SIMPLIFIED FIRST-PRINCIPLES MODELLING OF GLASS FURNACES FOR CONTROL PURPOSE

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Abstract : Control of glass furnaces has known a great expansion in the last decades, particularly with model-based operation optimisation methods. The challenge is to get models covering the whole operating range and at the same time presenting a low computational load. The most widespread models today are data-based or issued from CFD techniques, and the need for accurate fast models is important. Our model based on first-principles and using the zonal approach shows a good compromise, and we will investigate its applicability to control purposes in further studies. *Copyright © 2002 IFAC*

Keywords: Model-based control, optimal control, physical models, multivariable control, Non-linear models.

1. INTRODUCTION

Operation of glass furnaces is becoming more and more delicate due to ever increasing social and environmental constraints coupled with classical energy costs minimizing and optimal operating constraints. Glass industry is an intensive energy consumer and is therefore severely controlled by the environment experts. To help the operators in controlling the furnace, performing control structures are developed (Carvahlo, *et al.*, 1997, Chmelar, *et al.*, 2001).

Among them, model-based methods have shown a great success due to the increasing computational power of computers. Knowledge of the system behaviour thanks to mathematical relations allows to optimise the control decisions (Carvahlo, *et al.*, 1996). One of the most widespread method is the Model Predictive Method (MPC), which consists in determining the input sequence that optimises the system evolution on a future horizon. Models used in control structures are widely disparate. From first principles computational fluid dynamic (CFD) models to empirical fuzzy logic learning systems, the robustness and performance of the control will depends on the accuracy of the model. On the other hand, the computational cost of simulating the model is also important to consider. More generally, two things are required for models for control purpose :

- To cover the furnace operating range to be controlled
- To present a low computational load

Therefore, when developing such a model, the compromise between accuracy and CPU time leads the choices. Time to build the model and return on investment period is also an important criterion to consider.

Empirical models are obtained thanks to heavy identification tests on actual plants, and the slow dynamics of glass furnaces make the tests campaigns very long (several weeks). Moreover, identification models refer to particular operating points and present therefore important deviation from reality when furnace operation changes. However, the advantage of empirical models is to allow very fast simulation. CFD models cover the whole range of furnace operation with great accuracy at the cost of heavy computational load. Their greatest advantage is to predict non measurable phenomenon and their principal drawback is long development time.

Today, research efforts are made to provide fast models for control purpose that are still accurate enough to represent relevant dynamics (Backx, *et al.*, 2002, Huisman, *et al.*, 2001). We are working on the simplified modelling of a glass furnace, based on first principles applied to a rather coarse mesh in the three parts of the furnace (combustion chamber, bath and walls). The advantages of such a model is to avoid long identification tests and CFD models heavy computational load. We will investigate in further studies whether or not this kind of model can be used for control purposes.

We present first the glass furnace and some control features associated to it, and we describe then our model.

2. THE GLASS FURNACE

2.1 System description (Tooley, 1961)

The glass furnace is the kernel of industrial glass producing lines. Depending on the type of glass produced, the technology varies but the principle is the same. Raw materials are loaded to the bath and thanks to heat release from the heating system, glass forming reactions occur. The molten glass is then mixed and homogenised due to natural convection streams. At the end of its residence time in the bath, the molten material can finally be used for further processing (blowing or floating).

The melting temperature of raw materials (69% SiO2) is round 1500°K, and to achieve such temperatures in the bath, heat is obtained by oil or gas combustion in the combustion chamber and/or by electric Joule effect. The losses through walls make the furnaces overall efficiency low (50%). Glass furnaces differ mainly by their heating system (energy used) and their shape, both influenced by the type of product considered. We focus on regenerative or recuperative oil and gas fired furnaces. Regenerative systems stores the heat of combustion gases in huge refractory towers (regenerators) and use it back to preheat combustion air. The principle is to alternate the currents of cold air and hot gases in two regenerators. Recuperative systems are based on heat exchanger principle. The shape of the furnace depends on the type of glass produced, with following rule : the higher quality required, the longer the residence time needed in the bath, the longer the bath. Of course, the burners number and location will be influenced by the size of the melting zone.

2.2 Control tasks (Backx, *et al.,* 2002, Chmelar, *et al.,* 2001)

The control tasks inside a glass furnace are distributed on three different hierarchical levels (cf. table 1). The primary goal is of course the glass quality, which corresponds to purity from defects (blisters, cords, stones) in the molten glass ready for further processing. This control task is characteristic from glass industry, where as the other first level goals are classical industrial process control constraints. The overall control task is therefore optimisation of glass quality under optimal operating constraints.

Quality of molten glass depends on melting process and environment conditions. One distinguishes primary defects from secondary defects, where the firsts are consequence of a bad melting process due to bad reaction conditions, and the seconds come from perturbations of the reaction by the environment (reaction with flame, refractories exudation etc). So, quality control requires to create the optimal conditions in the bath for the melting reaction. Of course, every manipulated and controlled variable has to remain within specific limits.

Table 1 Hierarchical levels of glass furnaces control tasks

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

The bath is composed of different zones (cf. fig. a). The batch zone (1) is where the raw materials containing all the ingredients needed for glass forming are introduced as wet packets into the bath. They float on the melt surface until the chemical reaction of melting occurs thanks to heat transfers. During melting, the newly formed glass sinks in the bath within a second zone (2) characterized by a great amount of remaining sand grains and bubbles. At this stage, the molten glass is not yet usable for forming and it needs to be homogenised and refined. Temperature gradients and additional systems in the bath create laminar natural convection streams that allow this homogenising to occur. During its residence time in the bath strongly depending on the convection streams pattern, molten glass will purify from sand grains and bubbles (3). The tank is designed such that molten glass in the last section, called buffer zone (4), is ready for end-product forming. We don't study the conditioning and forming sections, but great control challenges are also involved in them.

The physical phenomenon just described are distinguished as melting, mixing and homogenising, and fining/refining. These phenomenon involve other processes, as for example fining which is constituted of diffusion of gases and chemical reactions with the fining agents. All these phenomenon strongly depend on temperature and temperature gradients in the melt, and they need time and particular conditions of mixing to perform well. Their control is allowed by manipulating heat input to the bath (control task of level 2 in table 1), which is often related to the crown and bottom temperature profiles. Bubbling, cooling and raw materials pull rate also influences the different processes.

Control of combustion remains the greatest 2nd level control task in a glass furnace, because it is the major heat production source for the melting processes and for the driving of the flow. It involves maximum

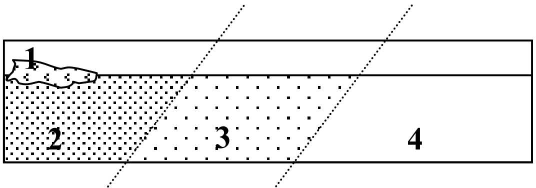

Fig a. Zones in the bath

flame temperature, total heat power and flame pattern. The manipulated variables are the air and fuel flows and preheating temperatures at each burner port. Many constraints directly linked on combustion process exist on pollutants emission, fuel efficiency, etc. Other technological constraints as refractories maximum temperature, direction of the flame are to be considered.

2.3 Control strategies (Chmelar, *et al.,* 2001)

The control of the above mentioned physical phenomenon in the bath is very complex for several reasons. There are strong couplings between them and also with the combustion process in the combustion chamber and the heat diffusion in the walls. This problem is typically a multi-objective optimisation problem of a highly-coupled non-linear multiple-input/multiple-output (MIMO) system.

To each level in the different control tasks table correspond adequate control strategies. Actually, a control task of one particular level will generate set-points for some control tasks located one level below. Level 1 control tasks use much operator knowledge and off-line simulations to determine the optimal operation conditions. Today tools include expert knowledge to allow automatic control at this level (at least help the operator in decision), and propose integrated control of the furnace. Level 2 control tasks are automated and state-of-the art control techniques propose very interesting strategies as will be shown below. At the bottom level, process variables are controlled in classical control loops as PID controllers.

PID controllers are still widely used today in 2nd level control tasks, as for example temperatures control in the furnace different sections. But the complex coupled dynamics, the long dead times as the multi-objective control tasks are hardly handled by PID strategies, better suited to single-input/single-output dynamics. Therefore, advanced process control seems to be the only solution, and multiple-input/multiple-output (MIMO) model-based operation optimisation methods have the greatest success. Model predictive algorithms optimise the future evolution of the plant according to multi-objective criterions by determining the adequate input sequence using the model of the system. The algorithm used is therefore known as prediction-optimisation. In the optimisation algorithm, the criterions of table 1 have to be translated into costs functions that will be minimized on a future horizon. To predict the system evolution, models are required and we later describe a dynamic model presenting an interesting alternative to today used models. There are namely first principles based CFD models and data-based models. The compromise that has to be considered with models for control lies between model accuracy and computational load.

CFD models cover the whole operating range with a great accuracy at the cost of very heavy computational load (Carvahlo, *et al*., 1997). They often include many physical phenomenon, but cannot be simulated in real-time and are thus unsuited for control. Reducing techniques like Proper Orthogonal Decomposition allow to get fast models from CFD ones that can be used for control purpose ((Backx, *et al.,* 2002). Data-based models use actual plant measures to identify a model behaviour. They result in fast models but are hard to obtain due to long and painful tests campaigns. Moreover, they are only valid for particular operating points. The model we present here is based on first principles applied to a coarse decomposition of the three parts of the furnace (combustion chamber, bath and walls). It covers the whole operating range at a low computational cost, and hence is typically what is required. We will investigate its use for control purposes in further studies.

3. MODELLING

The model has the manipulated variables as inputs, and the controlled variables as outputs.

Table 2 : model inputs and outputs

Inputs	Outputs
• Fuel & oxidant flow at each burner port	• Combustion chamber temperatures points
• Preheating temperatures and pressures of air & fuel flows at each burner port	• Combustion chamber pressure points
	• Refractories temperatures points
• Raw material pull rate	• Bath temperatures points

The structure of glass furnace models follows the spatial location of the different physical phenomenon (Carvahlo, *et al*., 1997). We therefore first decompose the furnace into three parts : the combustion space, the bath and the walls. This decomposition is done to handle the very different physical phenomenon occurring in these parts, in term of characteristic times principally. We thereby separately consider the turbulent reactive flow in the combustion space, the convection streams in the bath, and the heat transfers at and in the walls (see fig. b), and the coupling between these phenomenon.

The classical CFD approach (Ungan, 1996) is based on first-principles modelling, where conservation laws on energy, momentum, mass and mass fraction constitute the backbone of the model, and where closure models for turbulence, combustion etc. are used. Our model uses exactly the same concept, but to reduce the computational load, we have chosen to play on accuracy. The zonal method initially developed by Hottel (Hottel, *et al*., 1958) for combustion chamber modelling considers volume

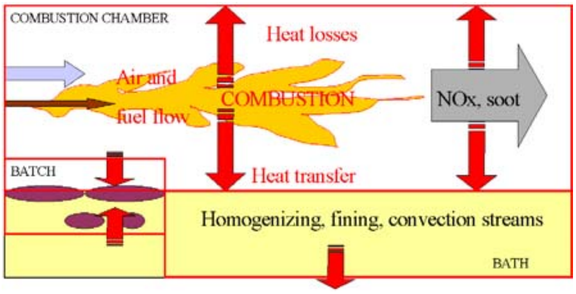

fig.b: Physical phenomenon

and surface cells in which the classical conservation laws with closure models are applied. By choosing a rather big size for the cells, the number of equations decreases accordingly. Compared to several thousands nodes in classical CFD computations, our model treats between few tens and few hundreds cells and considers only the main physical phenomenon. The computation load is greatly reduced. Of course, the model has to show as little as possible deviation from reality. The challenge is to choose the zones in order to correctly represent the relevant phenomenon.

We motivate our research on positive experiences of leading glass modelling research centres using this approach in the combustion chamber and in the whole furnace (Goodson, *et al.*, 1979, Liu, *et al.*, 2001, Huisman, *et al.*, 2001).

3.1 Modelling of the combustion chamber

We apply the approach of TNO with its Rapid Combustion Model (Paarhuis *et al.,* 2000). The heat input profile from combustion chamber to the bath is of major influence on the melting, mixing and fining processes. This profile is manipulated through the fuel and air flows. It mainly depends on the flames, and this leads the spatial decomposition process.

The phenomenon to take into account are the turbulent flow, the heat transfers by radiation and convection. The flow is complex, with recirculation of gases above the flames, but we simplify considerably by considering it unidirectional in the chamber height. The direction is given by the flames and the exhaust ports location. We do a 2D spatial decomposition in the horizontal plan with burner sections divided into cells (typically between 3 and 10 cells per section). See the example of a three burners combustion chamber in fig. c.

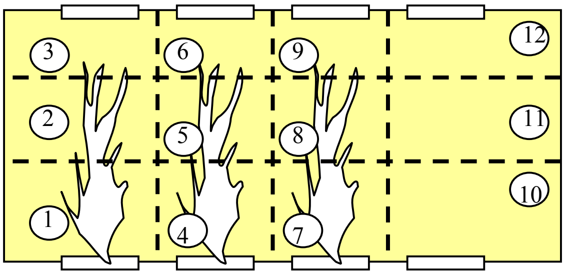

fig. c: 3 burners combustion chamber

The goal is to determine the heat release of the combustion gases in each cell. We have first to determine the *flow* in the cell, the *compositions* of the atmosphere and the associated *combustion reaction*. When this is done, we have to compute the *heat transfers* by radiation and convection to the load and to the surrounding (losses).

Modelling of the reactive flow

In each cell k of a combustion section, we have to compute the density ρ_k, the mass flow rates Q_k, the mass fractions Y_k^j of each specie j considered (specified later), the enthalpy h_k, and the temperature T_k, all assumed uniform. We assume the pressure known and uniform, as the mass flow rates at the entrance of the furnace. To compute these (4+s)*n unknowns for a n zones section in purely convective regime and a mixture composed of *s* chemical species, we use the following set of equations discretized with the one dimensional finite volume approach in the n volumes.

ρ : ideal gas law : (n equations)

$$\rho = \frac{P}{\sum_j \frac{Y_j}{M_j}.R.T} \tag{1}$$

Q_k : mass conservation : (n equations)

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0 \tag{2}$$

Y^j : mass fraction transport (s*n eq.)

$$\frac{\partial \rho Y^j}{\partial t} + \frac{\partial \rho u Y^j}{\partial x} = \dot{\omega}_j \tag{3}$$

h : energy conservation (n equations)

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho u h}{\partial x} = \dot{S} \tag{4}$$

T : iterative computation using enthalpy equation : (n equations)

$$\sum_{i \equiv all \quad species} Y_i \left(\Delta h_{fi}^0 + \int_{T_{ref}}^{T} C_{pi}\, dT \right) = h \tag{5}$$

Where M_j is the molar mass of specie j, C_{pj} the specific heat of specie j, and R the gas constant. $\dot{S}$ is the energy sink/source term. Δh_{fi}^0 is the standard formation enthalpy of specie i.

Let us explicit the combustion related source term appearing in (3), which is the production/destruction term of specie j ($\dot{\omega}_j$). We consider combustion of hydrocarbon (C_mH_n in general, but we focus on methane) with oxidant (oxygen and nitrogen). We use the Single Chemically Reacting System (SCRS) assumption (irreversible forward single-step reaction kinetic) together with the *mixed-is-burned* assumption (infinitely fast chemistry). Due to the SCRS hypothesis, we only consider CO_2, H_2O, unburned and inerts in the combustion products. The regime of the combustion has to be determined by studying the richness of the mixture in each volume and the reaction rate is proportional to the fuel flow according to the mixture richness.

Due to the mixed-is-burned assumption, combustion would occur in the first cell of a section only, inducing short flames. It doesn't well represent the reality, where the flows of fuel and oxidant are mixed in the turbulent eddies, creating long flames. To represent this behaviour, we introduce in each cell a weight $(\alpha_k < 1)$ on the reaction speed ($\alpha_k \dot{\omega}_k$). The coefficients α_k represent the influence of the mixing flow on the combustion. We tune the coefficients to best fit reference temperature fields.

Modelling of convective and radiative heat transfers

The source term $\dot{S}$ in energy equation corresponds to heat transfers by convection and radiation in the reactive flow.

Convection

Convective heat transfers between two adjacent elements i and j at temperatures T_i and T_j (flow cell i with flow cell j or with wall element j) presenting a common area A_{ij} is very simply computed by :

$$q_{ij} = h_{ij} \cdot A_{ij} \cdot (T_i - T_j) \tag{6}$$

At the current time, we estimate the forced convection coefficient h_{ij} (around 15 W/m²/K for flow/wall exchanges f.e.) but we will include an empirical method.

Radiation

Due to high temperatures, radiation is preponderant and particular attention is therefore paid for its modelling. Each element of the decomposition emits, reflects and absorbs radiation, and we have to take into account the presence of strongly emitting and absorbing particulates such as soot in the chamber atmosphere. The methods best suited to zonal models are those based on exchanges areas (Hottel, *et al.*, 1958) which use influence factors (called view factors) between all elements of a spatial decomposition (volumes and surfaces). The influence factors quantify the distribution of the power emitted by each element to all other elements of the decomposition. The greatest drawback that makes this method unsuitable for applications requiring precision is the grey body assumption. This leads to such great errors that one often prefers the computationally intensive resolution of radiative transfer equation. However, for our purpose, the exchange areas method is the more adequate.
We use the Gebhart formalism (Gebhart, 1971) which considers total absorption influence factors. In the computation of influence factors between two elements i and j, the 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.

The complexity of exchange areas method is to compute the view factors because there are volume and surfaces integrals. For surface-surface view factors, we found simple analytical relations based on contour integration. For volume-volume and volume-surface view factors, we had to compute them by using the method described in (Emery, *et al.,* 1987). This method extends a scan line algorithm, based upon surface-surface radiation, to the computation of surface-gas an gas-gas radiation transmittances.

Finally, the radiant heat fluxes (W) of all elements are obtained thanks to the net radiative balance in a very simple vector form :

$$q_{rad} = BW - W \tag{7}$$

Where the second term on the right hand side is the emitted powers vector ($W \equiv \varepsilon T^4$), and the first term is the distribution of emitted powers between all elements taking gas absorption into account (B is the so called Gebhart matrix containing total absorption factors, taking multiple reflection into account).

The preceding relations allow to compute the reactive flow, the heat release by combustion and the preponderant heat transfers by radiation. This constitutes a boundary limit for the bath and walls models, that we describe now.

3.2 Modelling of the bath

The phenomenon occurring in the bath are numerous and complex. We have described the principal in the control tasks description part : Batch melting, mixing/homogenizing, fining/refining are strongly dependent on temperatures and temperatures gradients fields. Other processes important for the dynamic of the bath, as bubbling and gas releasing, are also depending on temperature, but they are not taken into account in the modelling,. The convection streams are driven mainly by temperature gradients. The temperatures are therefore the controlled variables in the bath. We use again a zonal decomposition in the bath, and we get a temperature point per cell. The model is articulated around mass and energy balances in each cell, considered as a well-stirred reactor. The flow pattern corresponds to mass exchanges between cells. We assume it known, and take typically two circulation rolls due to natural convection (cf. fig. d). It is possible to modify it during simulation or control. The source terms in the energy balance are diffusion and radiation heat transfers. Radiation is taken into account thanks to the Rosseland method, adequate because the medium is optically thick. An additive term is included in the heat conductivity for the radiation inside the bath and in the convection coefficient for the radiation to the walls. We neglect the effects of chemical reaction

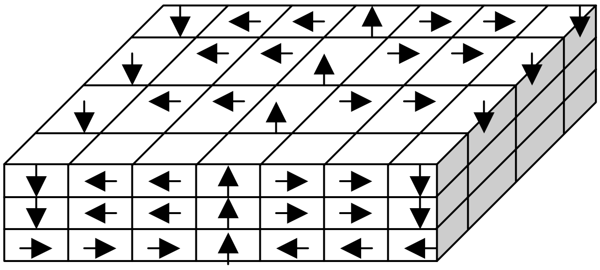

fig. d : coarse spatial decomposition in the bath

and refining in the glass. For simplifying, we consider the glass level constant.

3.3 Modelling of the walls

Refractories surface temperatures are very important to monitor, because they influence greatly the heat transfers to the bath. Crown and bottom temperature profiles are manipulated variables for bath temperature control. These temperatures have to remain in acceptable limits to avoid glass secondary defects.

The phenomenon to consider are the diffusion of heat in the walls, and convective and radiative transfers at the sufaces. We use the method of thermal quadrupoles (Maillet, *et al.*, 2000), which is based on time-Laplace transforming of diffusion equation and writing in a quadrupole form of the transfers of the temperature/thermal-flux vector in a flux tube. This formalism coupled with numerical inversion of Laplace transforms yields interesting results in term of rapidity, and the method is simple to implement.

In our case, the decomposition into volumes of the combustion chamber or bath induces a spatial decomposition of the walls into wall elements. We consider each wall element as a two layers slab (refractory and insulation) in 1D-diffusion and we compute the correponding transfer matrix of temperature-flux between internal and external sides. Knowing the temperatures inside and outside the furnace, as the radiative and convective flux at each surface of the wall element, we can determine the temperature at every point of the wall.

4. CONCLUSION

Control of glass furnaces is a so complicated task that advanced methods have to be used. Model-based methods are the more successful and the challenge is to get models showing short computation times for the best accuracy. We have proposed a model based on first principles applied to a coarse zonal decomposition.

In future studies, we will improve the modelling of the bath by testing different simple models, and we will test the applicability of the model to control. Its low computational load makes it anyway interesting for other applications like simulation for operator training.

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