Original Paper

Round robin for glass tank models

Report of the International Commission on Glass (ICG) Technical Committee 21 "Modelling of Glass Melts"

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Different numerical and physical models for glass tanks were compared by a simple round robin. Most models produced qualitatively similar velocity and temperature distributions. The minimum residence time of tracers in numerical models gave similar values too, but differed to the physical scale model. An explanation for this is the different kind of batch modelling in both methods of simulation. Especially the velocity vectors at some fixed test points showed larger deviations. In regions with steep gradients small variations in the local flow distribution can lead to large changes at fixed test points. These differences therefore should not be rated very high.

Ringversuch für Modelle von Glaswannen

Verschiedene numerische und physikalische Modelle für Glaswannen wurden anhand eines einfachen Ringversuches verglichen. Dieser Test ergab bei fast allen Teilnehmern qualitativ ähnliche Geschwindigkeits- und Temperaturverteilungen. Auch die ermittelten minimalen Verweilzeiten von Tracern zeigten bei den mathematischen Modellen eine gute Übereinstimmung, wichen jedoch von dem physikalischen Modell ab. Diese Differenz kann aus der unterschiedlichen Simulation des Gemengeteppichs erklärt werden. Einzelwerte an festen Testpunkten der Modellwanne zeigten insbesondere bei den Geschwindigkeiten größere Abweichungen. In Bereichen mit sehr starken Geschwindigkeitsgradienten kann dies jedoch durch nur kleinere Änderungen der Geschwindigkeitsverteilung hervorgerufen werden, so daß dieser Punkt nicht überbewertet werden darf.

1. Introduction

Measuring the velocity and temperature distribution in a glass tank is very difficult, so it has been done very seldom and then only for restricted parts of melting furnaces. An alternative method for getting information about what occurs in a tank is physical scale modelling. The physical model gives a reliable three-dimensional insight into glass flows and velocity and temperature profiles, but it is hard to simulate batch effects and impossible to incorporate the reaction mechanisms.

Velocity and temperature distributions can be calculated only numerically because the different parts of the process are strongly coupled. These calculations require fast computers, which have become available at reasonable cost only in recent years. Though proven numerical methods for solving the calculation of buoyancy-driven convective flows in fluids do exist, it is still a problem to meet the specific boundary conditions needed for a realistic simulation of a glass tank. A round robin for a strictly defined test case is therefore a valuable development tool, especially since many of the numerical glass tank models which exist are company-specific in-house developments. Therefore, in the first session of the then newly founded Technical Committee 21 (TC21 "Modelling of glass melts") within the 1990 Annual Meeting of the International Commission on Glass (ICG) in Düsseldorf (Germany) it was decided to make such a test the first task.

For the first round robin a very simplified tank, for which experiences with physical modelling existed, was chosen (table 1). The aims of this cooperation were specified as follows:

- testing of individual computer codes;
- comparing the results with those of physical models;
- comparing the influence of specific settings of each participant for the boundary conditions;
- providing a starting point and frame of reference for a discussion about basic modelling problems and about important sub-models.

As it can be seen from the list of participants in section 5., many glass-related working groups saw the urgent need for this work.

2. Details of the round robin

There have been five runs of this first round robin with the same geometry but somewhat altered conditions. Due to convergence problems of some models the ther-

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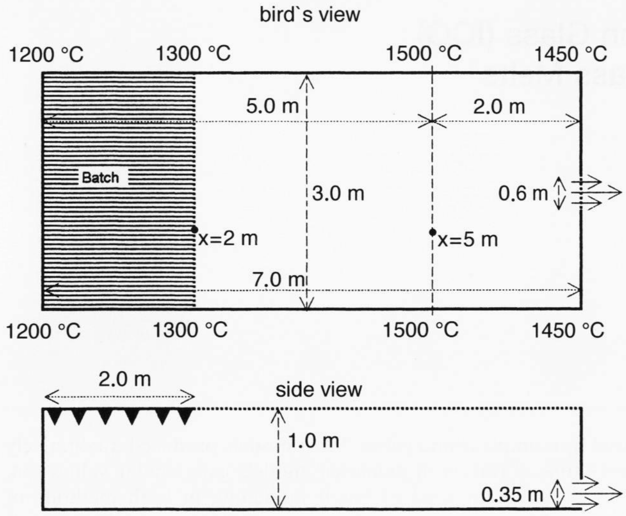
Table 1. Experimental conditions for the 5th run of the round robin no. 1

a) geometry of the simplified model tank



b) glass properties

η = $-1.58 + 4332/(T-248)$
with T in °C and η in dPa s

λ = 30 W/(m K)

C_p = 1300 J/(kg K)

δ = 2300 kg/m^3

β = $6 \cdot 10^{-5} \cdot K^{-1}$

c) boundary conditions

- fixed grid with spacing l = 0.2 m, h = 0.05 m, w = 0.25 m
- temperature at surface: see at a); no gradients to the sides
- heat loss (wall, bottom, throat): 2 kW/m^2
- batch: length = 2.0 m, thickness = 0 m, glass flow uniformly downwards, no slip under batch
- pull: 35 t/d, parabolic output flow at throat entrance

d) output

- minimum residence time at throat entrance
- mean temperature in plane of the throat entrance
- location of the mechanical spring
- values of velocity vectors in the centre plane at x = 2.0 m and x = 5.0 m and at heights of 0.2 m and 0.8 m, respectively
- velocity and temperature plots of central longitudinal plane
- temperature and velocity profiles in the height at x = 2.0 m and x = 5.0 m
- temperature profile along the centre line of the bottom (one cell or 0.05 m above bottom)

mal conductivity of the melt was shifted from 10 to 30 W/(m K). Also the boundary conditions at the walls have been changed from a fixed temperature (1400 °C) to a fixed-area heat loss (2 kW/m^2).

The batch was simulated by a fixed region with a "no slip" boundary condition, i.e. nominally zero thickness and fixed temperatures (no heat sink effect). A test run with a batch thickness of 5 mm gave no significant changes. The "batch" temperatures were changed in the course of the work because the convergence of most models was slowed down by localized melt movements under the batch similar to "Bernard cells", but even in the final runs these convection cells were still present. An increase in the pull from 35 to 50 t/d changed only the minimum residence time. All other test parameters stayed quite stable due to the other (unchanged) boundary conditions. Changing to a finer grid resulted in only minor alterations of the basic results, but was found to exacerbate the "Bernard cell" problem.

Most of the computer codes tested were finite difference programs designed or modified for the specific demands of glass tank modelling[2]. One participant compared such a code with a commercially available multipurpose finite element program. In that test it was quite difficult to get results with that particular multipurpose finite element program which were comparable with those of the rest of the participants. That this is not a problem of finite element codes in general was shown by the successful use of another commercially available multipurpose finite element program.

3. Results of the final (fifth) run of the round robin

In this report only the results of the fifth run are documented in detail. As can be seen in section 5., most but not all members engaged in the round robin took part in this final run. The results are summarized in figures 1a, b, 2a, b and 3, and in table 2. The figures in this report show only the results of the numerical calculations[4].

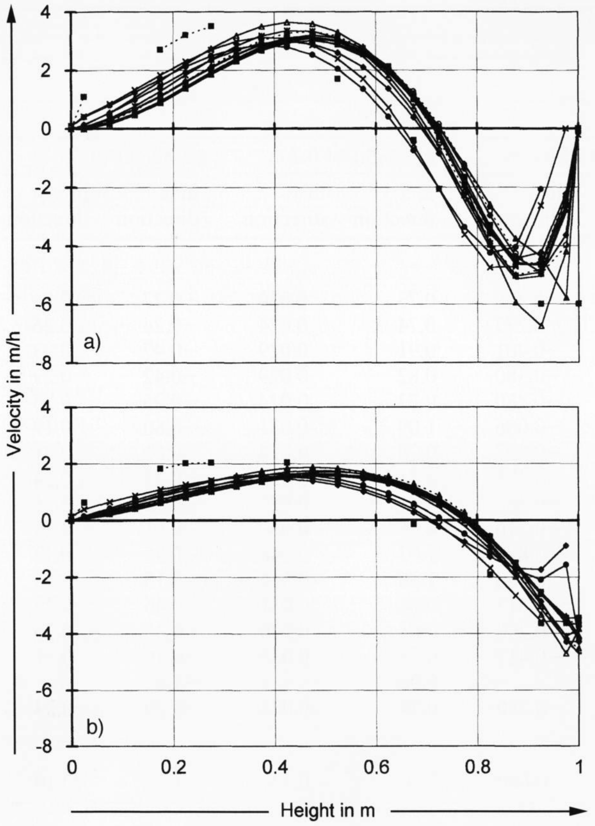
Figure 1a shows the vertical velocity distributions in the centre of the tank under the batch 2 m downstream of the charging end (at x = 2 m). Figure 1b gives similar information for a batch-free region 3 m further along the furnace (at x = 5 m). With the exception of two models all calculations yield closely similar distributions. The vertical temperature profiles at the same locations (shown in figures 2a and b) as well as the horizontal temperature profile 0.05 m above the bottom on the tank axis (figure 3) demonstrate similar levels of agreement. Nevertheless, the range in temperature across the different models is greater than 20 K.

The main purpose of this report is to compile a large number of results for a well-defined test case with uniform output definitions. Accordingly, table 2 shows the results for the minimum residence time, the temperature in the throat entrance, the location of the mechanical spring or uprise and some values of velocity vectors at specified locations. An intensive investigation of the observed differences and their possible causes is primarily the task of each participant. In this report only some general observations should be pointed out.

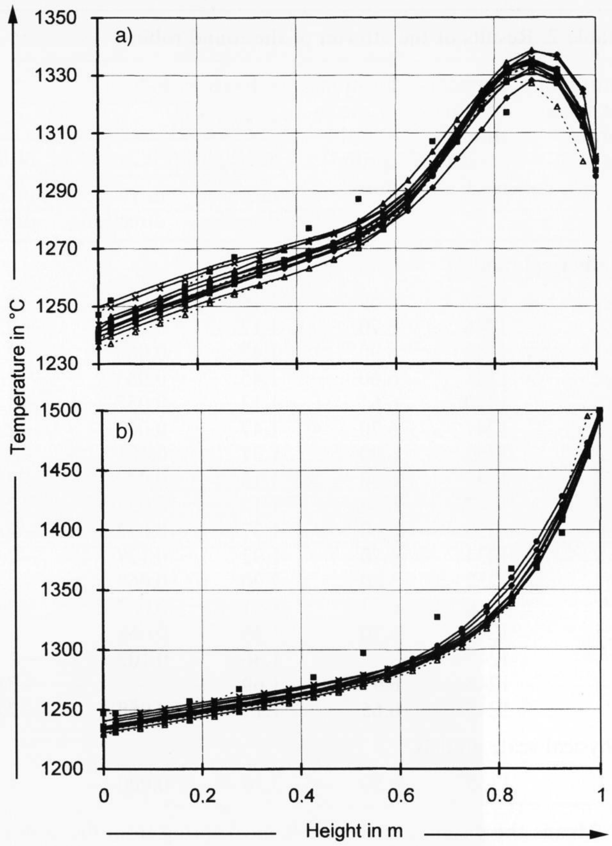
Although most of the models produced similar basic velocity distributions, the deviations of the single local test vectors within the different models were not small.

[2] Details are available at TC 21.

[4] The velocity and temperature distributions of the physical model are documented on a video tape, which was shown in the 1996 Technical Committee session.



Figures 1a and b. Vertical velocity distribution a) under the bath (at x = 2 m; see figure in table 1), b) in the batch-free region (at x = 5 m; see figure in table 1).



Figures 2a and b. Vertical temperature distribution a) under the batch (at x = 2 m; see figure in table 1), b) in the batch-free region (at x = 5 m; see figure in table 1).

Even if the results of the two models with the most extreme values are ignored and the lowest and highest values of each velocity vector skipped, still standard deviations of up to 41 % are obtained. The deviations of the vertical velocities at the upstream reference point (x = 2 m) can be explained by different treatments of the below-batch boundary conditions, but the broad and evenly distributed scatter of the horizontal back flow in the batch-free region (x = 5 m) needs further discussion. Possibly, these latter deviations are caused by the extreme situation of the mechanical spring found by all models to be directly in the neighbourhood of the back wall.

In contrast to the local velocity vectors, the minimum residence time results and the mean temperature values in the throat entrance are quite close together. Probably, the scattering of the local velocity vectors results from comparatively small variations in the local flow patterns, which together with the steep gradients leads to large changes at fixed test points. The comparison of the numerical and the scale models showed a basically similar velocity distribution, but larger absolute velocities in the physical model. In this model also the minimum residence time was much shorter and the throat temperature higher. Similar results had been found in one of the numerical model calculations too: the reason was a "wrong" heat balance for the defined

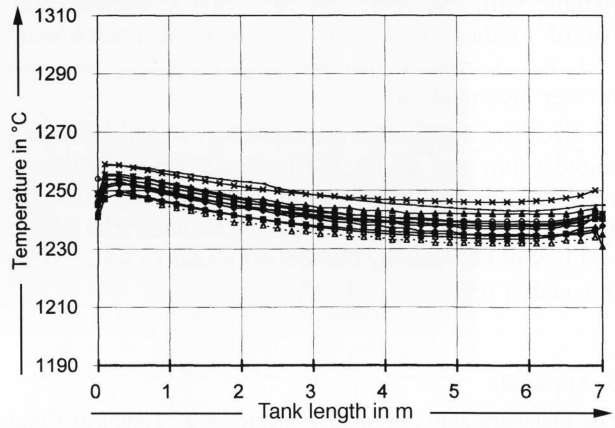


Figure 3. Horizontal temperature distribution in the tank axis 0.05 m above the bottom.

kind of "batch". Clearly, the batch has a large influence on the whole tank, and the very theoretical definition of the batch boundary conditions specified in the best case could not be simulated exactly by a physical model.

4. Summary and outlook

Though some differences in single local test values were found, it was decided to make no further runs with ad-

Table 2. Results of the 5th run of the round robin

minimum residence time in h	temperature at throat entrance in °C	location of mechanical spring[3] in m	velocity in m/h							
			at $x = 2$ m				at $x = 5$ m			
			at height of 0.2 m		at height of 0.8 m		at height of 0.2 m		at height of 0.8 m	
			in x direction	in y direction	in x direction	in y direction	in x direction	in y direction	in x direction	in y direction
numerical models										
6.7	1247	6.69	1.19	0.060	−2.16	−0.300	0.73	0.030	−0.27	0.24
7.4	1246	6.70	1.12	0.051	−2.49	−0.277	0.74	0.024	−0.24	0.25
7.1	1242	6.90	1.47	0.068	−2.64	−0.401	0.91	0.029	−0.47	0.23
6.2	1241	6.60	1.45	0.083	−2.65	−0.380	0.82	0.029	−0.42	0.29
7.8	1250	6.65	1.13	0.057	−1.90	−0.480	0.73	0.024	−0.25	0.25
7.3	1247	6.70	1.47	0.063	−2.71	−0.006	1.09	0.031	−0.80	0.19
7.2	1252	6.90	1.37	0.101	−3.26	−0.497	0.70	0.024	−0.61	0.31
7.7	1247	6.60	1.13	0.057	−2.73	−0.385	0.71	0.022	−0.23	0.24
7.7	1247	6.54	1.12	0.057	−2.67	−0.382	0.71	0.023	−0.22	0.24
7.1	1250	6.60	1.37	0.072	−2.66	−0.216	0.86	0.030	−0.61	0.25
6.5	1234	6.70	1.92	0.127	−2.95	−0.870	1.03	0.046	−0.45	0.32
	1257	5.40	2.20	0.068	−1.72	−0.860	1.56	−0.066	−0.15	0.18
	1248	6.72	1.51	0.087	−2.85	−0.313	0.84	0.031	−0.46	0.29
7.5	1248	6.70	1.35	0.061	−2.63	−0.290	0.84	0.020	−0.35	0.25
	1241		1.36	0.102	−2.99	−0.417	0.78	0.035	−0.16	0.31
	1245	6.99	1.69		−2.91		0.96		−1.02	
	1245	6.65	1.17	0.058	−2.02	−0.280	0.74	0.024	−0.29	0.24
physical scale models										
3.1	1335	6.50	3.50	0.000	−4.5	−0.600	2.50	0.10	−1.50	−0.10

3) Means the distance of the mechanical spring from the tank end wall.

ditional (smoothing) settings for this first test case. All the models involved gave generally similar temperature and velocity distributions, which were qualitatively comparable with the results of the physical model. With regard to the scatter of local values, each participant now has a good bench mark to form the basis for further investigations.

Because of the rather academic way in which the first round robin was set up, the basic agreement in the results gives no real insight about how correctly the models can simulate a real glass-making furnace. The link to reality will be made by the second round robin of TC21 in which a real glass tank will be simulated.

5. Appendix

The members and consultative members of Technical Committee 21 "Modelling of Glass Melts" of the International Commission on Glass, who participated in this investigation were:

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5) Not active at the ultimate run.

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