FIRST-PRINCIPLES SIMPLIFIED MODELLING OF GLASS FURNACES COMBUSTION CHAMBERS

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Abstract : To control glass furnaces, advanced techniques like Model Predictive Control are implemented in performing tools that allow a multi-objective optimisation of the system operation. In this model-based application, computation time is hardly constrained and rapid models are required. The first-principles modelling approach is showing interesting perspectives in comparison to usual black-box models, provided sufficient simplifications are made to lower the computational load. In this paper, the choice of the modelling approach is discussed and a rapid model of the combustion chamber is presented.

Keywords : industrial production systems, temperature control, model-based control, physical models, temperature profiles.

1. INTRODUCTION : THE NEED FOR MODELS of GLASS FURNACES

Glass has been manufactured since five thousands years, and the fabrication processes have been artisanal until the industrial revolution. During this first period in the glass history, people melted raw materials in small pot furnaces containing the quantity for one-day production. Since 150 years, glass is melted in huge continuous chemical reactors of several hundred square meters surface area. Schematically (cf. fig. 1), conventional glass furnaces are constituted of a melting tank below and a combustion chamber above. The size (typically 40m(L)*10m(W)*4m(H)) has increased a lot to allow massive production, and the process is operated continuously. The raw materials that will form glass are fed in at one end as a solid batch blanket that floats on the bath surface. The heat transfers to this zone allow glass formation to start, and solid particles melt and sink into the liquid glass bath where convection rolls slowly brace the masses. After a residence of ten to fifteen hours in the melting tank during which numerous chemical process homogenise and purify the molten glass, glass is pulled out of the bath at the other end to the forehearth where it is conditioned before the forming. The convection rolls are of prime importance for the furnace operation and are maintained by the heat flux pattern from the combustion chamber. The temperatures required to form glass are very high, such that the furnace mean temperature is around 1500°C and heat transfers mainly occur by radiation. The refractory walls isolate the enclosure but a great amount of heat is lost through them.

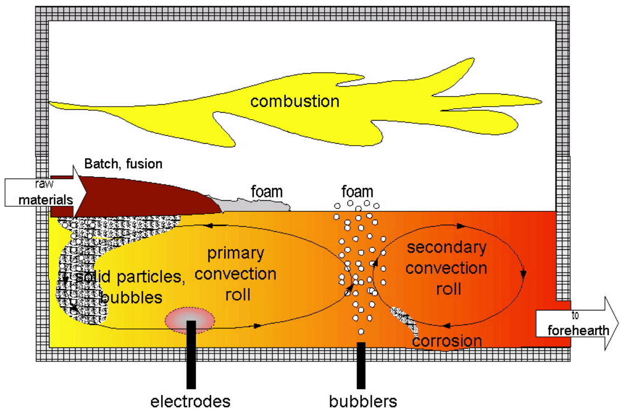

Fig. 1 : Physical phenomenon in a glass melting furnace

The energy consumption is very high in glass furnaces (5GJ/ton molten glass), and the combustion has a strong impact on the environment. These processes are therefore subject to stringent control, and the glass industry in many countries is facing a great challenge with the ever increasing regulations like Kyoto protocol. Optimal design and control is therefore a key area to remain competitive in the near future, and a current trend is to implement advanced control techniques, and particularly model-based control. For these methods, the choice of a model is crucial.

In this paper, some details about the furnace physic and the control tasks associated to it will be first described in section 2. It will be explained why advanced control techniques and particularly model-based control are indispensable. This will introduce the discussion about which model to use in faster-than-real-time control applications. There exists a lot of complex models representing in great detail what is happening inside the furnace, but there is a need for simpler models with shorter simulation time for applications like model-predictive control. It will be shown that the first-principles modelling approach presents interesting advantages compared to the classical identified models. In section 3, a simplified model for the combustion chamber developed during the PhD thesis of first author will be presented. It is based on the fact that since control is operated on mean temperature profiles in the furnace, the model doesn't require to be fairly accurate. In the final section 4, some applications of the model will be described.

2. GLASS FURNACES AND THEIR CONTROL

2.1 The process (Tooley, 1961; Trier, 1984) :

Let us take a closer look at the different parts in the furnace. **In the batch blanket first** (see the dark plots in figures 2 and 3 at the surface of glass). The recipe is continuously introduced as fifty kilos packets (for standard glass : 70% silica, 14% soda ash and 10% limestone), which are humidified to avoid dust release during conveying from the silos to the furnace. Due to the air contained in the mixture, the packets float over the bath surface, and they are heated by the flame above and the molten glass bath underneath. The high temperature starts different reactions that will finally become a molten mixture ("molten glass") able to vitrify during its cooling at the furnace output. The main reactions (Verheijen, 2003) in the batch blanket are dehydration (water evaporates), chemical dissociation and decomposition, and melting. As these processes occur, the molten glass sinks in the bath dragging down a certain amount of solid particles. The packets become smaller and smaller and at least disappear completely. The batch blanket shape and length greatly influences the heat transfers and the bath hydrodynamic. Typically, the heat transferred to the batch zone accounts for 80% of the net heat input from the combustion chamber (Beerkens, 2004).

In the glass bath. The melting tank contains up to thousand tons of molten glass, which need to undergo different fining and homogenizing processes to be ready for forming (Beerkens, 2004). The heating profile at the bath surface caused by the unequal burners power induces temperature and density gradients in the depth of the melt, which create natural convection driving forces. The pull rate also imposes a forced convective flow. Both natural and forced convection results in the most usual case (Beerkens, 1994) in two rolls turning unclockwise (see fig. 1). In the primary loop, the newly molten glass sinking from the batch still contains solid particles which have to be dissoluted before attaining the region where the two rolls join (Hrma *et al.*, 1986). At this last point, the flow is driven upwards to the surface to reach the zone of maximum temperature ("hot spot"). During the ascension, fining agents decompose and produce fining gases (Beerkens, 2003) that will coalesce with among others CO2 gas bubbles and chase them to the surface. After the residence in this zone, the fined molten glass bifurcates (see figure 1) :

- Either backward in the primary loop, back to the front end of the furnace. It will sink under the batch blanket and mix with the newly molten glass. The primary loop greatly contributes to heat the batch piles.
- Or forward in the secondary loop, where the temperatures are lower and remaining gas bubbles are dissolved. In this loop, the glass descends along the colder end-wall and some part flows through the throat, exiting from the melting tank to penetrate in the working end. The other part of glass returns to the hot spot zone.

These two loops play an important role in the melting tank operation, as they create different zones with different temperatures and chemical environment necessary for the phenomenon of glass elaboration (homogenizing and purifying, fining and refining the glass). They have to be maintained and this is achieved by the heat pattern from the combustion chamber, bubbler systems and the tank design. These parameters influence a lot the flow in the bath, that can differ from one furnace to the other. Anyway, one should remember that this motion in the bath is of prime importance. As an example, a particle can stay up till 60 hours (in float furnaces) in the tank before it passes the throat. Actually, according to the quality required for the final product, a certain time of residence in the furnace is necessary for the molten glass (Beerkens, 2004). The optimal operation of a melting tank consists then in having an average residence time closest to the required residence time, and maximum and minimum residence times closest to the average residence time.

In the combustion chamber. Flames develop in the firing ports axis. There are one or more firing ports depending of the furnace type, and each port is constituted of several burners injecting oil or gas under an air flow. Typically, each port has a burning power of several hundreds megawatts, with air flows of tenth thousands cubic meters per hour. The maximum temperature is over 2000 K and can reach 3000 K when pure oxygen is used as oxidant. Indeed, oxy-combustion is employed to enhance the efficiency of furnaces and to lower the production of thermal NOx (combination of N2 of the air and oxygen components).

The global flow pattern in the combustion chamber depends on the firing ports configuration. In this article, cross- or end-fired furnaces are considered, in which the flow is either globally U-shaped or transversal (see fig. 2 and fig. 3). In these furnaces, there is a flow between each firing port and its corresponding extracting port, presenting some recirculation under the crown. The combustion regime is turbulent, and the heat is transferred mainly by radiation to the load or lost in the environment through the walls. Pollutants like NOx and CO are present in the flames.

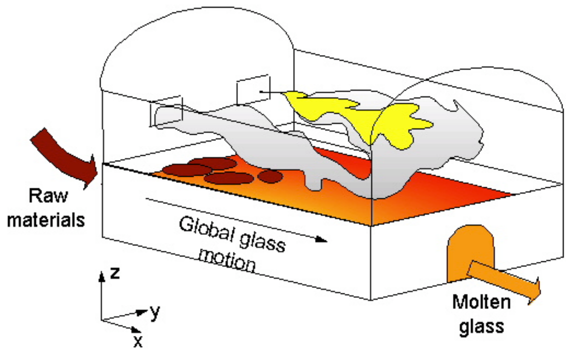

Fig. 2 : End-port glass furnace

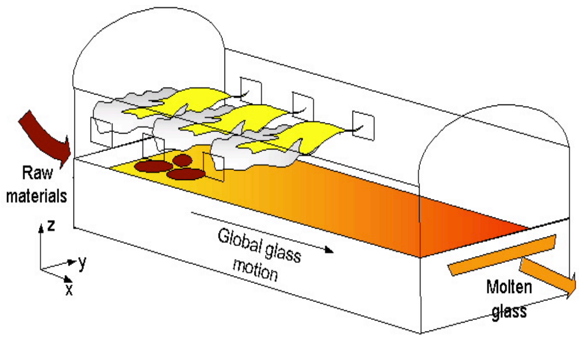

Fig. 3 : Side-port glass furnace

2.2 The furnace design :

Typically, industrial glass furnaces have a daily throughput of several hundreds tons. The process described above is general for conventional combustion furnaces, but their size and technology depends of the type of production. Indeed, flat glass for example (for window, windshield etc.) requires a very high quality in comparison to container glass, and the required residence time in float furnaces is therefore longer than in container furnaces. That's why float furnaces have a bigger L/l ratio than container glass furnaces. As previously mentioned, the convection rolls are depending on the temperature gradients at the glass surface and the burners are placed to achieve the right heat input profile to the bath. Long float furnaces are therefore cross-fired where as smaller container furnaces are end-fired (see fig. 2 and 3).

Furnace efficiency is largely improved thanks to heat regeneration or recuperation. These processes operate the heat exchange between hot gases and cold combustion air in huge refractory towers (regenerators for indirect heat exchanges) or recuperators (heat exchangers) for direct heat exchanges. Other technologies allow to optimise the furnace operation (for cleaner combustion and higher efficiency) already at the design phase, like oxy-fuel combustion, reburning, low-NOx burners, electro-boosting. But this paper is focused on online optimisation thanks to control, as will now be emphasized.

2.3 The control tasks :

Quality of the final product is the control major objective in a glass furnace (Chmelar *et al.*, 2001). The constraints on purity – absence of defects like cords and stones - and homogeneity of the molten glass at the furnace exit are very high because they will finally fix the quality of the windshield or the perfume bottle ! Quality depends on the fining and refining steps, on the residence time in the convection rolls and other large scaled phenomena. This means that although it is defined very locally, quality can be controlled through the global hydrodynamic and thermal behaviour of the glass bath, i.e. its temperature and velocity fields.

To this end, the operator monitors the temperatures, the foam that covers the bath, the different gas emissions measurements and he adjusts principally the heat transfers profile and the batch charging system. The tuning of burners power in the chamber will modify the heat transfers in the whole system, influencing the temperature and velocity fields in the bath. Usually, the heating profile has a maximum at the *hot spot,* i.e. the region where the two convection rolls meet together in an ascendant motion. The high temperature in this region maintains the natural convection necessary for the convection rolls.

Although quality is the main objective, there are numerous secondary criterions to optimise (Pina et al, 1999), as furnace efficiency, pollutants emissions, refractory temperatures etc. These are the classical operation constraints of any industrial process. Table 1 sums up the control objectives and actions.

Table 1 : Hierarchical levels of control tasks in a glass furnace

Level 1 : **Principal control goals**	Glass quality maximisation	Pollutants production and emission minimisation. Thermal efficiency maximisation	
	Furnace and refractory lifetime maximisation	Energetic consumption minimisation	
Level 2 : **Physical controlled variables**	bath level and temperature, residence time, residence time distribution	Air-to-gas ratio, exhaust composition	Crown and sole temperature profiles
	Atmosphere pressure and temperature		
Level 3 : **Manipulated process variables**	Batch charging system, bubbling, boosting	Fuel and air flows at each port. Batch preheating temperatures	Cooling air flows

2.4 *Model-based advanced control*

Control of a glass furnace is therefore multi-objectives, and the need for optimal control is all the more important since stronger regulations on energy consumption and gas emissions are to come. Today, the vast majority of glass furnaces are still controlled by PID loops tuned by operators (Chmelar *et al.*, 2001), but no multivariable optimal control is possible to achieved with such techniques. Therefore, advanced control strategies like model-based optimisation tools are more and more employed by glass producers.

Model Predictive Control (MPC) is developed for glass furnaces and has already been implemented in different products distributed on the market (Carvahlo et al., 1996), (Backx *et al.*, 2000), (Pina et al., 2002), (Op den Camp *et al.*, 2004), (Schill *et al.*, 2004). The current trend in many model-based tools, and also those for glass furnaces, is to use identified black-box models (Qin, 1997). Identification techniques are based on correlation studies between inputs and outputs dynamics. By exciting the system with pseudo-binary random sequences on the different canals and by analysing how the system evolves, one can build a set of transfer functions which can be used as a very rapid model with good precision.

Although, (Auchet *et al.*, 2004a, 2004b) affirms that first-principles models have greater advantages as identified models for MPC algorithms. Indeed, identification campaigns are long and tedious because glass furnaces are very slow and have a wide operation range. Moreover, identified models are limited to the regions where the measurements were done, and the control can be affected if the system comes in an unknown operating point for the black-box model, or if the parameters evolve during the furnace life. That's why the choice of a model for model-based control algorithms of glass furnaces is still an open question (Carvahlo et al, 1996).

What pleads for the first-principles approach are the performing reduction techniques of fine CFD models that have already shown interesting perspectives for the glass feeder (Astrid, 2003) and the glass bath (Op den Camp *et al.*, 2001). Moreover, zone models have already proven to be realistic for the modelling of furnaces combustion chambers (Tucker, 1990). There is a potential to get fast first-principles models of glass furnaces, and this constitutes a great perspectives for application of MPC algorithms to such systems.

A simplified first-principles model of the combustion chamber has been developed (Auchet, 2005) and will be described in the following. This is a first step towards a fast model of the complete furnace. The particularity of this model is that it contains empirical parameters located at strategic places to allow the tuning of the model against real furnace data.

3. SIMPLIFIED FIRST-PRINCIPLES MODEL OF THE COMBUSTION CHAMBER

3.1 Modelling approach

The phenomenon occurring in the combustion chamber are mainly the turbulent combustion and the radiative heat transfers. The problem enters the scope of high temperature turbulent non-premixed flames. The development of CFD models has followed the processors power (Ungan, 1996), and today, state-of-the-art solvers operate at a very fine scale, considering all known phenomenon (Auchet, 2005). Following equations are used.

- The gas flow is described thanks to the classical Navier-Stokes equations with turbulence closure models (most often the k-ε approach is used).
- Turbulent combustion models for fine CFD are extensively developed (Veynante, 2002). They represent how the turbulence influences the combustion. In particular, the Eddy-Break-Up and the mixture fraction approaches are implemented in glass furnaces models.
- Radiation is computed by solving the radiative transfer PDE. The different approaches used are those based on simulation of photons path (called Monte-Carlo techniques), discretization with finite volumes method or discrete-ordinates methods. These methods are computationally heavy, especially because of the spectral dependence of the gas and soot absorption coefficients.
- Powerful NOx and soot models are often included as post-processing.

These very precise models can be used at the design phase of furnaces, or to better understand how the phenomenon are involved in the system behaviour. However, their computation time is still very high, and totally inadequate for real-time or faster applications. Anyway, when operating a furnace, the control is conducted on only few measurements points : typically few tenth of thermocouples in the crown, sidewalls and sole and some laser pyrometers pointing in the furnace. Therefore, the model used for control doesn't require to be that precise, and a simpler representation of the furnace behaviour will suffice.

The present model was thought to compute the temperatures profiles in the gas and in the walls with a precision at least as fine as the measurements, i.e. the mean profiles. To this end, the mean behaviour of the phenomenon described above have been written, i.e. combustion and heat transfers inside the enclosure, at the scale of principal variations. Thus, the simplifying hypothesis are made first on the geometry and then on the physic modelling. The heat exchanges with the glass bath surface and with the environment through the walls constitute the boundary limits of the combustion model.

3.2 Geometry simplification

Principally, the heat transfers in a combustion chamber occur by radiation, and the geometry is of great importance. Though, as heat produced by flames radiates the whole enclosure and as the optical thickness of combustion gas is thin, the temperature profiles on the walls and in the combustion gas are homogenised by radiation. That's why details of combustion chamber geometry like air introduction ports, openings to the outside have little influence on the mean temperature profiles and can be neglected in the geometry definition. Their influence will be taken into account by putting artificial heat sinks in the heat balance as will be explained later in the paper. Finally, only the superstructure of the combustion chamber as depicted in figure 4 is considered.

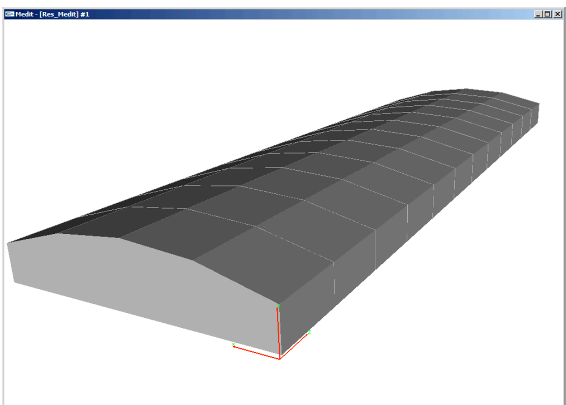

Fig. 4 : Superstructure of the combustion chamber

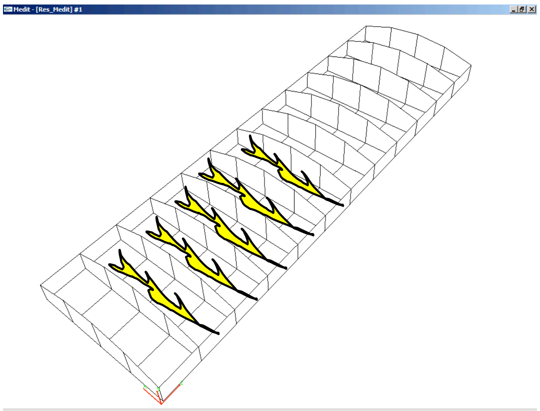

Fig. 5 : Compartments in a cross-fired furnace (mean profiles longitudinally and transversally)

3.3 Physic modelling

According to the furnace type, there are different zones in the combustion chamber where the gas are either in turbulent motion (flames), or at rest (as above the refining zone in cross-fired furnaces). Therefore, following simplifying assumptions on the flow pattern have been made.

First, the enclosure is decomposed into compartments in which the hydrodynamic can be considered independently. In these compartments, there can be a reactive flow, an air flow or no flow at all, and the compartments only exchange energy via radiation together (see example fig. 5 for a float glass furnace decomposed into twelve compartments). Secondly, in the compartments with a flow, the recirculation of gas under the crown is neglected and the flow is considered unidirectional. This is the classical *plug-flow* hypothesis, and the unidirectional convective transport of reactive species equations (1) are solved in each compartment thanks to the finite volume method, by decomposing each compartment into cells (4 cells are used in the figure 5). The gas mixture is assumed ideal.

$$\begin{cases} \rho = \dfrac{P}{\sum\limits_j \dfrac{Y_j}{M_j}.RT} \\ \dfrac{\partial \rho}{\partial t} + \dfrac{\partial \rho u}{\partial x} = 0 \\ \dfrac{\partial \rho Y^j}{\partial t} + \dfrac{\partial \rho u Y^j}{\partial x} = \dot{\omega}_j \quad \mathrm{j} = \{1; N_S\} \\ \dfrac{\partial \rho h}{\partial t} + \dfrac{\partial \rho u h}{\partial x} = w = w_{conv} + w_{rad} \end{cases} \tag{1}$$

x is the axis position in the flow direction, ρ is the density, P the pressure (assumed uniform and constant in the whole enclosure), R the gas constant, T the temperature, u the gas velocity along x, Y_j {1:N} the N chemical species mass fractions, $\dot{\omega}_j$ the production/destruction rate of chemical specie j, h the total enthalpy of gas mixture and w the energy source composed of a radiative and a convective part. To get the temperature of gas, one uses the total enthalpy relation.

Thanks to this approach, the temperature and atmosphere composition are computed in each cell of each compartment. The temperature gradients due to the fuel distribution over the burners are therefore known (longitudinally in cross-fired furnaces), and the transversal gradients are also detected. The mesh grid given by the compartments and their cells is the basis for all combustion and heat transfers computations, and provides the possibility to get the system mean temperature profiles.

Heat is produced by combustion, and heat transfers from the hot gases to the glass bath and the surroundings as losses occur by the three transfer modes : radiation, convection and conduction. Radiation accounts for ninety percent of the exchanges, and it is modelled on the simplified geometry described above thanks to the zone method. Convection between hot gases, the walls and the glass surfaces is computed by an empirical law. The conduction in the wall is considered unidirectional. In the sequel, a closer look on these different sub-models is taken.

Radiation

Due to high temperatures, radiation is preponderant and particular attention is therefore paid for its modelling. The simplified geometry described above is used, where the whole space is decomposed into zones having uniform temperature and radiative properties (either gas volumes, molten glass surfaces or refractory wall surfaces given by the segmentation into compartments and cells). Each zone emits and reflects diffusively, and absorbs radiation, and the presence of strongly emitting and absorbing particulates such as soot in the chamber atmosphere has to be taken into account.

The radiation modelling methods best suited to such coarse mesh grids is the Hottel zone method (Hottel, *et al.*, 1958), based on exchanges areas between every pair of zones of an enclosure (surface-surface SS, surface-gas SG and gas-gas GG). These view factors quantify how the elements radiate each other, and are only depending on the geometry and the photometric coefficients of the gas and the different surfaces filling the enclosure. In the present model model, all elements are assumed grey, i.e. with photometric coefficients not depending of the wavelength. This means that the heat transfers computations can be done globally on the whole spectrum.

Exchange areas are kind of visibility factors, and following expression shows the case of view factor between a surface element Ai and a surface element Aj (see fig. 6).

$$F_{ij} = \int\limits_{A_i}\int\limits_{A_j} \frac{\cos(\theta_i)\cos(\theta_j)\exp^{-\tau}}{\pi r^2} . d s_i d s_j \quad (2)$$

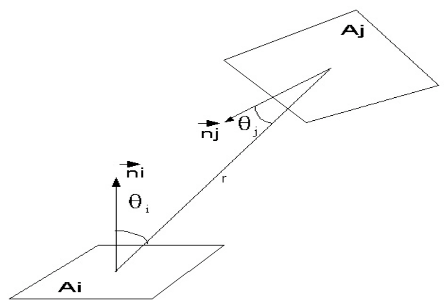

fig. 6 : Configuration between two surfaces

The Gebhart formalism (Gebhart, 1971) which writes the exchange factors as total absorption view factors has been used. In the computation of view factors between two zones i and j, this method takes into account the multiple path of a ray emitted by i and travelling in the enclosure by mean of successive reflexions at walls until it reaches element j. Finally, the influence factor Gij between element i and j accounts for the proportion of energy emitted by i and absorbed by j. Knowing the exchange factors for every pair of elements allow to do a total radiative balance in the enclosure. All view factors are stored in the so called Gebhart matrix **B**.

$$\mathbf{B} = \begin{pmatrix} SS & SG \\ GS & GG \end{pmatrix} \quad (3)$$

The complexity of exchange areas methods is to compute the view factors because they are volume and surfaces integrals. For surface-surface view factors like (2), simple analytical relations based on contour integration (Cheng *et al.*, 1998) are used. For volume-volume and volume-surface view factors, the method (Emery *et al.,* 1987) has been implemented, which extends a scan line algorithm based upon surface-surface radiation to the computation of surface-gas and gas-gas radiation transmittances.

Finally, the net radiant heat fluxes w_{rad} for all elements, either gas volumes, walls or glass surfaces, are obtained thanks to the net radiative balance in a very simple vector form. This is the heat source term w_{rad} of the enthalpy equation in the plug flow equation.

$$\begin{gathered}\text{net radiative flux = absorbed flux - emitted flux} \\ w_{rad} = BW - W\end{gathered} \quad (4)$$

Where the second term on the right hand side is the emitted powers vector ($W = A\varepsilon\sigma T^4$ for a surface or $W = 4V\kappa\sigma T^4$ for a gas volume), this is the energy lost by proper radiation. The first term BW is the distribution of emitted powers between all elements taking gas absorption into account. The influence of introduction ports or the batch heap can be taken into account by setting a lower emissivity on the corresponding surfaces.

Convection

Convective heat transfers between a gas volume i and its N adjacent walls j presenting an exchange surface area A_{ij} is very simply computed by :

$$w_{conv,i} = \sum_{j=1}^{N} h_{ij} \cdot A_{ij} \cdot (T_i - T_j) \qquad (5)$$

This is the heat source convective term appearing in the enthalpy equation. The forced convection coefficients h_{ij} are given by an empirical method.

Combustion

The most common simplification when modelling combustion is the so-called single-chemically-reacting-system (SCRS). Instead of taking into account the thousands of intermediate species and reactions of the actual flame, only the main species of the reaction equilibrium are considered (reactants CxHy and O2, products H2O and CO2, and inerts N2). Therefore, $N_s = 5$ in (1) and the reaction is :

$$\begin{gathered} C_x H_y + \left(x + \frac{y}{4}\right)(1+e)(O_2 + k.N_2) \rightarrow \\ x.CO_2 + \frac{y}{2}.H_2O + \left(x + \frac{y}{4}\right)e.O_2 + \left(x + \frac{y}{4}\right)(1+e)(k.N_2) \end{gathered} \qquad (6)$$

Where *e* is the mixture richness, k = 3.76 for standard air, and 0 for oxygen.

In the *plug flow* equations, the production/destruction rate term $\dot{\omega}_j$ of each specie has to be determined to compute the gas composition. This is the combustion modelling, and this term is theoretically given by the Arrhenius law but the non-linearity introduced by this relation is too stiff for classical solvers. The common method is therefore to assume the reaction infinitely fast, and the production/destruction terms are simply given by the mixture richness e (air/fuel ratio). In a 1D plug flow reactor, this means that the fuel is immediately burning at its introduction into the combustion chamber and the whole heat is released in the first cell. This is a very bad approximation for a flame and its temperature, and it will impact the heat transfers realism. To better represent the flame profile in the compartment, the fuel consumption had to be distributed in the different cells. To this end, empirical weights α_i ($0 \leq \alpha_i \leq 1$) were introduced in each cell *i,* to weights the theoretical amount of fuel which burns. One can therefore propagate fuel downstream in the next cell (i+1), which will burn according to the air/fuel ratio in this cell and according to the coefficient α_{i+1}. By appropriately choosing the set of weights α_i (i={1:N}) in a compartment of N zones, the flame profile can be shaped to better fit reality.

Figure 8 shows the flame temperature profile of methane burning in a compartment for four different sets of weights. One can see that the default configuration (α={1;0;0;0;0}) yields a non realistic profile (solid line). The temperature has a maximum at the gas entrance in the combustion chamber and then decrease due to heat losses. The other sets shape the flame profile within a great range, and the third and fourth profiles are much more realistic, the heat production being distributed along the flame.

Looking at figure 8, it seems natural that an optimal set of weights α corresponding to the real mean temperatures profile in the flame may exist. It can be determined by a least-squares optimisation method using a known flame profile or by combustion expert knowledge. Anyway, these empirical parameters allow to tune the model in a very interesting way. In picture 9, the temperature fields (left pictures) and the net heat fluxes to the bath (right pictures) are given for three different flames profiles in the Ford float furnaces (Round Robin Test 3 of the 21 Technical Comittee of the International Commission on Glass) (figure 7). Notice how the hottest point can be translated along the flow direction (shown by the arrow) of the furnace, only by modifying the flames profile. First author currently investigates how to tune these parameters to fit a particular furnace. This way of model tuning is more interesting than other ways (as empirical setting of walls losses to fit measurements for example), because it acts at the system heart, i.e. the heat sources by combustion.

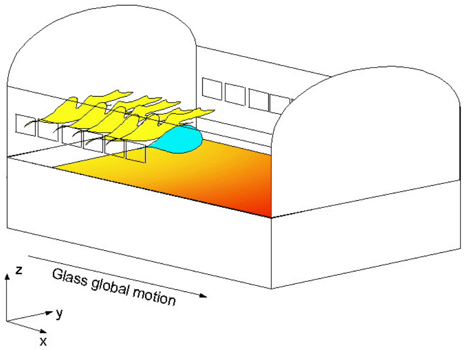

Fig. 7 : Ford float furnace (5 burners, 1 hot air input)

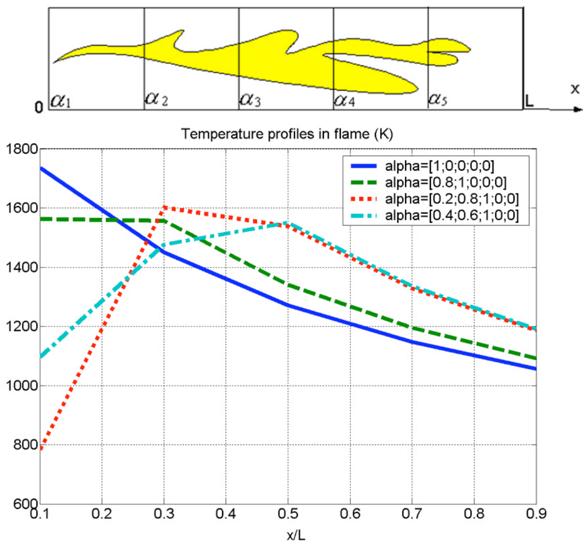

Fig. 8 : Flame decomposed in 5 cells and influence of the weights on temperature profile

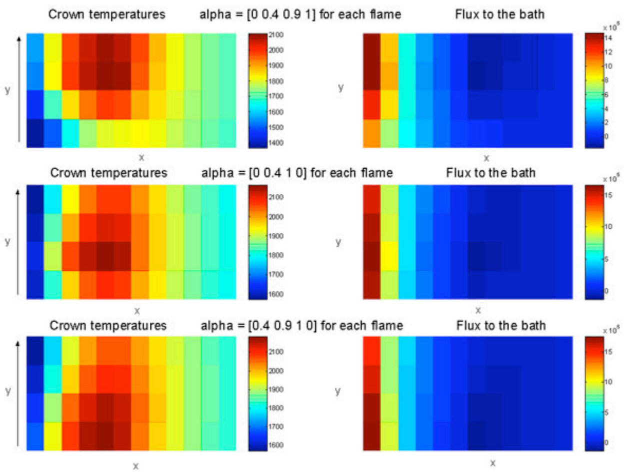

Fig. 9 : Influence of 3 combustion set of weights on the gas temperature (left) and the net heat flux to the bath (right)

The preceding sub-models allow to compute the reactive flow, the heat released by combustion and the heat transfers by radiation and convection in the combustion gas. This constitutes the kernel of the combustion chamber model, and it is interfaced to a walls models, described below.

Walls modelling

The walls are composed of a refractory layer at the inner side of the enclosure and an isolation layer at the outer side. They isolate the enclosure from the environment and they are assumed in unidirectional conduction through their thickness. They exchange heat by convection and radiation on both internal and external side.

Again, the temperature mean profiles on the walls are modelled to provide the boundary limit for the combustion chamber. Therefore, the phenomenon have been written on a mesh grid smaller than the principal variations. The walls are decomposed into small parallelepipedic elements following the space decomposition in the combustion chamber (compartments + cells). In each wall element, the 1D heat diffusion equation is solved thanks to the finite volume method with few nodes in the thickness of the wall (typically less than 10 as in fig. 10).

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda . \frac{\partial T}{\partial xt}\right) \qquad (7)$$

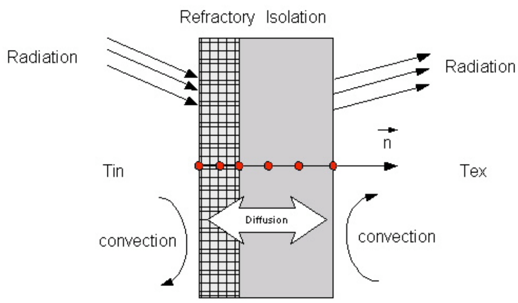

Fig. 10 : Wall element with 6 nodes

The global model of the combustion chamber is constituted of Nc times the equations set (1) (where Nc is the number of compartments) and Ns times the equation (7) (where Ns is the number of wall elements). The coupling between the combustion gas equations and the walls equations is done by writing the heat exchanges by convection and radiation between the gases and the refractory surface. Expression (5) and the zone method (4) are used to this end.

Similarly, the combustion chamber model can be coupled to a separate glass tank model by writing the heat exchanges between the gases, the refractories, and the glass tank occuring at the bath free surface. Some applications will be shown in the last section.

3.4 Performances and validation of the model

When simulating a multi-equations system like this one, the model is decomposed into sub-parts to optimise the simulation. Particularly, the characteristic times of combustion and radiation are much shorter than the one of conduction through the walls. Therefore, it is judicious to separate the combustion solvers from the conduction solvers and to synchronise them according to their characteristic times. The coupling algorithm between the different much solvers is based on heat fluxes-temperatures exchanges at the interfaces between the combustion gases and the wall interior surfaces, and the load free surface. The combustion characteristic time being more rapid than the other phenomenon, the combustion chamber regime can be assumed quasi-steady for transient simulations. Pictures 14 to 16 shows the coupling of the solvers, the steady-state gas temperature profiles longitudinal in the cross-fired furnace of figure 7, and transient simulation of combustion gas temperatures during the starting-up.

The model speed using this coupling algorithm is very interesting. In steady-state, the computation time is one second per zone in the spatial decomposition, and in few minutes, one get a prediction of temperature field on a mesh grid of several hundreds points, i.e. with a finer spatial resolution than the sensors ! In transient regime, the model requires 10-5 second per zone per second, reaching several hundreds time the real time speed.

The present model has been validated against TNO reference (Paarhuis, 1999) datas on the Ford float furnace in Nashville (USA) for the cross-fired case. For the end-port case, other reference datas of TNO were used. The comparisons showed very good agreement (within few percents) between the two models.

4. APPLICATIONS

Rapid simulation : The model presented in the last section can be used for rapid simulation, to quickly test the combustion chamber behaviour in steady-state or in transient regimes. This is interesting for rapid what-if scenarios, for parametric studies and operator training, and industrials show great interest for such tools. The model of combustion chamber has therefore been implemented in a simulation software in Matlab. It can be used with several rapid load models. For example, a very simple model of a load moving longitudinally under the combustion chamber with uniform velocity, and with homogenous thermal properties was included. It is more like the flow in glass feeders, where the molten glass coming from the refiner zone is conducted to forming machines. By lack of time, any model of an actual glass bath with convection rolls could be developed.

Picture 12 shows the results of a parametric study in a continuous furnace, with the load model described in the previous paragraph. The pull rate (kg/s) is varying and one investigates how the burner powers (around a nominal value Pn) influence the load surface temperature at the furnace outlet. The results of this study could be used to support the operator in setting the operating point of burners regarding the pull rate.

Control : The use of the combustion chamber model in model-based control algorithms is the most interesting perspective, provided it is coupled to a model of the bath to allow a complete control of the furnace. A test has been conducted to investigate this possibility, using the same load model as presented previously with temperature dependent molten glass properties putted as parameters. Following problem was posed : the pull rate and the input temperature of the glass flow is varying with time. How to control automatically the burners power so that the temperature of the gob at furnace exit remains constant ? This is a typical feeder control problem, very similar to the parametric study presented picture 12. The only measures available are the temperatures in the melting tank walls, and the burners power in the combustion chamber are used as manipulated variables. The whole system is decomposed in three zones along the load motion (see picture 11).

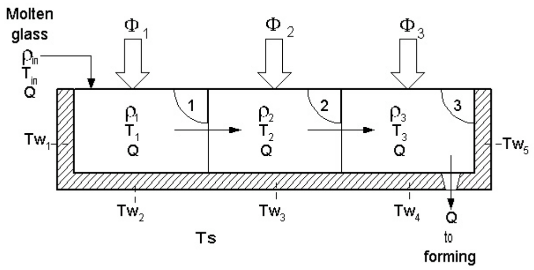

Fig. 11 : Glass bath to control with burners power

To use the nonlinear model for the synthesis of a classical model-based control algorithm, it is convenient to set it in a linear form. Linearised models have to be derived around the typical operating points to synthesise the corresponding controllers, and an interpolation algorithm allows to switch from one to the other. Yet an other advantage of first-principles models is that it is possible to get linear models at every operating point, at every time during the furnace lifetime.

The LQ control has been tested on the non-linear model around one operating point (Ressencourt, 2004). Pictures 13 show how the temperatures in the three zones evolve when the pull rate presents periodic step variations. The temperatures are oscillating without any control, and the LQ controller stabilizes them.

Coupling to a fine glass bath model : Usually, when simulating the glass bath with CFD models, people use uniform and constant temperatures and gas composition in the combustion chamber atmosphere, with the black body assumption for the radiation. The simplified model of the combustion chamber provides rapidly realistic boundary conditions for such simulations, in steady-state or in transient regimes, and it is likely to influence greatly the results. Indeed, the model was coupled to a glass bath 2D model with a precise modelling of radiative transfers. The results showed (Berour *et al.*, 2005) that the glass temperatures were much more realistic with present combustion chamber model than with classical boundary limits. Pictures 17 to 19 show the coupled combustion chamber and 2D glass bath, some axial temperature profiles and the 2D temperature field in the glass bath.

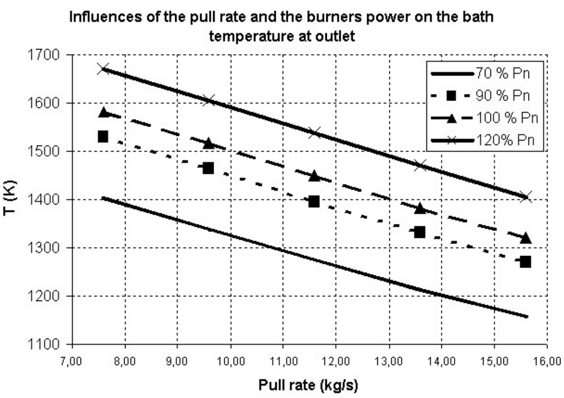

Fig. 12 : Parametric study

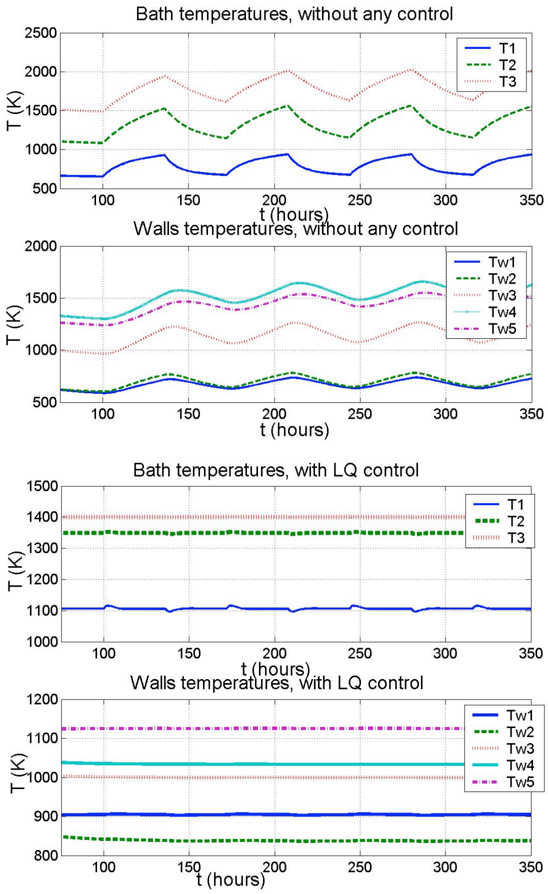

Fig. 13 : Influence of LQ control on temperatures

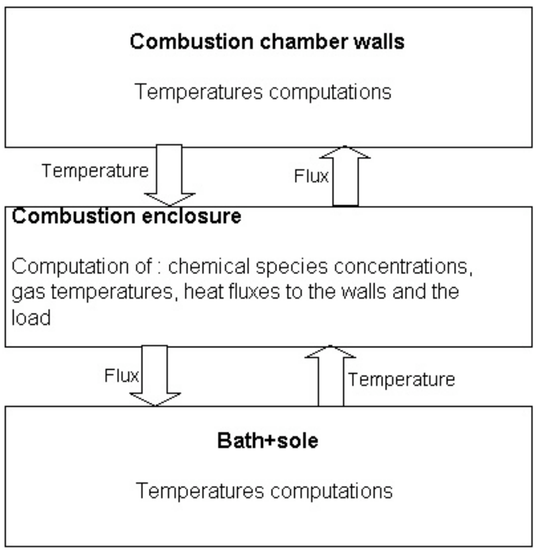

Fig. 14 : Coupling of solvers

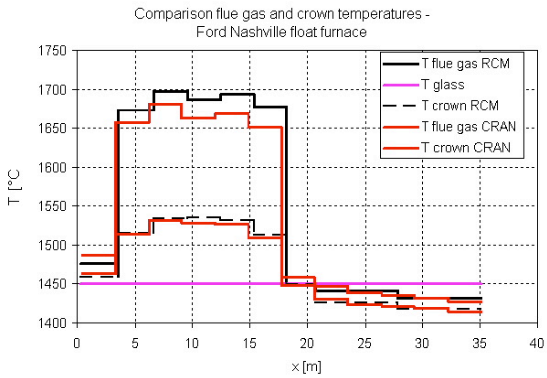

Fig. 15 : Axial T profiles in Ford float furnace

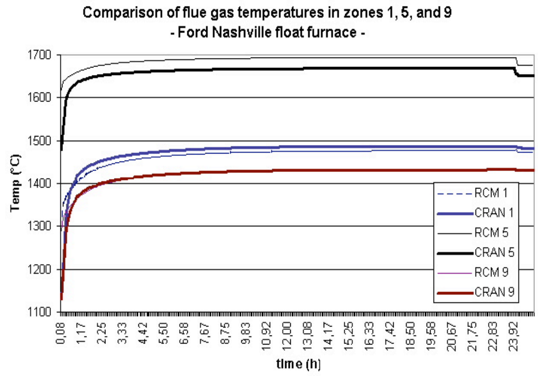

Fig. 16 : Transient responses

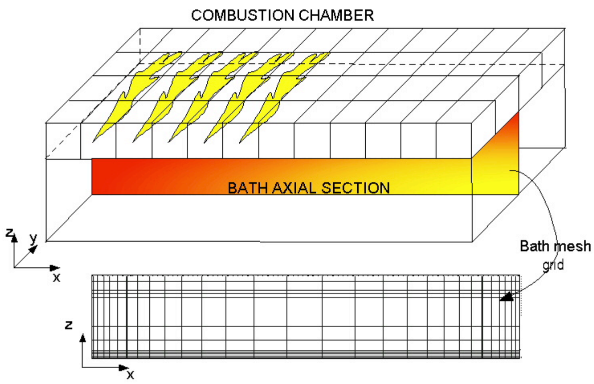

Fig. 17 : Coupling of the combustion chamber and the 2D glass bath

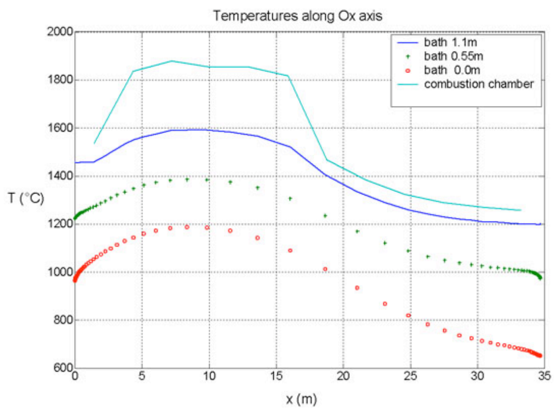

Fig. 18 : Axial temperatures in the gas and at different depth in the glass bath

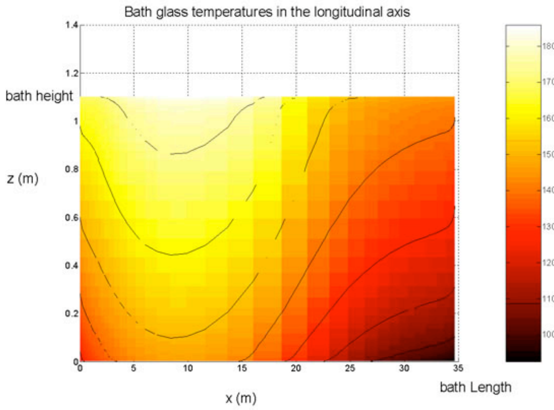

Fig. 19 : 2D temperature field in the glass bath

5. CONCLUSION

Numerical modelling is the best tool to optimise glass furnaces, subject to ever stringer regulations on pollution and energy efficiency. Depending on the application, different kind of models are used. Rapid and relevant models have to be developed for model-based control. Indeed, identified black-box models used currently in such applications hardly accommodate with the strongly coupled and moreover, they require long and tedious identification campaign, without any guarantee of validity on a broad spectrum of operating ranges. First-principles modelling approach presents great advantages thanks to performing reduction techniques of fine models and simplified zone models.

There is a potential for development of fast models of the complete furnace, and this paper shows the first step towards this goal : one presents a fast combustion chamber model based on the resolution of classical conservation equations on a coarse mesh grid with simplification hypothesis on the furnace physic and geometry. Particular attention is paid for combustion and radiation modelling. The model predicts the walls and gas temperature mean profiles, as the heat fluxes to the glass bath surface. Empirical parameters on the local reaction rate allow to fine-tune the model against real furnace data.

This model is used for rapid what-if scenarios, particularly interesting for operator training. In the current race of glass producers for optimising the furnace operation, the perspective of this model is to be used in model-predictive control algorithms. To enhance the model performances and to broaden its applications scope, further development on non-grey radiation in combustion gas, simplified combustion modelling and reduced models of glass bath are necessary.

REFERENCES

Astrid P, Weiland S, Twerda A. *Reduced order modeling of an industrial feeder model*. In Proc. 13th IFAC Symposium on System Identification 2003, Rotterdam, The Netherlands; 1437–1441.

Auchet O, Remy B, Lacroix D, Degiovanni A. *Simplified modelling of glass furnaces for rapid simulations*. In Proc. of XX International Congress on Glass 2004a; Kyoto, Japon.

Auchet O, Riedinger P, Iung C, Malassé O. *Simplified first-principles modelling of glass furnaces for control purpose.* In Proc. International Symposium on Dynamics and Control of Process Systems 2004b; Boston, USA.

Auchet O. *Contribution to simplified modeling of glass furnaces*. PhD Thesis at Institut National Polytechnique de Lorraine ; 2005.

Backx T, Ludlage J, Koenraads A. *Model based control ensures predictable process operations*. In *Glass* 2000; 180–182.

Berour N, Auchet O, Lacroix D, Jeandel G. *Coupled conductive radiative transfers in glass furnaces. Influence of heating parameters on bath temperature field*. In Proc. Congrès Français de Thermique 2005 ; Reims , France; 1 : 421-426.

Beerkens R. *Analysis of advanced and fast fining processes for glass melts.* American Ceramic Society Bulletin 2005; 141.

Beerkens R. *A deeper look into industrial glass melting processes.* In Proc. 20th Int. Congress on Glass 2004; Kyoto, Japan.

Beerkens R, Muijsenberg H, Van der Heijden T. *Modelling of sand grain dissolution in industrial glass melting tanks.* Glastech. Ber. Glass Sci. Technol 1994; 67(7) :179–188.

Carvahlo MDG, Xeira AP, Nogueira M. *Model-based operation optimisation of glass melting furnaces.* Int. Glass Journal 1996; 89:31-37.

Cheng X, Müller U. *Turbulent natural convection coupled with thermal radiation in large vertical channels with asymmetric heating*, International Journal of Heat and Mass Transfer 1998; 41:1681-1692.

Chmelar J, Bodi R, Muysenberg E. *Supervisory advanced control of glass melters and forehearths by expert system.* In Proc. Int. Congr. Glass 2001; 1: 247-254.

Gebhart B. *Heat Transfer*. 2^{nd} ed. New-York : McGraw-Hill. 1971.
Hottel HC, Cohen ES. *Radiant heat exchange in a gas-filled enclosure: allowance for non-uniformity of gas temperature.* AIChE Journal 1958; 4(1) : 3-14.
Hrma P, Barton J, Tolt TL. *Interaction between solid and liquid and gas during glass batch melting*. Journal of Non Crystalline Solids 1986; 84 : 370–380.
Op den Camp O, Verheijen O, Huisman L, Van Deelen S, et Backx T. *The use of glass process simulation for control of glass quality in glass production.* In Proc. 20th Int. Congress on Glass 2004; Kyoto, Japan.
Op den Camp O, Gerlings P. *Fast hybrid simulation models*. In Proc. VI. International Seminar on Mathematical Modeling and Advanced Numerical Methods in Furnace Design and Operation 2001; Velke Karlovice, Czech Republic.
Paarhuis B, Lankhorst A, Riepen M, Velthuis JFM. *A rapid simulation model of the combustion space of glass melting furnaces.* In Proc. 5th Int. Conf. on Technologies and Combustion for a Clean Environment 1999; Lisbon, Portugal.
Pina J, Lima P. *A multiobjective optimisation system for a glass furnace.* In Proceedings of the European Control Conference 1999; Karlsruhe, Germany.
Qin SJ, Badgwell TA. *An overview of industrial model predictive control technology.* In Proc. 5th Int. Conf. on Chemical Process Control. AIChE Symposium Series 1997; Edinburgh, Scotland.
Ressencourt H. *Temperatures control in a glass bath – feasibility study*. Student Final Year Project; Institut National Polytechnique de Lorraine ; 2004.
Schill P. *Progress in mathematical simulation and advanced control of glass aggregates*. In Proc. 20th Int. Congress on Glass 2004; Kyoto, Japan.
Tooley FV. *The handbook of glass manufacture.* Ashlee Publishing Co., Inc; 1961.
Trier W. *Glass melting furnaces, design and operation*. Berlin : Springer Verlag; 1984.
Tucker RJ. *Evaluation and development of the zone method for modelling metal heating furnaces.* PhD Thesis at The Open University, Milton Keynes; 1990.
Verheijen OS. *Thermal and chemical behaviour of glass forming batches.* PhD Thesis at Technische Universiteit Eindhoven, Netherlands; 2003.
Veynante D, Vervisch L. *Turbulent combustion modeling*. Progress in Energy and Combustion Science 2002; 28 : 193–266.
Ungan A. *Numerical simulation of glass melting furnaces : a review.* In Proc. of Int. Symp. on Glass Problems 1996; Istambul, Turkey.