{M}_{bal}(k_1)$ is the uniform flow characterized by high space utilization and consequently, high melting performance.
- Two curves $\dot{M}_{eq}\,(k_1)$ can be conventionally defined describing the flow type being not too far from the uniform flow at v_{lc}=v_{fr} (v_{fr} is the maximum througput velocity of the melt), specifying thus the region of beneficial $\dot{M}$ and k_1.
- The position of $\dot{M}_{eq}\,(k_1)$ curves was experimentally verified.

Backflow.avi Uniform.avi Forwardflow.bmp.avi



- The velocity component of the transversal circulations can be expressed with the assistence of the transversal energy distribution in the second part of the space:

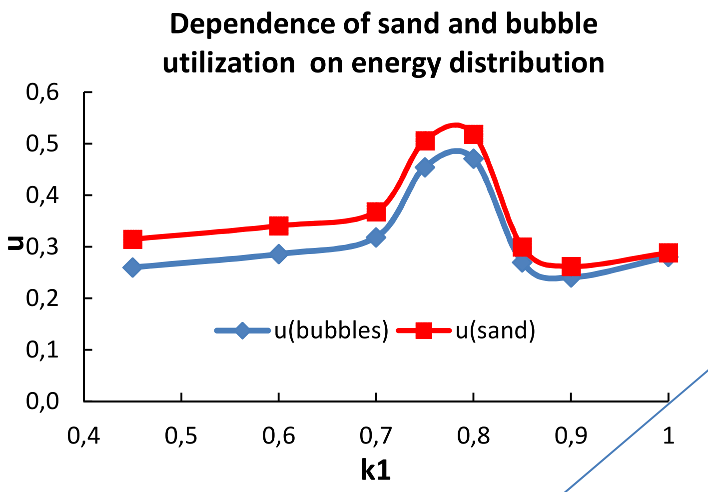
$$v_{tc} = C_3\left[(1-k_1)\left(\dot{M}H_M^T + \dot{H}^L\right) + \dot{H}^L(side)\right]$$

- The equation is valid if all the energy is situated in the longitudinal axis of the space
- C_3 is a constant. v_{tc} is defined on the melt level between the longitudinal axis and sidewall. $\dot{H}^L(side)$ is the flux of heat losses through sidewalls in the second pat of the space.

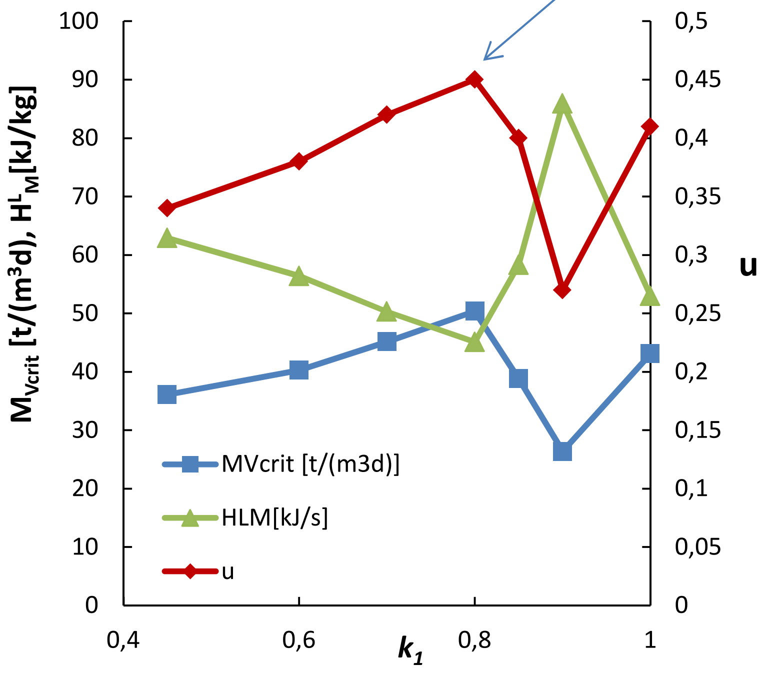
Opportunities of the energetic model

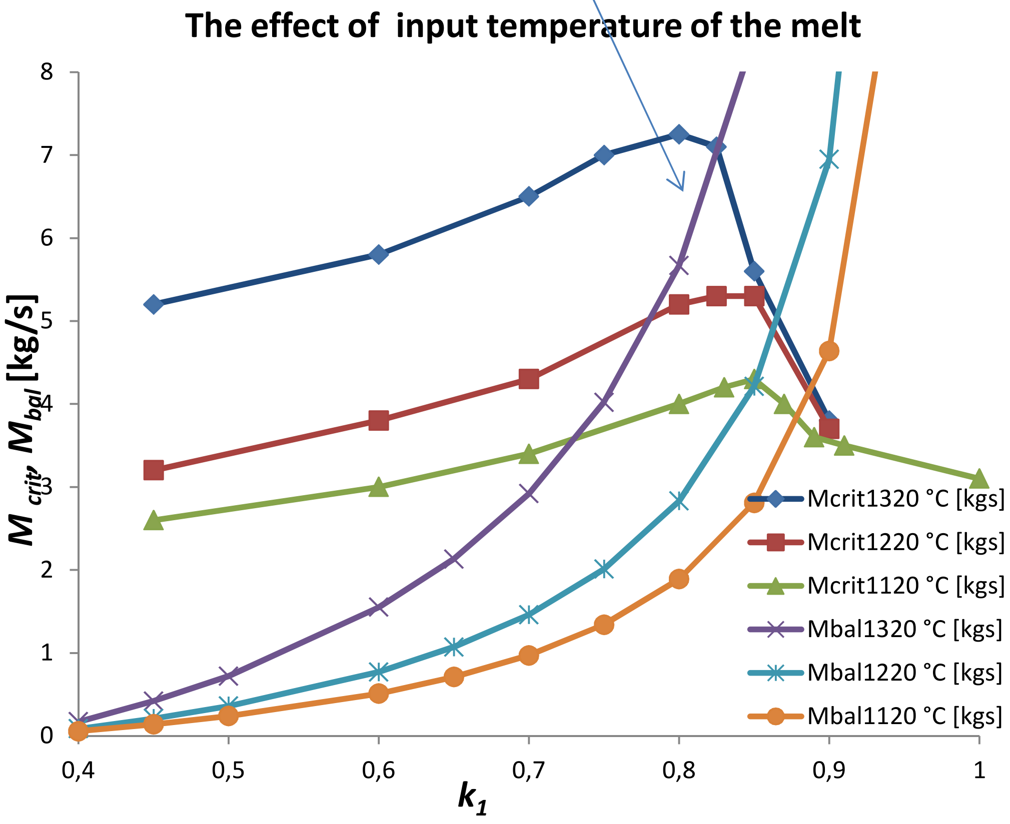
- The energetic model described by the $\dot{M}_{bal}(k_1)$ curve and by characteristic velocities v_{lc} and v_{tc} faciltates the predictions of beneficial melt flow types to achieve the high melting performances and consequently, low specific heat losses.
- The variable k_1 *simulates* the effect of longitudinal transfer of energy, the variable $\dot{M}$ the effect of the melting rate.
- The variable H_M^T simulates the effect of the theoretical heat, practically the effect of preheating of the batch or the temperature of inputted glass.
- The variables ξ and $\dot{H}^L$ $\left(\dot{H}^L(side)\right)$ simulate the effect variable insulations, practically the effect of approaching the uniform flow, and support of the transversal circulations (helical flow).
- The energetic model does not simulate the effect of detailed energy distribution or the vertical energy distribution but helps to understand it.
- *Any mutual approach of the* $\dot{M}_{bal}(k_1)$*curve and the region of calculated* $\dot{M}_{crit}$*values increases the space utilization and correspondingly, the melting performance.*
- The effect of k_1, the melt input temperature and the vertical energy distribution (the length of electrodes) is involved in this presentation.

Effect of longitudinal energy distribution, k_1. Input temperature 1320 °C, electrodes 0.3 m long

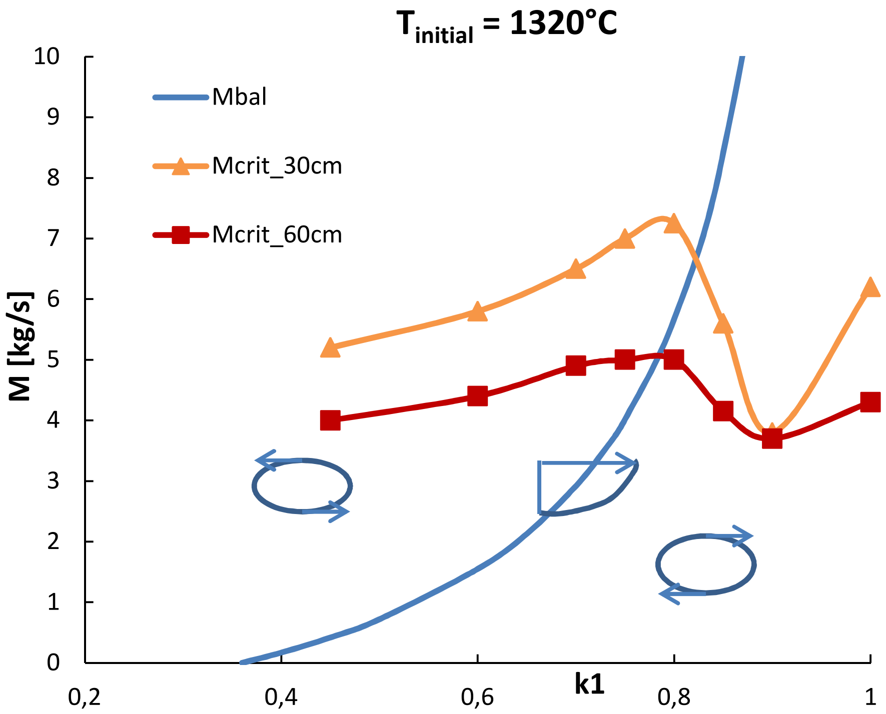


- Utilization values of both homogenization phenomena show the same tendency.
- The melt flow character affects both phenomena in a similar way.
- After relocating 70 - 80% of energy to the input, melting performance reached maximum and heat losses minimum. The best values are close to the $\dot{M}_{bal}(k_1)$ curve



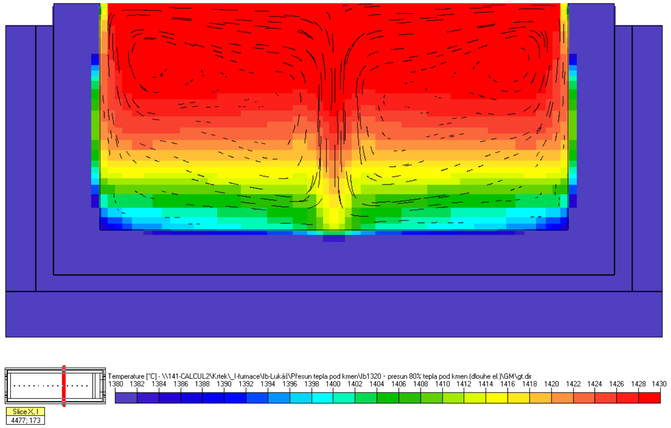


Effect of vertical energy distribution, electrodes 0.3 and 0.6 m long



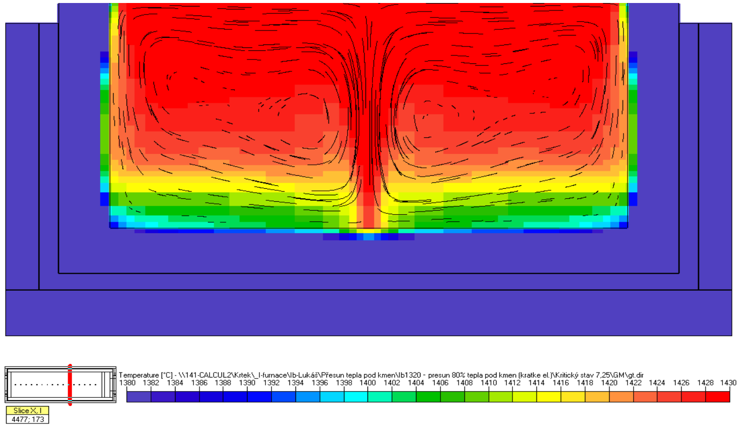
- If we are approaching the curve $\dot{M}_{bal}$ either by varying $\dot{M}$ or k_1 , the space utilization grows.
- The maximum values of the melting rate at k_1 = 0,8 correspond to the combinatinon of the almost uniform flow with the very slow longitud. circulations of the type ↺ and weak transversal circulations.
- Such type of the melt flow was found the best also for other examined type of the horizontal melting space.
- The increase of the melting rate between k_1= 0.9-
- 1 is caused by the ultimate shift of the spring point to the input.
- The higher values of melting performance in the case of shorter electrodes are caused by the development of more symetrical transversal circulations.

0.6 m



Temperature [°C] - \\141-CALCUL2\Krtek_I-furnace\Ib-Lukáš\Přesun tepla pod kmen\Ib1320 - presun 80% tepla pod kmen (dlouhe el.)\GM\gt.dir

0.3 m



Temperature [°C] - \\141-CALCUL2\Krtek_I-furnace\Ib-Lukáš\Přesun tepla pod kmen\Ib1320 - presun 80% tepla pod kmen (kratke el.)\Kritický stav 7,25\GM\gt.dir

Conclusions

- The relevant character of the melt flow allows *simultaneous beneficial course* of dissolution and fining phenomena in one homogenization module.

- The module can serve as a significant part of a *new two-space glass melting furnace.*
- The desired uniform or helical-like melt flow can be set up by the justified *concentration of heating energy* to the input and central longitudinal axis of the module.

- The maximal values of the melting performance and minimal heat losses are found in the *diagram of melt flows*, close to the curve of balanced longitudinal energy distribution.

- Using the mathematical modelling and diagram of the flows, the *optimal conditions* of the module operation can be reliably *predicted*.