UNSTEADY NUMERICAL SIMULATION OF CIRCULATION AND HEAT TRANSFER IN A GLASS MELTING TANK

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Various numerical simulations are currently available for the representation of flow and heat transfer in glass melts. Increasing computer performance allows 3D complex simulation coupled with electrical boosting, flame radiation heat transfer, chemical reaction, bubbling, etc. We present the numerical results of unsteady modeling of glass flow and heat transfer in the glass melting tank. The use of finite-element spatial discretization decreases the total number of degrees of freedom required to achieve acceptable accuracy, while efficient integration schemes (implicit predictor-corrector) lead to time step sizes which reduce the number of solutions even for studies of long term duration.

First, different variations on the TC21 test-case (modification of the pull rate, thermal boundary profiles) are performed. This reference situation was selected by the 21st Technical Committee of the International Commission on Glass. Following this, a reduced-scale mixed electrical-fuel furnace is studied, allowing the modeling of unsteady boosting heat transfer. Finally an unsteady advection-diffusion problem is solved to represent the mixing of two different types of glasses. The interest in unsteady modeling is two-fold: (1) the accurate time evolution of flow and temperature sheds light on the structure and stability of the flow related to a given set of physical properties and boundary conditions; and (2) the transient solution gives reproducible and inexpensive information for the definition of a control process.

The main result of this study is the clear distinction between kinematic and thermal time constants and the feasibility of direct exchanges between unsteady simulation and control models.

SPACE AND TIME DISCRETIZATION

Glass tank modeling has been a topic of intense study in the last decade [1-4]. The spatial discretization selected for the thermoconvective simulation has generally been the finite volume method. We choose another technique for this study by using the environment of the Polyflow [5] finite element code.

As indicated by the high value of the Prandtl number, thermal boundary layers are observed even though the velocity field usually presents a smooth profile. For this reason, we select different interpolations for the velocity and the temperature unknowns. A quadratic thermal and a linear velocity interpolation (on the same grid) provide sufficient accuracy at a low CPU cost. The pressure is interpolated with constant discontinuous functions, ensuring the incompressibility of the molten glass. Time integration is performed through a predictor-corrector scheme. The implicit corrector allows large time steps, while analysis of the difference between predictor and corrector provides robust indication for time step variation.

TC 21[*]

The test-case of the TC 21

This test reference situation is the benchmark proposed by the TC 21 [6], for which several simulation models have been compared. In this case a small glass furnace (7 × 3 × 1 m) is considered with a pull rate of 50 tons/day. The viscosity law is an exponential function of temperature while a low constant thermal conductivity (30 W/mK) is imposed. The operating conditions are: a flat isothermal batch is located at $0 < x < 2$ m and parabolic output is imposed at the exit ($x = 7$ m; $0 < y < 0.25$ m; $1.2 < z < 1.8$ m); the temperature profile generates a global one-cell recirculation flow (see Figure 2a for the circulation patterns).

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

2D/3D simulations and conductivity effects

It is now generally accepted that 3D simulation is requested to embody the complex structure of molten glass flow in industrial melting tanks. However, 2D simulations still present some interest due to the advantage of a low CPU cost. For this reason, we will compare the 2D and 3D transient responses of the TC 21 model perturbed by two sudden modifications of the boundary conditions: (1) a 7 degree decrease of the temperature level; and (2) 10% increase of the pull rate. For all these simulations, the initial state is the steady-state of the reference TC 21 case. Figures 1*a-b* show the comparison between 2D and 3D results for the sudden decrease of the temperature level. A set of three reference points (x = 2.4 and 6 m; y = 0 m; z = 1.5 m) was selected. While the time constants of both 2D and 3D temperature evolutions are nearly equal (1 day), the spatial temperature distributions are quite different. The 2D simulation preserves the spatial temperature gradient

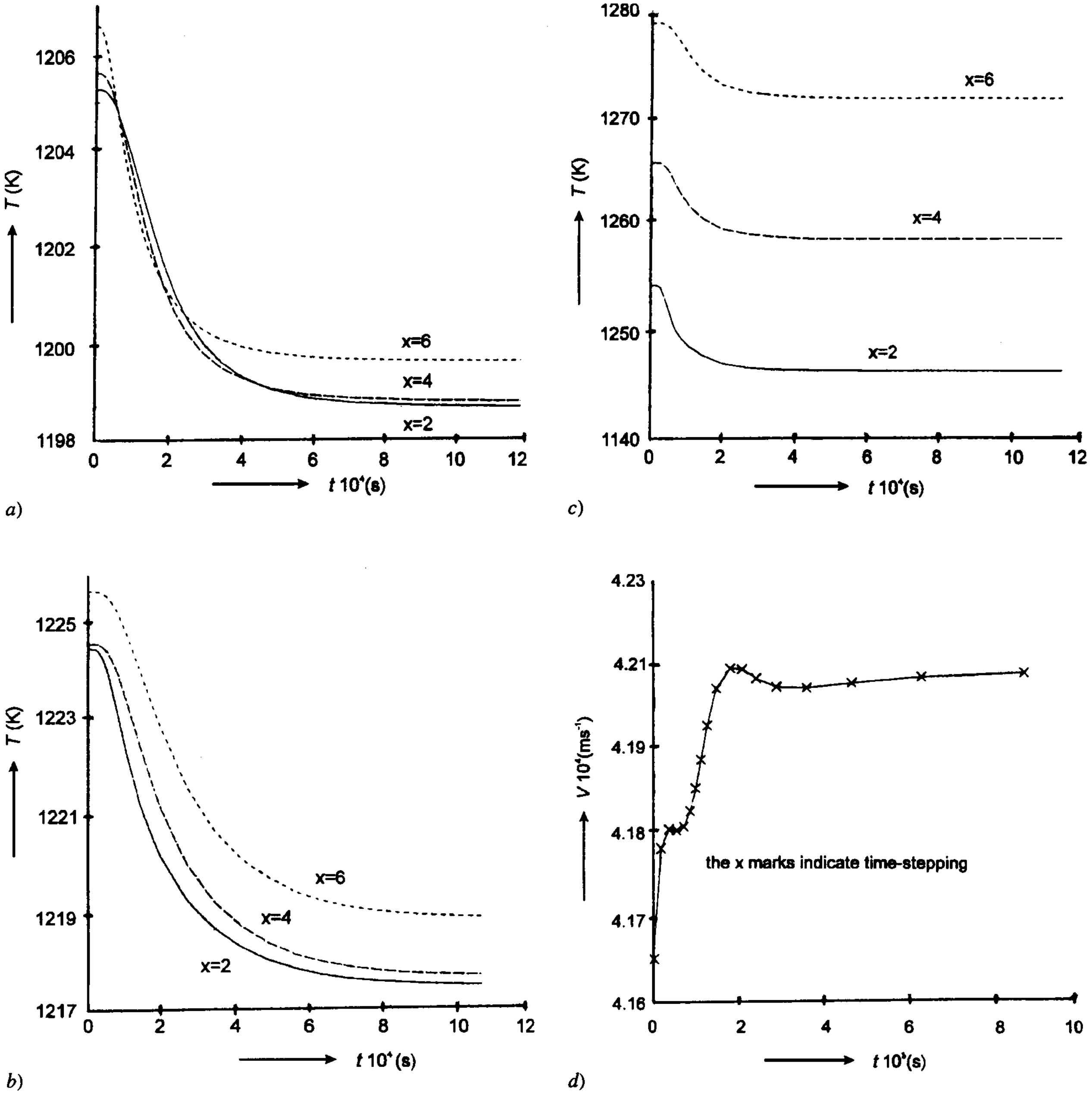

Figure 1. Time evolution of the TC21 test case
a) - 3D simulation of sudden temperature increase, temperature measured at x = 2,4 and 5 m (y = 0 m, z =1.5 m); *b*) - 2D simulation, same reference points; *c*) - 2D simulation, higher conductivity; *d*) - 3D simulation of sudden pull increase, U velocity at point x = 2 m, y = 0.5 m, z = 1.5 m

at the earth but 3D evolution gives a quasi-isothermal profile with spatial temperature modification. The velocity evolution (not reproduced here) yields a much lower value of the time constant (15 min). The value of the Prandtl number (150) appears, therefore, to be a good indication of the ratio between thermal and viscous time constants. A verification of this relationship can be found on Figure 1*c* where the simulation considers glass with a conductivity 3 times greater. As expected, the temperature evolution results in time constants reduced by the same ratio while no significant difference can be found for the velocity evolution.

A sudden increase of the pull rate produces the velocity evolution represented on Figure 1*d*. For this kinematic evolution, two time constants can be observed: a typical viscous reaction after 10 min., and the reorganization of the convection cells appears after 1 hour. This second evolution structure is not detected for 2D study.

Unsteady Mixing Simulation

When operating an industrial furnace, changes of glass types do not occur suddenly in the whole domain but an unsteady mixing is realized. Figure 2 shows the numerical simulation of the mixing evolution for the TC21 case. The concentration evolution is the result of an unsteady advection-diffusion equation. We choose a low diffusion coefficient (10^{-6}) an thus a high Péclet number (10^3) to show the accuracy of the numerical resolution. It should be noted that the concentration is not the result of a tracking calculation but another variable of the global set of partial differential equations. Depending on the concentration, the conductivity varies from 30 to 100 W/mK. Temperature evolution (not shown here) shows the effects of two time constants that can be observed on the concentration evolution. The advective dynamics-related to the velocity fields- produces a time constant of 15 min. while diffusion only acts for much longer term (3 days). Similarly with the comparison of thermal and viscous time constants, the ratio of the diffusion and advection time constants is related to the value of the Péclet number.

Unsteady Boosting Simulation

The second test case we consider is and unsteady simulation of a mixed electric-fuel melting furnace. A sudden potential difference imposed between electrodes generates an evolution of the thermoconvective currents and the temperature distribution. Figure 3*c* shows the temperature evolution for 7 points represented in Figure 3*b*. Steady state is reached after 14 hrs. Combined effects of thermal and viscous evolutions can be detected on the velocity profile (Figure 3*d*) where a rapid modification is then carried away by long-term boosting evolution. The succession of increasing potential, steady-state solutions is compared with the time evolution in Figure 3*e*. Clearly, no equivalence can be deduced between successive steady solutions and unsteady evolution.

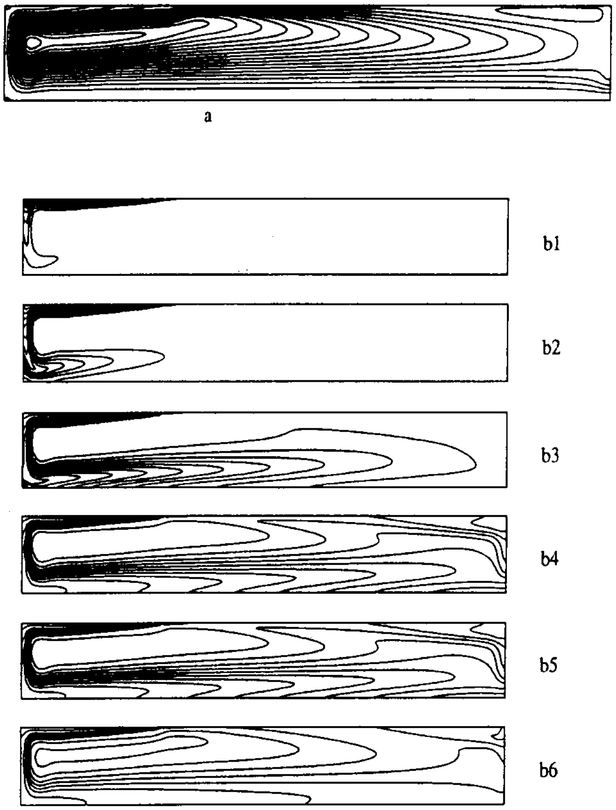

Figure 2. Time evolution of the concentration for Unsteady Mixing Simulation
a) - Isovalues of the stream function for the initial steady state;
b) - Isovalues of the concentration at different times: 1. - 10 min., 2. - 40 min., 3. - 3 hrs., 4. - 5 hrs., 5. - 8 hrs., 6. - 1 day

CONCLUSION

Unsteady simulations have been realized for glass melting tank reference situations. Accurate measurements of the thermal and kinematic dynamics are now attainable. In collaboration with regulation/identification studies [7], the regulation of a "numerical" furnace provides reproducible and inexpensive information for "industrial" furnace control.

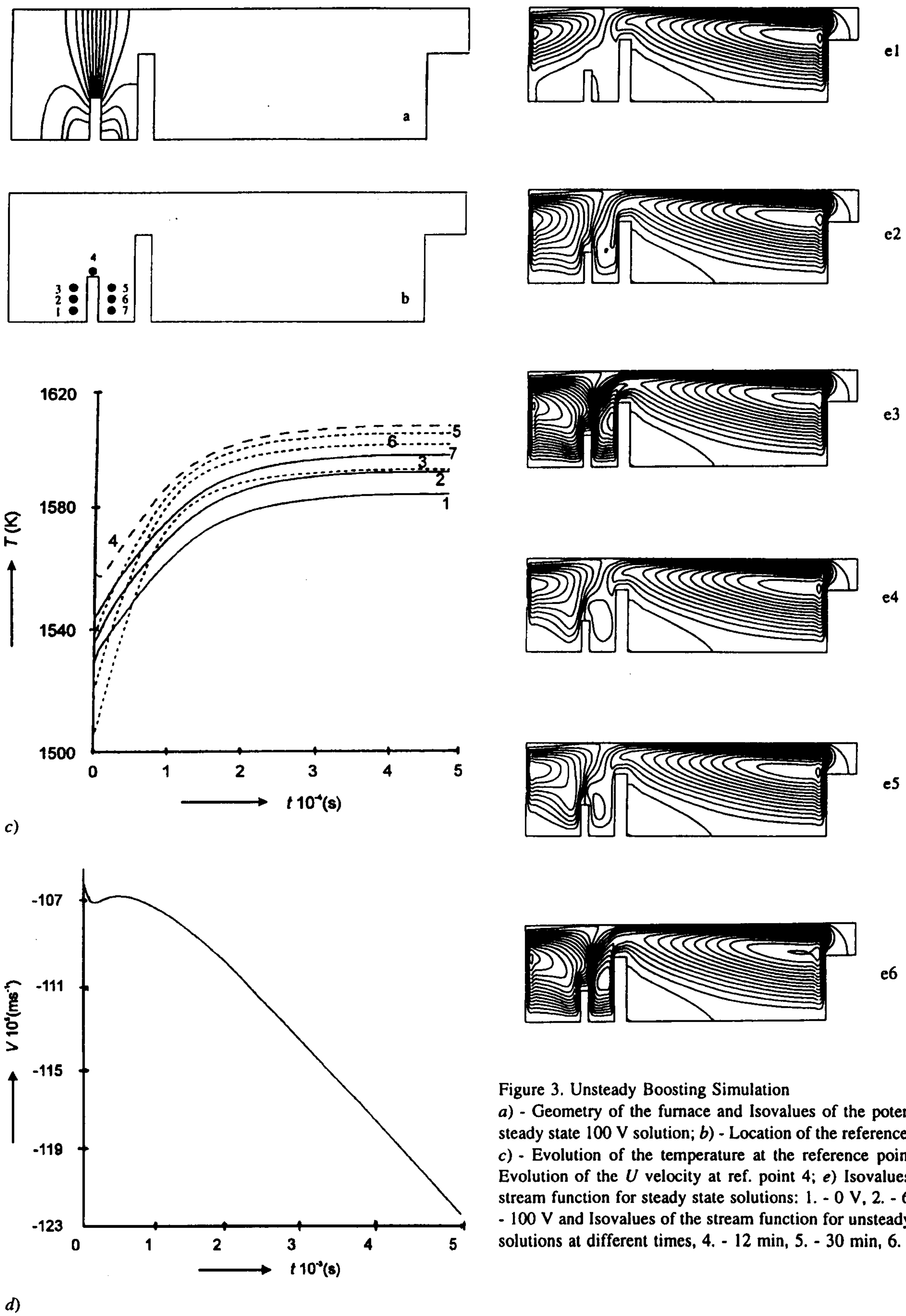

Figure 3. Unsteady Boosting Simulation
a) - Geometry of the furnace and Isovalues of the potential for steady state 100 V solution; *b*) - Location of the reference points; *c*) - Evolution of the temperature at the reference points; *d*) - Evolution of the *U* velocity at ref. point 4; *e*) Isovalues of the stream function for steady state solutions: 1. - 0 V, 2. - 60 V, 3. - 100 V and Isovalues of the stream function for unsteady 100 V solutions at different times, 4. - 12 min, 5. - 30 min, 6. - 5 hrs

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MATEMATICKÉ MODELOVÁNÍ NEUSTÁLENÉHO PROUDĚNÍ A PŘENOSU TEPLA VE SKLÁŘSKÉ PECI

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Pro popis proudění a přenosu tepla ve sklovině jsou v přítomné době k dispozici různé matematické modely. Zvýšená výkonnost počítačů umožňuje trojrozměrné modelování včetně elektrického příhřevu, přenosu tepla radiací, chemických reakcí, vlivu bublinek, atd. Zde uvádíme matematické řešení modelování *neustáleného* proudění taveniny a přenosu tepla v kontinuální sklářské peci. Použití prostorové diskretizace konečných prvků umožňuje snížit celkový počet stupňů volnosti potřebný pro dosažení přijatelné přesnosti, přičemž uplatnění efektivních integračních postupů (implicitní prediktory a korektory) vede k takovým velikostem časových kroků, které snižují počet řešení i pro delší časová období.

Nejdříve se řeší různé varianty zkušebního případu TC 21 (změny intenzity odběrového proudění, mezní tepelné režimy). Tento referenční stav byl zvolen 21. technickou komisí Mezinárodní sklářské komise. Poté je předmětem studia sklářská vana zmenšeného měřítka, s elektrickým příhřevem, umožňující modelování neustáleného přenosu tepla příhřevem. Posléze se řeší případ neustáleného případu advekce-difuze, který představuje mísení dvou odlišných druhů sklovin. Modelování neustálených stavů má dva cíle: 1) přesné časové podchycení průběhů proudění a teplot poskytuje informace o struktuře a stabilitě proudění v závislosti na daném souhrnu fyzikálních vlastností a mezních podmínek, a 2) příslušné přechodné řešení poskytuje reprodukovatelné a levné údaje potřebné pro definování procesu řízení.

Hlavním výsledkem této studie je jasné oddělování kinematických a tepelně časových konstant, a proveditelnost přímých výměn mezi modely neustálených stavů a modely řízení.