Some aspects to the minimum residence time in glass tanks and its mathematical modeling

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The performance of glass furnaces is of major importance in the glass industry. Basic demands are best glass quality, with minimum energy consumption and pollution. Melt convection and temperature fields directly impact the glass tank performance and glass quality. The melt convection determines the Minimum Residence Time (MRT), which is frequently used as a criterion for glass quality and tank performance. Computational fluid dynamics (CFD) constitutes a very efficient tool to simulate the melt thermo-convection and to improve design and operation of glass tanks. A working group of the International Commission on Glass, the Technical Committee 21, proposes Round Robin Tests as benchmarks for the CFD modeling of glass tanks. The results of these tests reveal that still considerable difficulties persist in the calculation of the MRT, according to existing literature. This paper presents the importance of the numerical precision for the calculation of the MRT for glass furnace. However, the sub-models of the TC21 participants and their respective differences might have a significant impact on the simulated melt convection and the found MRT. To check the impact of the batch sub-models, a parametric study of the boundary conditions of our 3D reference cases is presented.

Minimun residence time, transition function and glass quality

Continuous glass melting tanks represent thermo-chemical reactors with stationary flow under normal operation. The minimum residence time (MRT) of such a flow system is given by the shortest passage time of a small flow volume on a critical trajectory. The MRT is the starting point of the transition function $tf(\tau)$ of the flow system. The transition function presents the answer of the system on a step change at the flow inlet. This is illustrated in Fig.1. The transition function and the MRT can be obtained experimentally by slight composition changes or tracer experiments. Step changes at the inlet result directly in transition functions, inlet concentration peaks near to δ-functions result in residence time distributions *rtd*. The transition function is then obtained by integration of the *rtd*: $tf(\tau) = \int rtd(\tau)d\tau$

Simple analytical solutions exist for two principal flow situations:

Perfect mixer : $tf(\tau) = 1 - \exp(-\tau)$ with MRT=0

Piston flow : $tf = \begin{cases} 0 & for \quad t < t_{geo} \\ 1 & for \quad t > t_{geo} \end{cases}$ with MRT=1

Traditional glass melting tanks present a very complex flow pattern, which makes impossible a simple analytical calculation of the transition function. Numerical methods are required to simulate flow, tracers or virtual particle trajectories and transition functions. The glass melting process needs minimum process times for grain dissolution, cord homogenisation, bubble removal to obtain a required glass quality, based on the complete dissolution of each spherical silica grain with the initial diameter R_0 [1]: $t_{\min} \propto R_0^2/(D(T)\cdot Sh)$.

Higher temperatures increase the diffusion coefficient D and intense convection increases the Sherwood number. This reduces the required minimum time but increases the energy consumption and refractory corrosion at the same time.

Typical MRT and transition function of glass tanks

Glass tanks present quite different sizes and shapes depending on the glass type, quantity and quality to be produced. Nevertheless, normalised transition functions allow a general comparison of the melt convection in such systems. Fig. 2 compares the *tf* of a float[2], a bottle glass[3] and a lamp bulb furnace[4]. The transition functions were obtained by integration of the measured residence time distributions. The normalisation of the concentration is limited in precision with an error of at least 10% due to experimental uncertainties (uncertainties of injected, recovered and measured concentrations, time limitation of experiment). The experiment on the lamp bulb furnace was realised with a long term pulse instead of a δ-pulse. Only the first part of the curves represent the transition function. The following conclusions can be drawn from this comparison.

- The MRT is only 10-20% of the geometric residence time (a well known fact for glass tanks).
- Low slopes at the start of the *tf* make the definition of the MRT more difficult because the low quantity may be irrelevant for the glass quality.
- Higher glass quality (float) does not systematically require longer MRT compared to bottle glass.
- Bubbling has in general only a minor impact on the MRT (a fact often confirmed by numerical modelling).

Mathematical modelling is expected to contribute significantly in the analysis of MRT and to evaluate the impact of critical trajectories on the glass quality.

Requirements on the precision of MRT calculations

The basic relationship of the MRT and the melt currents is illustrated Fig. 3. A virtual particle is taken up at t=0 in the batch area by the combined pull and recirculation flow. The residence time on the critical trajectory is inversely proportional to the particle velocity. The mean particle velocity is proportional to the melt flow: $\bar{v} \propto \dot{M}_{rec} + \dot{M}_{pull}$.

Taking, for example, a MRT 10% too short to insure a good glass quality for a given pull rate, all standard means like bubbling are already in operation. The only mean left is a longer critical trajectory by the increase of the furnace length. A 10% surface area increase of a medium size float furnace means a considerable higher investment cost. So the challenge for the mathematical modelling is clear. The precision of trajectory calculations shall be significantly better than 10% in time with an adequate precision in temperatures and velocity gradients, if modelling is to be used for quantitative predictions of glass quality and the size determination of glass tanks. It is a crucial feature of classical glass tanks that the MRT is mainly determined by the internal recirculation and not only by a simple pressure head due to pull and tank geometry. Such flow situations significantly increase the requirements on mathematical modelling.

Benchmark tests of MRT calculations

The Technical Committee 21 (TC21) proposed three round robin tests (RRT) including a comparison of the MRT predicted by the different participants. The first example (RRT1) concerns a virtual, simple tank with a parallelepiped cavity and a throat[5]. Geometry, boundary conditions and numerical grid were precisely fixed in this test. Despite these precise conditions, quite different MRTs were found by the participants varying from 6.2 to 7.8 hrs. Test no. 3 (RRT3) concerns the formerly Ford Nashville float glass furnace for which numerous experimental data were made available[2]. This time, the participants were more or less free regarding their sub-models (batch, combustion etc.) and their numerical approaches. Again, quite significant differences in the MRTs were found. The measured MRT lies in-between 8-10 hrs, whereas 11.8 hrs were published as a numerical result[6]. The RRT4 actually running is a refinement of the RRT1 integrating batch melting and combustion space radiation. Again, quite significant differences in the predicted MRTs appear varying from 7.3 to 18 hrs for 25t/d. However, this test is not finished yet.

Numerical aspects of MRT calculations

Apart from the material properties and boundary conditions of a tank simulation, the standard criteria for numerical MRT calculations are:

- Full convergence of the flow field simulation
- Short time steps for the trajectory calculations.

However, these conditions are incomplete and not sufficient to guarantee the precision of MRT calculations[7]. The following tests should be added:

- Comparison of number of injected and recovered virtual particles
- Verification of trajectory looping with recirculation without pull
- Comparison of trajectory calculations with stream line calculations
- Successive numerical refinement of grid and time steps.

The feasibility of such verifications depends, of course, on the available options of a numerical code. In 7, the RRT1 was thoroughly recalculated. All mentioned trajectory tests were realised. A striking result is the change of the critical trajectory with grid refinement (see Fig. 4). The new critical trajectory is now in the middle plane of the tank. The MRT decreased from 7.7hrs with the prescribed grid to 5.5hrs with 8000 cells. A further increase changed only slightly the MRT to a final value of 5.25hrs (see Fig.4).

Impact of boundary conditions and melt properties on MRT

The MRT is largely determined by the melt recirculation. Hence, all factors influencing the thermo-convection also influence the MRT. The batch boundary condition of the RRT1 may serve as an example. The batch inlet boundary as defined by the TC21 [5] results in a MRT of 5.25hrs after numerical refinement. A batch heat flux boundary condition according to [8] gives the same MRT if the batch heat flux is identical in both cases (91kW). The increase of the batch area heat flux causes a decrease of the MRT as shown in Fig.5. At the same time, the bottom temperature decreases significantly. Further factors influence the MRT: bottom heat losses, melt depth and length, effective thermal conductivity, free surface temperature profiles…

Conclusions

Because MRT, glass flow and temperatures have a significant impact on glass quality, precise calculations of the critical trajectory are compulsory for tank simulations to be used for dimensioning. This requires high precision simulations of the thermo-convection in glass tanks. As a consequence, melt properties and boundary conditions shall be thoroughly known. Attention shall also be paid to the numerical aspects of MRT calculations.

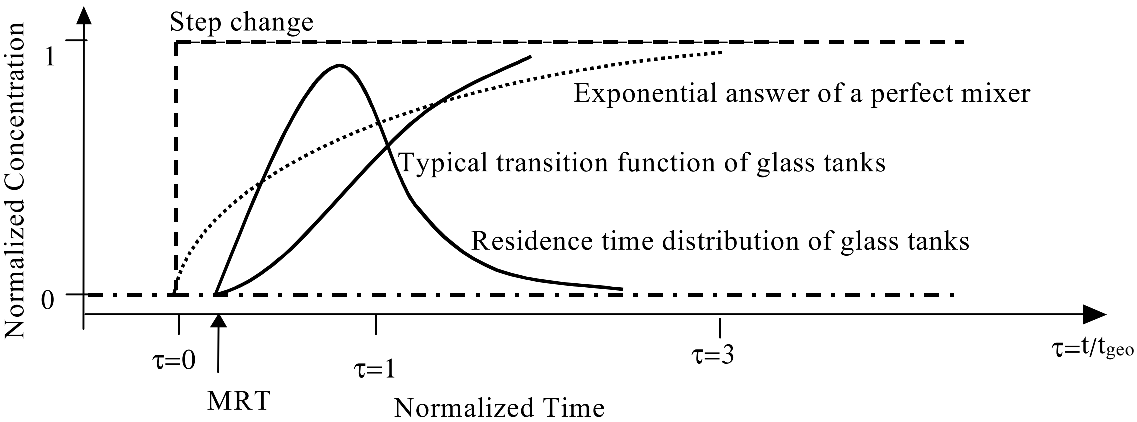

Fig1:Typical transition function, residence time distribution and MRT of glass tanks

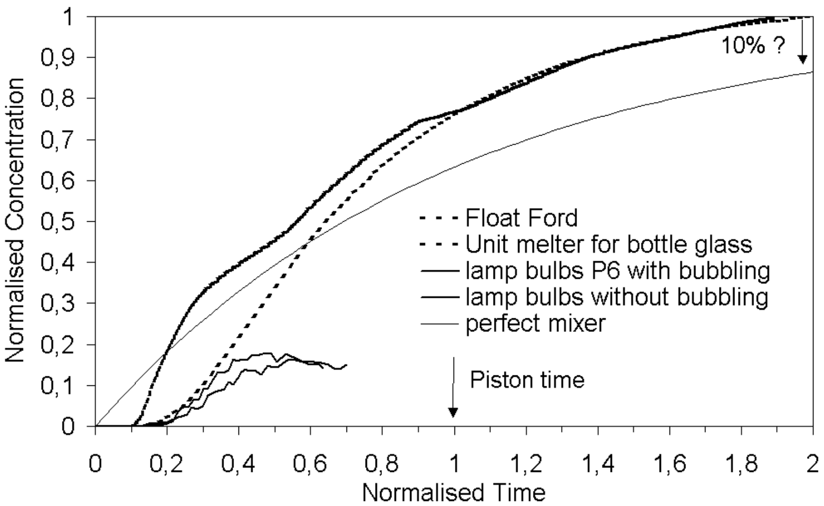

Fig.2: Measured transition function of glass tank

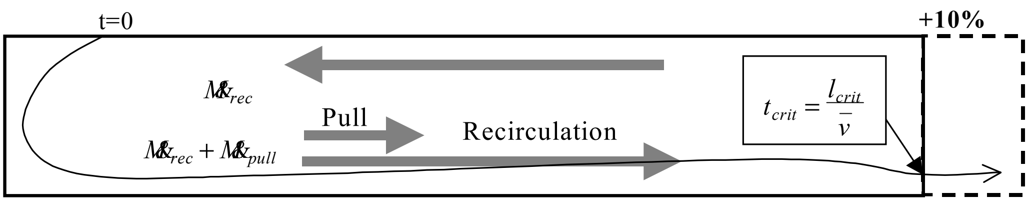

Fig.3: Basis relation of MRT and the melt convection

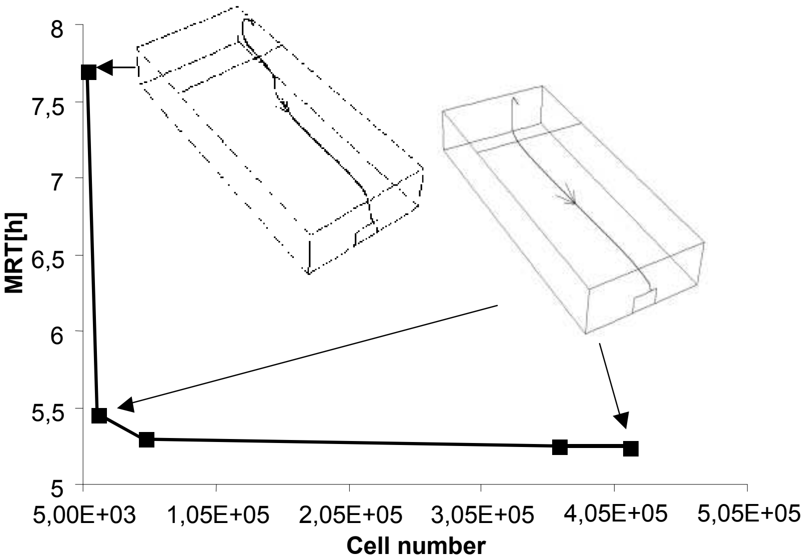

Fig.4: Variation of the critical trajectory and MRT with grid refinement on the example of the TC21.

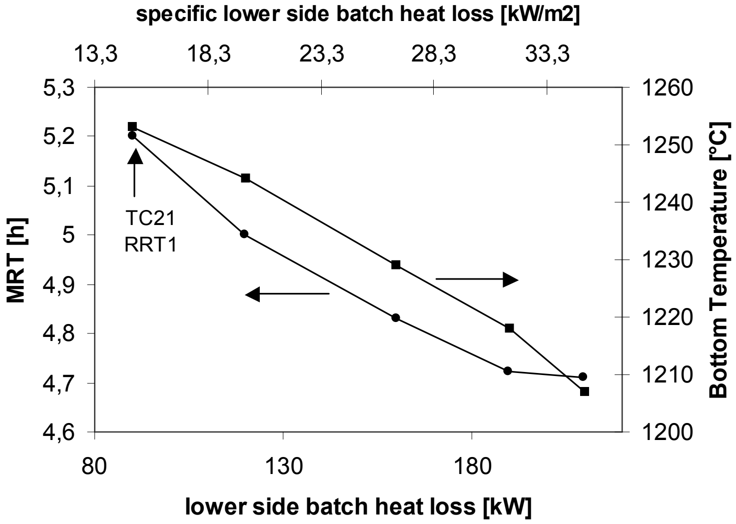

Fig.5: MRT and bottom temperature as a function of the batch area heat loss of the RRT1

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