NUMERICAL SIMULATION OF UNSTEADY COLOUR CHANGE IN GLASS MELTING TANK

NICOLAS VANANDRUEL

Université Catholique de Louvain,
Unité de Mécanique Appliquée (CESAME), Bâtiment Euler, Av. G. Lemaître, 4-6,
B-1348, Louvain-la-Neuve, Belgium

Received June 15, 1995.

Melting glass furnace mathematical modelling currently includes coupled simulations of electrical boosting, bubbling, flame radiation, etc... Increasing modelling complexity may also result from consideration of unsteady solutions. Different sources of thermoconvective unsteadiness can be considered: pull modification, time variation of bubbling and/or boosting, shift of the temperature profile or, finally, colour change [1], this paper will present the numerical solutions to the last unsteady coupled mixing problem.

PHYSICAL SITUATION

The physical situation selected for this study is the second TC 21[*)] reference furnace. This benchmark considers an operating SORG end-fired deep refiner furnace running at 175 tons per day with a melting area of 61 m^2. The geometry of the furnace and the flow structure in the (assumed) plane of symmetry are presented in figure 1. The symmetry hypothesis allows to perform the calculation only on half the furnace. The computational costs are therefore significantly reduced. The furnace over-all dimensions are $L \times w \times h = 10 \times 6 \times 3$ m. The scalar measurements in the plane of symmetry are located at the reference points (#1, ..., 12) in the figure 1.

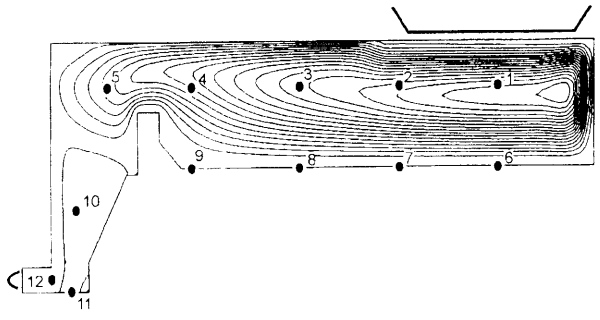

Figure 1. Geometry and flow structure of the TC 21 test case furnace.

Following instructions of the first run of the TC 21 benchmark, a linear temperature profile is imposed at the glass surface. As this benchmark is mainly concerned with the thermoconvective currents, neither crown- nor batch-models are used. Prescribed heat fluxes at the boundaries simulate the heat loss through refractories and the thermal conductivity is supposed constant and equal to 60 W m^{-1} K^{-1}.

The unsteady mixing equation is added to the classic Boussinesq set of equations (Navier-Stokes and energy equations) for unsteady incompressible flow of molten glass:

$$\frac{DC}{Dt} = \frac{\partial C}{\partial t} + v \frac{\partial C}{\partial x} = \nabla (d \nabla C) \quad , \tag{1}$$

where the diffusion coefficient, d, was chosen to ensure convection-dominated distribution of the "colour" concentration C. The value selected for this study is $d = 10^{-4}$ m^2 s^{-1}, resulting in high value of the mixing Péclet number:

$$Pé_{mix} = \frac{VL}{d} \cong 10^3 \quad , \tag{2}$$

where V and L are typical velocity and length values.

The coupling between the concentration field and the set of basic unknowns (temperature, velocity and pressure) is performed through the linear variation of the conductivity in the energy equation:

$$k(C(x)) = 30\ C(x) + 60\ (1 - C(x)) \quad . \tag{3}$$

Paper presented at the 4th International Conference on Advances in Fusion and Processing of Glass, Würzburg, May 1995.

*)] 21 st Technical Committee of the International Commission on Glass "Modelling of glass melt".

The initial situation (C = 0 everywhere) therefore corresponds to the standard TC 21 situation while the final concentration distribution (C = 1) leads to an uniform conductivity value of 30 W m^{-1} K^{-1}. Starting at time t = 0, a C = 1 concentration is imposed at the furnace entry. The aim of this study is the accurate description of the evolution between the two thermoconvective solutions.

An implicit time scheme, combined with a predictor-corrector evaluation, is used. That allows increasingly large time steps (from 30 s up to 1 day) while the integration time ends up to 10 days. Spatial discretization results from a Finite Element method [2], decomposing the computational domain in 2300 elements while the selected interpolation leads to a set of 11000 velocities and 25000 temperature unknowns.

TIME CONSTANTS IN MELTING GLASS THERMOCONVECTION

The study of unsteady thermoconvection in melting glass furnace introduces different time constants:

1. The kinematic time constant, associated with the convective contribution of heat and mass transfer, is trivially estimated by the ratio L/V. This time constant is directly related to the distribution of the residence time [3], it was estimated, in this study, to $T_{kin} \cong 15$ min.
2. The viscous time constant, associated with the viscous flow of molten glass, is measured by the ratio L^2/ν, where ν is the kinematic viscosity, $T_{visc} \cong 1$ hour.
3. The thermal time constant, associated with the heat conduction (or conductive equivalent in case of the Roseland approximation), is given by the ratio L^2/κ, where κ is the thermal diffusivity, $T_{the} \cong 1$ day. The ratio between viscous and thermal time constants was previously [4] shown to be experimentally close to the theoretical *a priori* value estimated by the Prandtl number ν/κ.
4. The mixing diffusion time constant; is associated with the concentration diffusion and measured by the ratio L^2/d, $T_{mix} \cong 5$ days.

Other time constants, related to crown- or batch-interactions, can be encountered. The regenerative cycle [5] is a well-known industrial cause to (periodic) time evolution, and generates a cycle about 20 min. The symmetry hypothesis, that was assumed in this study, leads to neglect this cycle.

RESULTS

Evolution of temperature profiles along the bottom line (through reference points # 6, 7, 8 and 9), is represented in figure 2. Note that, even if this line crosses the step, the temperature profiles are continuously plotted. Dotted lines in figure 2 represent the steady solutions obtained for 5 different values of the conductivity between the extreme values of 60 and 30 W $m^{-1}K^{-1}$. The main result observed on this figure is the evolution of the temperature gradients for the unsteady solutions while quasi-parallel profiles are obtained for successive steady situations.

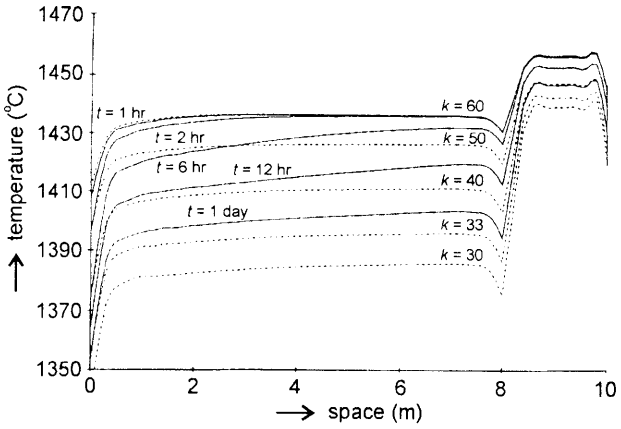

Figure 2. Spatial distribution of steady and unsteady temperature profiles.

The evolution of the concentration distribution is shown in the figure 3. While early-time concentration gradients (beneath the batch) are mainly driven by convection and appear therefore within the first hours, long term distribution is acting through at the time scale of 1 day (diffusion is also acting in the cross stream direction). Some local concentration evolutions are represented in the figure 4*a* where the enclosed figure details the start-up delay (up to 3 hours for the "exit" point #12, that value can be regarded as a close indication of the minimal residence time). Evolutions of the concentration at reference points # 11 and 12 are shown to be very close at all time values. The coupling between concentration and velocity distributions is quantified in the figure 4*b* where horizontal u and vertical v velocity evolutions are represented for the reference points # 1, 3 and 5. Significant variations of the velocities values are observed and motivate the coupling between concentration and Boussinesq equations. The similarity between velocity and concentration dynamics shows that convection is dominant for the concentration early-time evolution.

The evolution of temperature is illustrated in figures 5*a* and 5*b* for which a different time scale is used (up to the final time value of 10 days). Like in the figure 2, both steady and unsteady values are represented. Continuous lines represent the time evolutions of temperature at selected reference points while markers

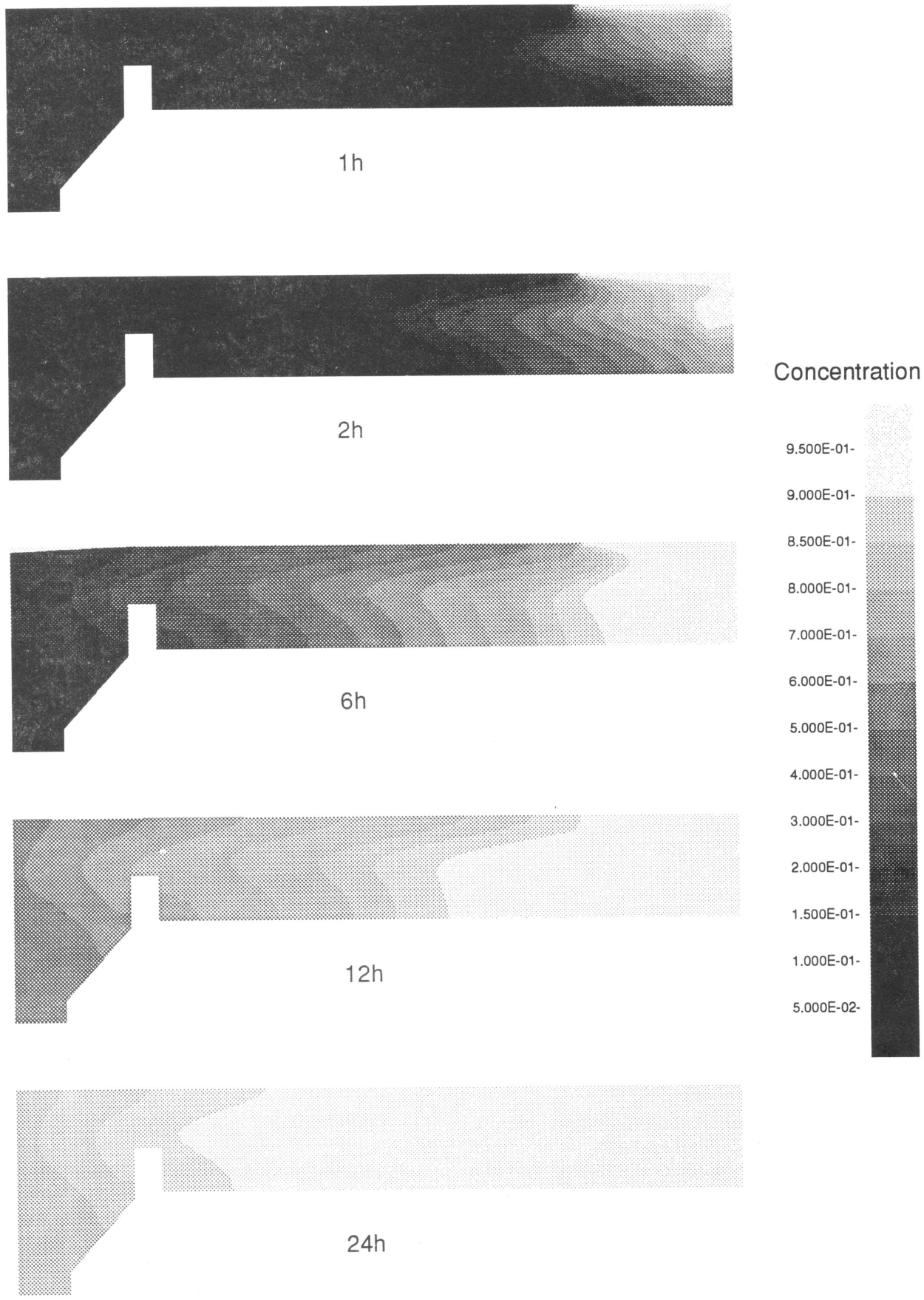

Figure 3. Evolution of the concentration distribution in the plane of symmetry.

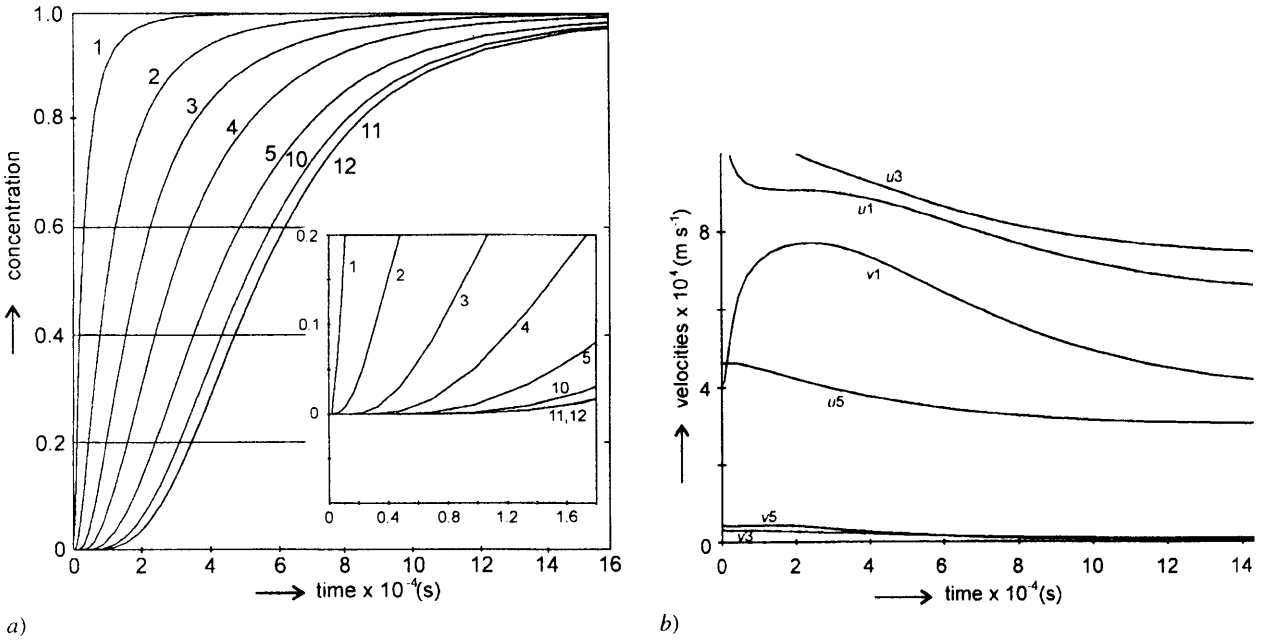

Figure 4. Concentration *a*) and velocities *b*) evolutions.

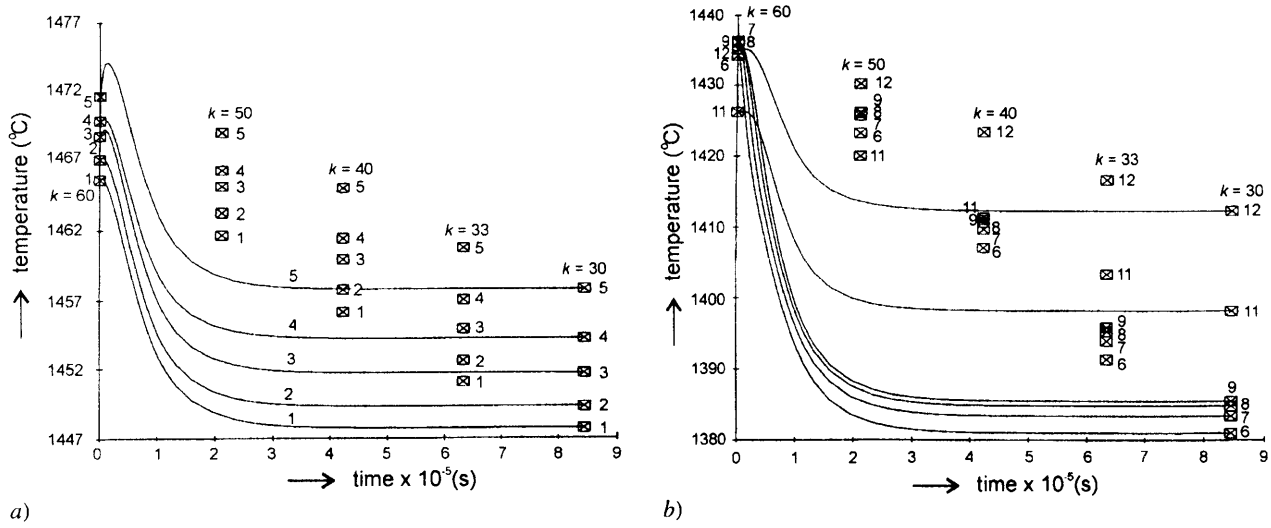

Figure 5. Steady and unsteady temperature evolutions.

indicate the temperature value for steady solution at uniform conductivity distribution. Interesting phenomenons are the temperature overshoot at the early time of the # 5 reference point temperature (due to convection) and the modification of the temperature hierarchy between reference points # 11, 12 and # 6, 7, 8 and 9. For the k = 60 steady solution the temperature at the exit lies between earth values while lower conductivities increase the gradients.

CONCLUSIONS AND PERSPECTIVES

The unsteady mixing was numerically simulated for a short deep refiner furnace. Coupling between concentration and thermoconvection equations appears to be a necessary complexity to ensure realistic evaluation of the transient evolution. No equivalence between time and conductivity can be deduced from this simulation. Further research would consider other important

sub-models simulating crown, batch, boosting or bubbling interactions.

Acknowledgement

The author want to express his acknowledgements to the GLAVERBEL Company and the Walloon Regional Government for their fruitful collaboration and financial support.

References

1. Pieper H.: Proc. Int. Symp. on Glass Sci. and Technol., p.71, Athens, October 1993.
2. Vanandruel N.: Proc. Int. Symp. on Glass Sci. and Technol., p.95, Athens, October 1993.
3. Beerkens R.G., van der Heiden T., Muysenberg E.: Ceram. Eng. Sci. Proc. *14*, 139 (1993).
4. Vanandruel N., Deville M.: Proc. 2nd ESG Conference, p.85, Venice, June 1993.
5. Carvalho M.G., Nogueira M.: Silva P.: Proc. 2nd ESG Conference, p.619, Venice, June 1993.

Submitted in English by the author.

MATEMATICKÉ MODELOVÁNÍ NEUSTÁLENÝCH ZMĚN BARVY SKLOVINY VE SKLÁŘSKÉ VANĚ

NICOLAS VANANDRUEL

Unité de Mécanique Appliqueé (CESAME),
Université Catholique de Louvain,
Bâtiment Euler, Av. G. Lemaître, 4-6,
B-1348 Louvain-la-Neuve, Belgium

Matematické modelování dějů ve sklářských pecích se dosud zabývalo elektrickým příhřevem, probubláváním, přenosem radiačního tepla plamene atd. Při řešení neustálených stavů se může značně zvýšit složitost příslušných matematických modelů. Lze uvažovat různé zdroje neustálených stavů přenosu tepla: změny výkonu pece, časové změny intenzity probublávání a elektrického příhřevu, změny teploty skloviny a konečně i změny barvy skloviny. Vzhledem k zájmu sklářského průmyslu o modelování změny barvy [1] se tato práce zabývá řešením uvedeného problému neustáleného sdruženého mísení.