MODELLING AND CONTROL OF A GLASS MELTING TANK VIA NUMERICAL SIMULATION

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The results presented in this paper concern the analysis and the design of a controller for a purely numerical furnace. The mathematical nature of the simulated furnace allows a wide range of perturbations and an unlimited set of measurements. Although both the furnace and the identification tool selected for this study are simplified models, the design of complex control strategies for industrial process may also be tackled by this method.

Description of the Furnace and the Modelling Method

The furnace considered is the mathematically idealized box furnace defined as a first benchmark for the TC 21[*)] (figure 1). The physical properties of this test case are the following:

- Pull rate of 50 tons per day associated with a fixed zero-thickness melting batch,
- Exponential variation of the viscosity with the temperature,
- Constant thermal conductivity of 30 [W/mK],
- Flat input velocity profile at the batch, parabolic output at the throat,
- Imposed temperature profile at the melt surface, imposed flux at the refractory walls

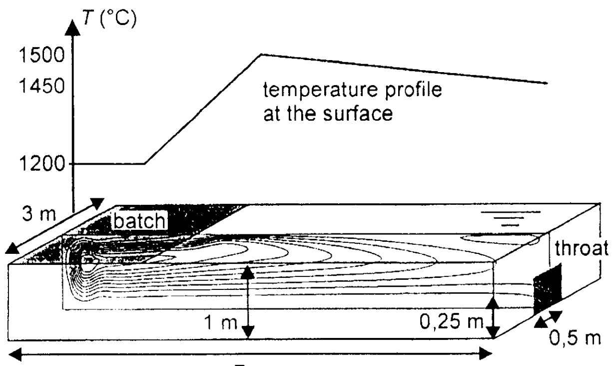

Figure 1. The TC 21 furnace.

The furnace geometry is depicted in figure 1 where the flow structure in the (assumed) plane of symmetry is also represented. As a result of the imposed temperature profile, the flow structure reveals globally a one-cell recirculation. The minimal residence time was estimated to be 6 to 7 hours.

The finite element grid used for this study contains $28 \times 28 \times 6$ ($L \times h \times w$) elements to decompose the computed half domain. A quadratic interpolation for the integration of energy equation leads to 32000 degrees of freedom for temperature to be added to a total of 18000 velocities and pressure unknowns [1]. Integration with respect to time is realized through a stable implicit scheme while a predictor-corrector method allows automatically variable time-stepping (and thus significantly reduces the number of time iterations).
The mathematical difficulty of this furnace model result mainly from the convective nature of the energy equation (high Péclet number flow) and the non-linearity associated with the variation of the viscosity with the temperature.

Periodic unsteadyness

A succession of unsteady calculations have been conducted by considering different periodic variations of the imposed surface temperature profile. The shape of the profile remains parallel to the initial profile while the other boundary conditions (heat flux, batch and output velocity) do not change with time. The amplitude of the surface temperature periodic variations was kept constant and equal to 70 K while the period varies from 1 hour to 1 month. The effect of the well-known regenerative cycle [2] (generally about 20 min) has thus not been studied here.

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

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After a startup-delay the numerical solution becomes periodic anywhere. The amplitude of the temperature variations are then measured at 5 different points located in the plane of symmetry. The positions of these reference points are, at mid-length of the furnace and 1) 10 cm, 2) 20 cm, 3) 30 cm below the surface, 4) at the surface bottom and, finally, 5) at the throat output (figure 2).

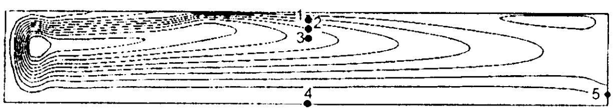

Figure 2. Position of the 5 reference points in the plane of symmetry.

A quantitative measure of the attenuation of the temperature periodic evolution is realized by dividing the measured amplitude by the imposed variation amplitude at the surface. It is then possible to study the evolution of that ratio (or gain) for different values of the period.

The measured temperature gains for the 5 reference points are represented in figure 3. On this Figure, ω is the pulsation ($\omega = 2\pi/T$ where T (s) is the period of the surface temperature variation). Although this representation is close to a Bode diagram the selected Y-axis measures the log of the gain instead of the classical 20 log expression. Another and more important difference is the non-linear nature of the presented result: reported values are obtained for the above mentioned operating conditions and become rapidly invalid for different variation amplitudes or temperature levels.

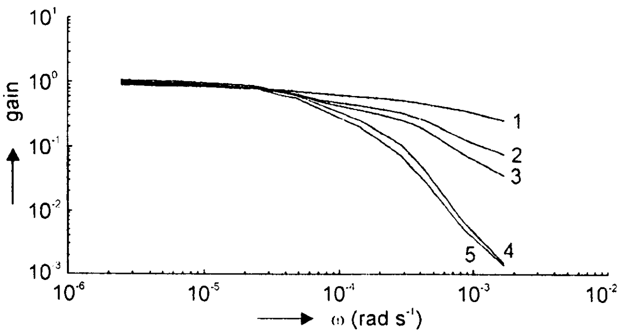

Figure 3. Temperature Bode diagram for the 5 reference points.

The most important result illustrated in figure 3 is the shape of the different gain curves.

From numerical experiments (i.e. variations of the conductivity, modification of the temperature profile [3]) it had been previously observed that, due to their respective positions in the furnace, the temperature evolution of the points 1), 2), and 3) is mainly driven by diffusion while temperature evolution at the bottom and at the output (points 4) and 5)) is rather the combined result of convection and diffusion. That assumption may now be quantified.

Typical values of thermal and viscous time constants have also been estimated through different numerical simulations [3]. It has been shown that convection is acting within hours while thermal equilibrium may require some days to reach a steady state. The ratio of thermal and viscous time constants is approximatively given by the Prandtl number (in this case Pr = 150).

Different control strategies have been proposed to increase the quality of molten glass produced in melting tanks. In that context, the importance of the knowledge of bottom temperature evolution has been previously established [4]. For this reason, the gains measured at the bottom of the furnace (point 4)) will be detailed (figure 4).

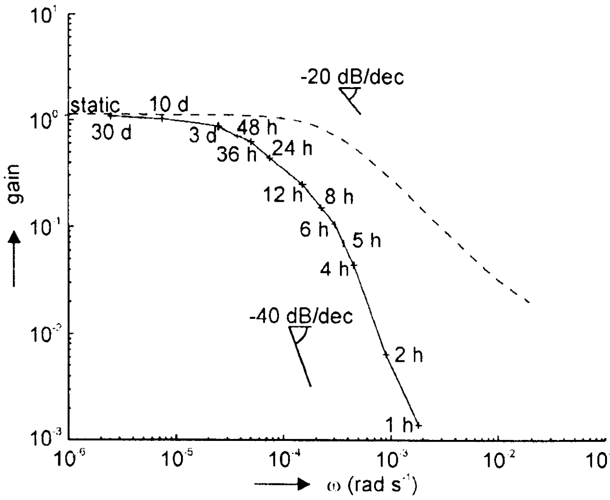

Figure 4. Bottom temperature Bode diagram.

On the figure 4, the evolution of the slope seems to indicate a two poles transfer function between bottom and surface temperature. A first pole is located within the range of 2 to 3 days while another pole lies more clearly between 6 and 8 hours. These values are to be compared to the above mentioned time constants for temperature and velocity or, more quantitatively, to the minimal residence time. The bottom temperature dynamics results thus from short- and long-term interactions.

Furthermore, the first 3 reference points do not present the some evolution (figure 3). For those points, only a one pole dynamics seems to be relevant.

The computational cost of the Bode diagram is important: each of the reported values is the result of an unsteady calculation coupling the 50000 temperature, velocity and pressure unknowns. Typical number of time steps is 200 to 300 to ensure that the periodicity is fully developed.

A similar diagram for the phase shift cannot be obtained without excessive care in the time integration (an enormous computational costs). Classical time integration methods are unable to give phase shift information with acceptable accuracy.

The static gain measured for the bottom temperature is slightly greater than one. This results from the interaction between temperature and velocity that reorganizes the flow structure and modifies the temperature profile at the bottom. This flow shifting is already observed for slowly variating surface temperature profiles (period greater than 1 month).

Process simulation

Despite their meaningful representation, Bode diagrams are generally not available for identification and control of an industrial process. While a succession of periodic evolution of one input is almost always economically and technically unpracticable, a single set of successive steps may generally be tested on industrial equipments.

A more realistic unsteady simulation was therefore conducted.

Figure 5 shows the evolution of the temperature profiles for a time interval up to 8 days containing a succession of 9 steps imposed at the surface. The sampling period selected is 5 minutes.

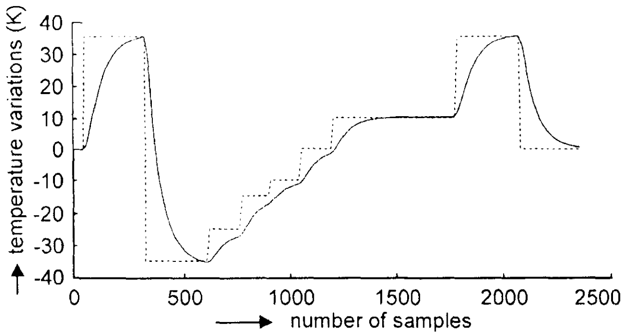

Figure 5. Evolutions of surface (dotted) and bottom (full) temperature.

With these time evolutions, it is a simple exercise to find a model that selects the surface temperature as input and the bottom temperature measurement as output. A first order model already provides a non predictive accuracy within 5 K. The Bode diagram of this first order model is represented (dotted lines) in figure 4. The only pole contained in that model lies at 7 hours. It seems thus that the long-term contribution could be neglected without affecting the accuracy of that first-order model.

Consideration of multivariable identification and control may take full benefit of this kind of numerical experiments.

Velocity periodic evaluation

Velocity measurements are less commonly used in furnace control. The mathematical nature of the furnace allows however to detail the evolution of the velocity with periodic variation of the surface temperature. Figure 6 represents the Bode diagram for the horizontal (axial) velocity measured at the surface at mid-length of the furnace. An increase of the velocity variation amplitude is observed for periods smaller than 4 hours. Sudden velocity overshoots [3] seem to explain these short-term variations.

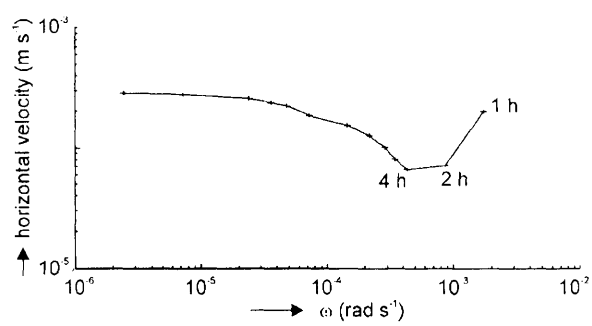

Figure 6. Surface horizontal velocity Bode plot.

Conclusions and future works

The main result of this study is the quantitative measurement of time constants acting on the complex thermoconvective equilibrium that takes place in melting glass furnaces. The relevancy and accuracy of control strategy may be measured within the mathematical laboratory of furnace modelling. The consideration of industrial furnaces should include a list of sub-models (refractories, batch, crown, ...) which may add their own time constants.

Acknowledgment

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MATEMATICKÉ MODELOVÁNÍ A ŘÍZENÍ PROVOZU VANOVÉ SKLÁŘSKÉ PECE

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Výsledky uvedené v tomto příspěvku se týkají analýzy a konstrukce systému řízení pro čistě počítačový model sklářské pece. Tento model umožňuje zvládnout široký rozsah provozních výkyvů a získat nekonečné množství měřících údajů. I když jak matematický model pece tak identifikační nástroje jsou zjednodušené, lze metodu použít pro navrhování strategie komplexních systémů pro řízení průmyslových procesů.