

Modelling of glass melting industrial process

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The present paper emphasizes the potentialities of the industrial use of three-dimensional mathematical modelling of glass melting tanks for optimization of working conditions, design and control of industrial furnaces. A short review of related recent relevant works is presented and industrial needs and requirements in modelling are discussed. A modelling procedure to solve the heat and mass transfer in glass melting furnaces based on the integrated treatment of physical phenomena in combustion chamber and glass melting tank is presented. An application example is provided.

INTRODUCTION

Glass is normally produced in open-hearth furnaces in which the glass constituents are flame-heated from above to form a melt. The raw materials, sand, limestone, aragonite, dolomite, soda ash, alumina, and recycled glass are fed into the furnaces through a continuous or intermittent feeding system. The charge reacts and melts, and subsequently exits through the feeders at the opposite end of the furnace.

The product quality, efficiency, pollution and equipment durability awareness gave a strong motivation for the development of sophisticated modelling procedures able to handle the complex character of the industrial glass-melting process. In next chapter an overview on last years achievements in this field is summarized.

OVERVIEW ON MODELLING OF GLASS MELTING TANKS

Improvements in the glass tank design and operation have to be based in an enhanced knowledge about the thermal phenomena occurring inside the glass melting tank. Measurements of velocities and temperature are particularly difficult to obtain in real glass melting tanks. The main reasons for that are the high temperature levels typical in such equipment and to the corrosive character of the glass-melt. The use of physical models is limited by the difficulty of having a confident scale-up of the several properties involved mainly due to the importance of the radiative transfer and the peculiar glass viscosity behavior. Therefore, mathematical modelling of glass melting tanks coupled with combustion chamber models, appears as a consistent alternative to the development of engineering tools able to support the improvement of the working conditions. Last decades developments in numerical solution methods and in the computational availability allow the development of reliable models able to represent whole the three-dimensional studied domain and to interpret a large number of effects which must be considered in a glass quality improvement effort, as discussed by Wall [1] and Meunier [2].

Several recent achievements in the field of numerical modelling of industrial melting furnaces have been published. Most of these works report developments aimed to supply engineering tools able to support the study of optimized solution to improve industrial furnaces. Several recent publications are referred below.

McConnel and Goodson [3] presented a simplified model of whole the furnace system. Three energy equations were solved for the crown, batch and refractory temperature. The radiation in the combustion chamber was calculated through the Hottel zone model. For the glass-melt, streamlines pre-defined patterns were assumed. The radiative heat transfer was described by a temperature dependent effective thermal conductivity. The results were compared with operating data indicating a very good agreement.

Following a similar approach, Mase and Oda [4] solved the 2D flow and temperature pattern for a glass-melt. The batch velocity was considered constant and an energy balance equation was solved for the temperature. The combustion chamber temperature was formulated by using Hottel's zone method as in the previously referred work.

In the previous works the heat transfer in the combustion chamber was treated in a very coarse way. Gosman et al. [5] presented a prediction procedure for a glass furnace combustion chamber in which the 3D flow field, together with the reaction and heat transfer — using the discrete transfer method was solved. The prediction agreed with the few isolated data existent for the crown and exhaust temperature. Extending this modelling approach Carvalho and Lockwood [6] simulated an oil- or gas-fired end-port furnace. This work was used to evaluate the operative differences between both firing modes [7]. The use of the discrete transfer method allowed the accurate prediction of the effect of non-uniform fields of radiative properties of the gas in the combustion chamber enclosure. This feature is of particular importance when sooty (oil flames) are predicted.

Extending the principles above referred to 2D model of glass-melting tanks, Simonis et al. [8] presented a detailed 3D model of glass melts. This 3D model allowed the prediction of molten glass residence times in industrial furnaces. This was a significant development since the residence time is one of the critical parameters in the control and operation of glass melting furnaces.

Combining a 3D modelling procedure of the glass-melt flow with several sub-models, Urgan and Viskanta [9] presented a sophisticated model of the circulation and heat transfer in a glass melting tank in which air bubbling, electric boosting and glass melting were considered. A detailed modelling procedure for the batch melting reactions was proposed. Glass refining process was simulated predicting the size distribution and number density of gas bubbles. Comparisons with results from physical models indicate very good agreement. A zonal model for the radiative heat transfer in the combustion space was applied.

Using a modelling procedure based on the Finite Element Method, Murnane [10] published 3D results of temperature and flow calculation in molten glass.

The detailed modelling of the phenomena occurrent in combustion chambers is a basic requirement for a realistic prediction of the working conditions of glass melting furnaces. Post and Hoogendoorn [11] proposed a 3D modelling procedure for turbulent flow and heat transfer in the combustion chamber of a glass melting furnace. The radiative heat flux was modeled by the Hottel's zone method. The radiative heat transfer model was compared against a well-stirred furnace model.

The use of modelling to study product quality require, among other aspects, the detailed study of the several phenomena involved in glass finning. Simonis [12] linked a 3D glass-melt flow model with a method to calculate the redox distribution based on the concentration of the fining agents. The model was applied to an industrial glass furnace for which two study batches with redox number 0 and -20 were tested. Nemeč et al. [13] used a 3D model of the glass-melt flow to study the sand dissolution and a single gas bubble behavior in a simulated flat glass melting tank. The study was aimed to find more favourable types of glass flow for intensive melting in tanks with controlled glass convection.

Carvalho and Nogueira [14] proposed a 3D integrated model of the turbulent flow, combustion, heat transfer and pollutants formation in the combustion chamber, and buoyancy driven glass-melt flow and air bubbling in the melting tank. A result interpretation methodology was suggested to relate results of 3D modelling with glass quality indexes. The model was used to test the effect on the expected quality of the glass production of several changes in current operation parameter (e.g.: fuel injection) and design parameters (e.g.: location of a step in the tank).

Wang J. and Zhou Z. [15] proposed a detailed 2D model of flow and heat transfer in symmetrical glass melting tanks. The model is based in a very accurate numerical solution and presents an excellent

agreement with the experimental data gathered in a physical model. The numerical model was applied to study several improvements in glass melting tank geometry.

Combining the feature of the models described in [8] and [11], Muysenberg et al. [16] presented a complete glass tank model in which a sub-model for the heat transfer for the combustion chamber to the glass-melt is included. The model follows the conventional finite-volume approach to solve the flow and Discrete Transfer Model to simulate the thermal radiation in the combustion chamber. The tank model includes melting kinetics, redox and refining, interaction with the refractories and foam presence. Using the model the effect of variations in the extinction coefficient of combustion products were analysed. Beerkens et al. [17] uses this modelling procedure to a detailed study of the degassing process considering the bubble behaviour determining the influence of redox state, temperature and concentration of fining agent. This study was applied to sulfate refined glass-melts.

Dente et al. [18] applied a glass batch model to predict the batch surface coverage and batch blocks consumption. Some simplifying hypotheses for the behaviour of batch-melt have allowed to solve the heat transfer equation and to deduce the values for the floor temperatures. The interaction with the combustion chamber allowed the prediction of crown temperatures in discrete positions. The results obtained compare in a satisfactory way with several data of real industrial furnaces.

In spite of all the developments above referred, the mathematical formulation and numerical solution of modelling procedures still requires further developments. Research work is required in the following areas: Flow modelling. The solution of buoyancy driven flow still requiring some developments aimed to improve the stability and robustness of the modelling procedures specially if radiative diffusivity is predominant. Batch melting. This is one of the most complex phenomena occurring in glass furnaces for which still having a strong demand for a 3D model of the transport process considering detailed formulation to treat reactions and rheology.

Fining and Refining. More general and accurate models are required for the calculation of local redox, bubbles growing, gases dissolution and diffusion, bubbles life.

Foam formation/elimination. Reliable models for foam formation are required to make possible an accurate calculation of the heat transfer from the combustion chamber to the glass-melt. Special attention has to be given to the radiative properties of foam.

Homogenizing. There is a strong demand for an accurate simulation of the formation of heterogeneities (specially due to the convection of silica grains in the melt) and stretching-diffusion process combined with the flow 3D calculation and linked with the presence effect of the presence of bubbles and seeds.

Refractories. An accurate calculation of the refractories dissolution requires the prediction of the heat transfer process and concentration of chemical species near the wall region. The actual geometry of the refractories/melt interface still representing a difficulty to the development of an accurate model.

Radiative transfer. Radiation is the predominant heat transfer mode in the melt. Radiative diffusivity approximation is not sufficiently accurate. There is a real demand for a novel procedure to simulate radiation in glass-melting tanks.

Mass transfer between the melt and the combustion chamber. This topic was not considered in the known 3D models which link combustion chamber and glass tank 3D model. A model able to handle this aspect is required in order to allow the prediction of vaporization and seeds entrainment.

Experimental extensive characterization of real glass-melting furnaces is strongly needed to support the developments of new sub-models and to allow the validation of integrated models.

At the present developing stage modelling is becoming a powerful tool to solve operative troubles in industrial glass melting furnaces as well as to help the innovative design of more efficient furnaces. The use of modelling to improvement and new ways of glass melting is discussed by Nemeč [19].

INDUSTRIAL REQUIREMENTS OF MODELLING

The industrial relevance of using mathematical models is mainly related to a possibility of to predict accurately the effects of modifications in the furnace geometry and operation conditions. Benefits from the use of mathematical models can be significant in the following areas: improvement of molten glass quality levels, reduction of energy consumption, pollutant emissions abatement, reduction of thermal stress in the structure, decrease of the entrainment of particulate materials from the melt and the batch, limitation of the

cost of the equipment, increases in the operating flexibility (allowing efficient operation at intermediate pull rate levels).

Sophisticated 3-D mathematical models are available. However, there is several aspects where future work is required to improve the applicability of the models, their robustness (in particular for design applications), their capacity to be used by process engineers (and not necessarily model engineers), their accuracy and adaptability for intricated geometries, as discussed by Anterion [20].

The model capacity to give practical answers to industrial problems is limited by the accuracy of the involved sub-models and the limited capacity of the numerical solution procedures to deal with complex geometries. The steady state character of the current modelling procedures also constitutes a limitation for a realistic description of the real working conditions. The computational time required to run the models continues making difficult the current use of modelling procedures.

Future work in modelling may be aimed to solve the above referred limitations. Several topics for further developments may be listed as follows:

- extensive validation of the well accepted modelling approaches against data gathered in industrial furnaces allowing a confident application in design.
- generalization of integrated modelling procedures considering combustion chamber, batch and glass melt.
- use of non-orthogonal grid systems allowing models able to solve real geometries.
- continued developments of the individual sub-models — radiation, combustion, turbulence, pollutants formation, batch melting — and improvement of their interactions.
- integration of new sub-models aimed to embody glass quality simulators.
- extention of the computational domain integrating in the same model forehearts, regenerators and refractories.
- application/development of numerical algorithms for faster convergence.
- improved treatment of thermophysical properties.

Future developments will be strongly driven by the interest of the industry in the mathematical modelling approach. This interest is a reality and part of them are using modelling procedures (e.g. Saint Gobain, Corning, Pilkington, Siseecam, Asahi, Schott, among others). Several design and consulting companies have in last years starting to accept mathematical modelling as a current engineering tool (e.g. Sorg, STEV, Glass Service).

A PHYSICAL - MATHEMATICAL MODEL FOR GLASS MELTING TANKS

The complexity of the phenomena occuring inside a glass furnace and the strong and complex interlinks between the different sub-domains (combustion chamber, batch and glass tank) require the use of a three-dimensional numerical procedure able to predict the whole furnace in a integrated way. Such modelling approach was followed in the presently referred work, which embodies sub-models able to deal with the turbulent combusting flow and thermal radiation in the combustion chamber, and in parallel, with the laminar buoyancy driven flow, air bubbling, radiation transfer in the glass-melt tank, as well as with the fusion rate distribution of the batch unmelted materials floating over the melt.

In the following sections the individual modelling procedures for glass-melt, batch melting region and combustion chamber are described. Particular emphasis will be given to the glass-melt model.

Glass-Melting Tank

The thermal fluid behavior of the glass melt is predicted by solving the governing partial differential equations set in its steady-state time-averaged form. Transport of momentum, mass and energy, is solved for the 3D space taking a general conservation equation which may be stated as:

$$\operatorname{div}(\rho \vec{u} \phi) = \operatorname{div}(\Gamma_{\phi} \operatorname{grad} \phi) + S_{\phi} \quad (1)$$

where ϕ represents the transported scalar, ρ the specific weight, \vec{u} the velocity vector, Γ_ϕ the diffusion coefficient and S_ϕ denotes the source term. The quantities which ϕ , Γ_ϕ and S_ϕ stand for each differential equation are referred in table 1.

Table 1. Transport equations.

EQUATION	ϕ	Γ_ϕ	S_ϕ
CONTINUITY	1	0	0
MOMENTUM	u_i	μ	$-\frac{\partial p}{\partial x_j} \delta_{ij} + \frac{\partial}{\partial x_i} \left(\mu \frac{\partial u_j}{\partial x_i} + \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) + g_i (\rho - \rho_0) + \dot{S}_{u,B}$
ENERGY	h	$\Gamma_{h,eff}$	$\dot{S}_r + \dot{S}_{h,B}$

The formulation above is based on the following main assumptions:

- the glass-melt may be considered as a newtonian flow;
- the glass melting tank is steady state;
- Bousinesq approximation is followed.

This approach is detailed in [7, 21, 22, 23].

Radiation Model In the present model the radiative fluxes are considered as expressed in terms of an integral over the wavelength. Therefore the radiative transfer is assumed as a transport of energy rather than the direct solution of radiation.

Current glass has significant metal contents and, consequently, is a highly absorbing media. Such fact is indeed fortunate since allows the solution of the radiative transfer phenomena in glass-melts as a diffusion process. This approach, which yields a large computation effort saving, was used in earlier two dimensional models. However near the boundaries, or in general, near the discontinuities, such diffusive radiation approach is not easily applicable as discussed in [24,25]. In the present work a straightforward correction to the diffusion model near boundaries is proposed, based on the assumption that that, even in clear glasses, the radiation exchanged directly between surrounding surfaces is not significant.

The radiative and conductive transfer in the bulk glass was handled using an effective radiation plus conduction diffusivity coefficient in the energy equation (see Table 1).

Near the walls and the free surface, a different treatment, considering one-dimensional transfer, is used, providing a radiative source to be included in the energy transport equation. This source is given by the radiation attenuation law in a diffuse media and corresponds to the imposed flux boundary conditions for the glass-melt. In the free surface, the imposed flux condition corresponds to the net radiation flux exchanged with the combustion chamber. Below the batch region, the melting (transition) temperature is imposed.

Those assumptions are valid in optical thick media, which is the case of the considered type of glass. The absorption coefficient, K , was assumed to vary linearly with the glass temperature.

Air Bubbling Model The air-bubbling is used in glass melting tanks as a way to improve glass mixing, molten glass residence time and provide an actual barrier able to avoid unmelted parts presence in tank back region. These effects are obtained by injecting air through a bubblers row placed transversely. Such

injection causes a rising flow of air bubbles, independent of other eventual gaseous presence in the glass melt.

The present air bubbling sub-model is directed to predict the effect on the glass-melt flow of forces due to the air flow. Therefore, particular attention was dispensed to the heat and momentum transfer terms, which are present in table 1, as source terms, respectively $\dot{S}_{h,B}$ and $\dot{S}_{u,B}$.

To describe the air-bubbling effect same approximations are considered:

- Horizontal components of forces due to air bubbles flow are neglected.
- Air-bubbles have a spherical shape.
- Coalescence is not considered.
- The number of released air-bubbles is proportional to the injected air flow rate.
- The rising velocity is given by the air bubble terminal velocity.

The air temperature, the terminal velocity, the specific weight, the bubble radius, the force acting on the glass-melt flow and the heat transferred with the glass-melt are calculated along the bubble trajectory. In the present model the bubble properties are considered, for a given position, as time constant, i. e., the weak fluctuating nature of this two phase flow is neglected. The bubble rising velocity, u_b , has been taken from the terminal velocity concept. At injectors exit a temperature of 363K is estimated (bubblers are normally water cooled).

Combustion Chamber Model

The heat transfer, fluid flow and combustion phenomena occurring inside the combustion chamber were predicted by solving equations for the mass continuity, transport of momentum, energy, turbulent quantities, reactants and combustion products, soot and nitric oxide concentrations. Details of this sub-model are given in [7, 21, 22]

Sub-models for turbulence, combustion, thermal radiation, soot and NO production/dissipation are required. The adopted combustion modelling approach is based on the ideal of a fast single step reaction. A statistical treatment to describe the temporal nature of the air/fuel mixture fraction turbulence due to fluctuations was considered [26]. The turbulent field was predicted through the well establish two-equation, "k-ε" model [27].

Radiation Model The "discrete transfer" radiation prediction procedure [28] was utilized in this study. Such method combines ease of use, economy, and flexibility of application. This last feature is of particular importance in the real world of geometrically intricate combustion chambers. The "discrete transfer" method is founded on the direct solution of the radiation transfer equation for one direction:

$$\frac{dI}{ds} = (K_g + K_s) \left(\frac{\sigma T^4}{\pi} - I \right) \quad (2)$$

where I is the radiation intensity, s is a distance, and K_g and K_s , the gas and soot absorption coefficients. That relation was applied along a chosen direction (representative of a discrete solid angle), from a boundary, where the emitted flux is assumed known (from a last iteration, for instance), up to the opposite boundary. From each considered emission point, on a boundary, a number of "rays" is emitted dividing the visible space in discrete solid angles. Each of those "rays" is considered representative of partition of the visible hemisphere, within which the intensity is considered to be uniform. On the opposite wall, the arriving flux is the summation (over each surface zone in which the walls are divided), of the arriving radiative intensity from all the directions. For a given position in the enclosure, the energy gain (or loss) due to radiative transfer is the summation over a considered volume zone (representative of such position) of the radiative intensity decay (or increment) on all directions crossing it. This summation is noted in Table 1, by S_r , as a volumetric power source in the energy transport equation.

The gas and soot absorption coefficients, K_g and K_s , were calculated from the "two gray plus a clear gas" model due to Truelove [29], which takes in account the spectral dependence of K_g .

Batch Melting Region Model

In glass-melting furnaces the batch (composed by a mixture of sand, cullet and other materials) floats over the melt covering a significant part of the molten glass volume. Glass furnaces may be fed from side or back walls. A batch continuous blanket is normally formed near the feeding port. Depending on the operating conditions, furnace geometry, type of glass, batch composition (raw materials/cullet) this batch dense region may be divided into a large number of islands spread over the glass melt surface flow.

Modelling of the batch dense region The batch melting blanket floating over the melt was modelled as a two-dimensional flow where three different substances are present: frit, cullet and molten glass. The frit and cullet are assumed to behave as solids. A conventional viscosity law was used to the molten glass formed over the batch blanket.

In practice, the cullet consists of discrete pieces of broken glass of irregular shape and size. There is air in the spaces between the glass pieces and thus the bulk properties of the material are not the same as those of the glass. Both the density and the thermal conductivity of the cullet are corrected to account for the presence of air.

The frit is presumed to behave as an inert solid up to 850° and at this temperature the frit reacts to form liquid glass. The phase-change (endothermic reaction) is assumed to occur over a finite but small temperature range. In similar manner the treatment of the melting process is controlled by the cullet temperature. When the calculated cullet temperature reaches a prescribed value, the cullet is assumed to change phase and form a liquid. The present model was solved in a parabolic basis along the streamwise direction. Details of this model are given in [21].

Modelling of the melting rate for a given batch distribution The complexity of the glass-melt and combustion products flow in the vicinity of the batch melting region, the eventual intermittent batch feeding and the periodical change of the firing side cause the splitting of the batch unmelted parts in a group of dispersed floating islands. Such feature of batch region is particularly difficult to predict, aspect which may be easily confirmed by the absence of models capable of handle this phenomena.

In the present work the shape of batch melting is prescribed through the definition of functions which represents of the distribution of the batch over the melt of ψ defined as:

$$\psi = \frac{\text{Local area occupied by batch unmelted parts}}{\text{Total local area over the glass-melt}} \quad (3)$$

For a given furnace configuration, the stationary shape of the melting region, which may be affected by accidental unstable effects, is mainly dependent on the batch composition. Typical stationary batch distributions may be taken from observations through a video CCD camera which are often installed in industrial glass furnaces.

The mass transfer between the batch region and glass-melt flow, (due to the vitrification process) takes place through two different mechanisms: i) under the batch blanket (or islands) the molten mass transfer is due to the melting supported by the heat exchanged between batch and ii) the molten glass originated in the top layer is transferred to the glass-melt after flowing over the batch dense regions.

The batch melting rate is calculated through local heat and mass balances considering the melting process as a single step transformation. In order to conserve the overall batch mass balance, the calculated local molten rates are normalized by the batch inlet mass flow rate. An empirical expression was estimated to represent the impossibility of glass, molten at batch top surface, entering in the melt flow crossing the dense region ($\psi > 0.95$). Details of this model are given in [22].

Glass Tank/Combustion Chamber Coupling Algorithm

The whole glass furnace was calculated decomposing the domain in two parts. One part concerns the combustion chamber and the other the glass melting tank plus batch region. A parallel procedure, in which two processes are sharing a memory block, was adopted to deal with the above referred decomposition. The interface zone is, in the physical system, coincident with the glass-melt free surface and top layers of the batch unmelted floating parts.

The interface variables are the temperature field and the distribution of the heat fluxes crossing the interface between the combustion chamber and glass or batch. These relevant variables were set in the above referred shared memory block together with relevant geometrical information. Specific conversion procedures had to be developed, since the fluxes and temperatures should be defined on both, combustion chamber and glass tank, computational grids.

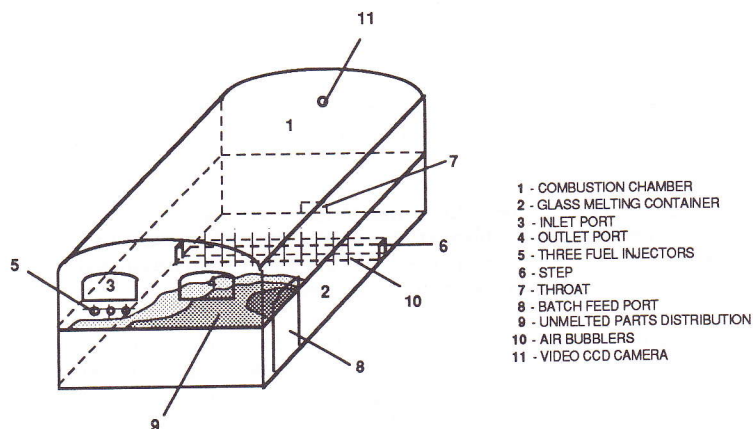
Numerical Solution

A finite volume methodology was used to solve transport equations summarized in table 1. The velocities and pressures are calculated by a variant of the SIMPLE algorithm [30]. Advantages of SIMPLE algorithm are mainly the robustness and the simplicity of implementation which does not imply further additional memory requirements, when compared with other similar algorithms as detailed in [31]. Each individual equation set was solved by a form of Gauss-Seidel line-by-line iteration.

Example of industrial application

The industrial case The present model was applied to an industrial glass melting furnace installed in a plant where glass bottles and other containers are produced. The furnace which is of the end-port regenerative kind, is sketched in figure 1. The batch enters via (8), while the molten glass exits from the throat (7). The step (6) and the air bubblers row (10) are used in order to provide a division able to prevent the batch unmelted parts displacement towards the back regions of the furnace and improve the mixing. Typical values, which describes the essential features and the operation pattern of the furnace, are as follows: fuel flow rate - 0.18 Kg/s; air inlet temperature - 1325°C; batch feed rate - 90t/day; inlet batch temperature - 40°C.

Figure 1. Sketch of the studied furnace.



Results In the present section results of the application of the 3D model above referred are presented. To complete convergence (residual fluxes of all the transported variables below 0.5%) 956 iterations were required. The predicted velocity field is plotted in figure 2 considering three planes in the first half of the furnace. The flow is represented by trajectories of marker particles imaginary seeded in every grid node. The time step referred in the figure indicates the time during which those particles are followed. The effect

of air bubbling in the mixing of molten glass is evident in the central region of the tank. The buoyancy effects are predominant in the region below the batch coverage. In the back region of the tank the flow is mainly driven by the convective effects due to the presence of the outlet. The combined effects of the step and bubbling creating an actual division between the tank melting and refining regions is well apparent in the figure. An effective division between the melting-refining region and the homogenizing region is therefore achieved. However, air bubbling typically causes the presence of high velocities near the refractories as may be seen in the first plane in the figure. This effect is also driving the melting region to a well accommodated position. Air bubbling has also a strong mixing effect in the melt which will improve homogenization of the produced glass and reduce the level of the hot spot in the glass surface with positive consequences for the thermal efficiency.

In figure 3, the temperature field is plotted using the same plans as in the previous figure. Temperature is by far the more important parameter in the glass refining and homogenizing process. The effect of air bubbling produces a thermal barrier above the bubblers row, which is due to the rising flow of cooled glass from the tank deeper regions. That barrier effect is well visible in the surface where the temperature is uniformed. Cold regions below the batch coverage (visible in figure 3) are responsible by the downwards flow occurring there (visible in figure 2) since in this region buoyancy is the dominant effect (flow driving mechanism).

CONCLUSIONS

In the present paper, an overview on modelling of glass melting furnaces is provided. Several modelling procedures reported in the open literature are referred. A three-dimensional model able to deal with the phenomena in glass-melting tanks (considering air bubbling, radiation and melting) and combustion chambers (considering radiative heat transfer, combustion, pollutants formation and turbulent flow).

The advent of advanced physically-based multi-dimensional models of the processes occurring in glass furnaces offers new possibilities of improvements in operation. Useful information, from the point of view of optimization of glass quality, pollutant emissions and thermal efficiency, may be extracted.

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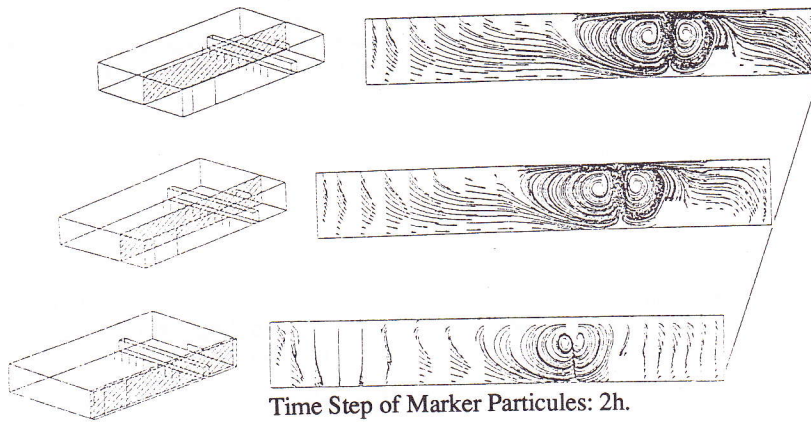


Figure 2 Glass-melt flow pattern inside the melting tank of an end-port furnace.

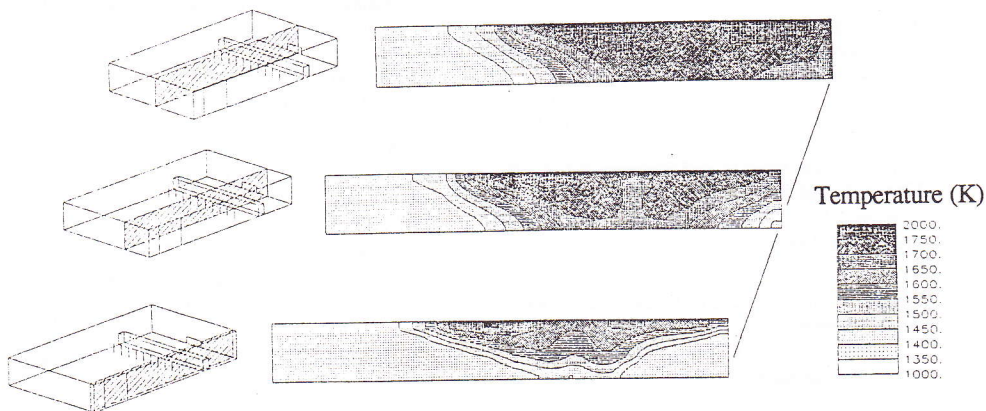


Figure 3 Temperature field inside the melting tank of an end-port furnace.