Glass Furnace, Simplified Modelling for Control and Real Time Simulation

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Abstract — **Glass furnace is an intensive energy consuming industrial process, and the efforts made to optimise its operation are great. Currently, in many countries over the world, the most important challenge for glass industrials is to meet at low cost the more and more severe environmental constraints on pollutants emissions. Control of combustion and better furnace operation are two fields where much can be gained. The need of rapid models for control algorithms and real time simulation is therefore important. Already good results have been obtained by using the zonal approach for the combustion chamber. We present here the application of this method to the whole furnace, aimed at obtaining a rapid model for the global plant.**

Index Terms—**glass furnace, zone methods, low computational load.**

I. Introduction

The guidelines of the huge R&D efforts made around glass furnaces have changed at the 80-90 turn. First dedicated to optimisation of the still very poor system efficiency (50%) and reducing of energy costs, priorities since one decade are more dictated by the expanding environmental regulations. With earth global warming in background, more and more constraints on gas and particulates emissions (NOx, SOx, CO2, soot) are applied to industries. The key areas are therefore improvements in emissions control, recycling methods and solid waste management [1]. The additional costs to meet environmental compliance in form of gas treatment installations for example as the widely disparate regulations in the different regions of the world constitute a tremendous challenge for the glass industry in the next few decades.

Glass makers have to step forward on a narrower and narrower way, as the productivity of furnaces can still be increased interestingly [2]. An important area of interest is the combustion chamber, with study of staged and oxy-fuel combustion, reburning, low-NOx burners. The focus is also set on a better understanding of heat transfer mechanisms in the furnace, and on finding better ways to minimize losses. More than never, simulation remains the best way to investigate new designs and operating conditions. In the applications just mentioned, Computational Fluid Dynamic (CFD) simulation implemented on fine mesh grids allow to get very precise prediction at the cost of heavy computation load.

However, these models are inadequate for the numerous applications requiring short computation times, as model-based control of glass furnaces operation (temperatures and pollutants emission). Faster than real-time prediction has to be run, and the only solution is to use simpler yet precise enough models [13]. Today, the most widespread method is data-based, with black-box models issued from expensive on-site identification campaigns that are valid around the identified operating point only [6].

Simplified first principles models don't have these drawbacks, and their flexibility make them very interesting for such applications. Development of this kind of models for glass furnaces has already been investigated in different institutes, and the use of zonal method is the most widespread [12]. It is based on spatial decomposition of the furnace into macroscopic zones, in which one applies simple balance equations [8] and represents the different physical phenomenon. An other method consists on reducing complicated CFD models thanks to proper orthogonal decomposition.

The current results of zones method show very interesting perspectives. In [12], the zonal method is applied in the combustion chamber, and simulations present less than 5% variation from classical CFD results for a rapidity up to 6 times faster than real time. In [5], an other application of zones method to oil-fired furnaces is focused on transient state calculation with good accordance to reference.

Motivated by the need of such models and the good results of zone method, we investigate the validity of a first-principles model based on a coarse spatial decomposition of combustion chamber, bath and walls. We present here first the glass furnace and the modeling approach We conclude with applications and perspectives.

II. The Glass furnace [14]

The glass furnace is the kernel of industrial glass producing lines. Depending of the type of glass produced, the technology varies but the principle is the same. 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. The losses through walls make the furnaces overall efficiency low (50%).

Glass furnaces differ mainly by their preheating system of combustion air and by their shape. Figure *a* shows the principle of the type of furnace we consider : namely a regenerative side-port glass furnace. The raw materials are loaded through the doghouse to the bath in form of 50 kilos packets. Thanks to the heat release from combustion chamber above the bath, the glass melts in the first part of the bath and is slowly driven towards the furnace end by natural convections streams in which it is homogenised and refined. At the end of its “trip” through the bath, the molten material can finally be used for forming.

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 allow heat exchanges with counter flow.

The shape of the furnace depends on the type of glass produced. The main rule is : the more quality required, the longer the residence time needed in the bath, the longer the bath. The size of the bath influences the heating system. For long ones, the burners are located on the side of the furnace (side-port type) and for shorter ones, one burner suffices and it is often located at the front end of the furnace (end-port type).

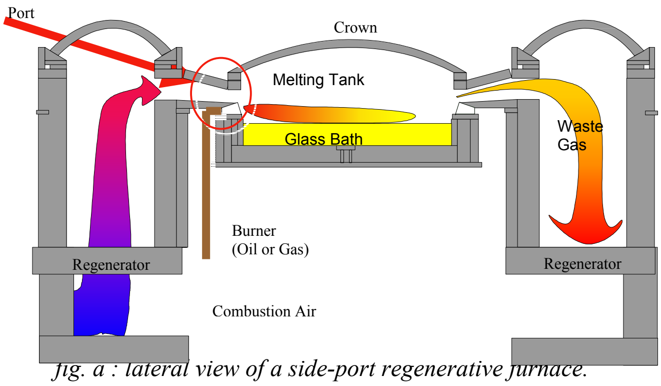


fig. a : lateral view of a side-port regenerative furnace.

III. MODELLING

We first decompose the system 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 will 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). Of course, these parts are coupled by heat transfers.

In classical simulations, a good level of precision is required and one uses computational fluid dynamic modelling methods (see for example [3]). We are of course also interested in precision, but we have to find a compromise with simulation rapidity. We have therefore chosen a zonal approach [8], which is based on energy and mass balances in macroscopic zones where coarse uniformity assumptions are made. We apply this method in the three mentioned parts, using adequate modelling methods for each physical phenomenon. We motivate our research on positive experiences of leading glass modelling research centres like TNO (Holland), using the zonal approach in the combustion chamber [12], [5].

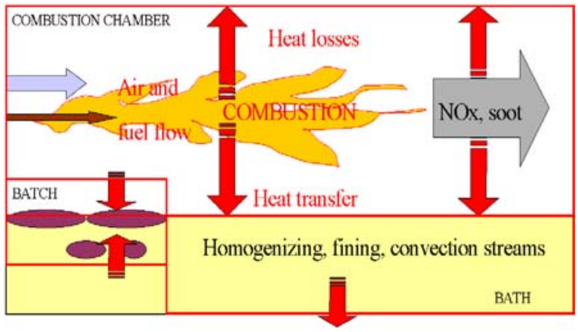


fig.b: Physical phenomenon

A. Modelling of the combustion chamber

The objective is to determine the heat release of the combustion reaction. We have first to determine the *flow* in the enclosure, 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).

We do a 2D decomposition of the combustion chamber enclosure (fig. c for a 3 burners furnace seen from above). The choice of the zones has to be adequate with the uniformity hypothesis, and the rule is one section per burner (cells 1,2,3 for ex.) and between three and ten cells per section, [12] and [5]. For us, the flow is first the definition of mass transfers between cells, and we assume it one directional in the flames direction. Then, the volumetric flows depend on the input flows of fuel and air, and on the combustion reaction.

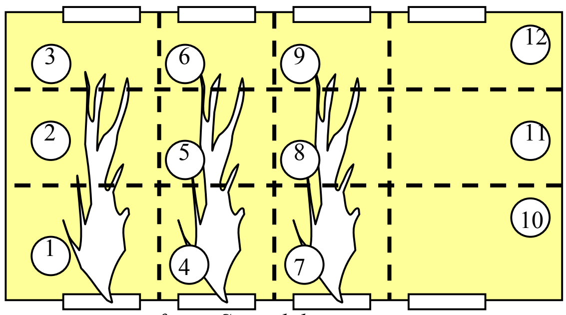


fig. c: Spatial decomposition

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)

$$\rho = \frac{P}{\sum_j \frac{Y_j}{M_j}.R.T} \quad (1)$$

Q_k : mass conservation : (n equations)

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u A}{\partial x} = 0 \quad (2)$$

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

$$\frac{\partial \rho Y^j}{\partial t} + \frac{\partial \rho u A Y^j}{\partial x} = \dot{\omega}_j \quad (3)$$

h : energy conservation (n equations)

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho u A h}{\partial x} = \dot{S} \quad (4)$$

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

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

Where A is the section area, M_j 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, propane and octane) 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 $(\alpha_k < 1)$ over the reaction speed ($\alpha_k \dot{w}_k$). The coefficients α_k represent the influence of the mixing flow on the combustion. We will tune the coefficients to best fit reference temperature fields.

We give here some samples of simulation results of the above model. The study of adiabatic temperature behaviour against typical amounts (equivalence ratio (fig. d), N2/O2 ratio) shows good accordance with theory. The dynamic behaviour (fig. e) also approaches [5] results.

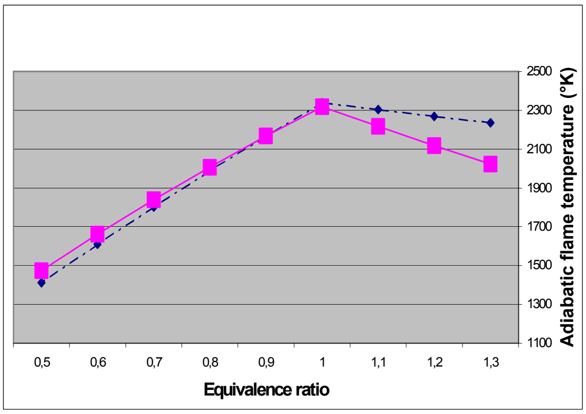


fig. d : Equivalence ratio influence on the adiabatic temperature of methane combustion (our model : solid lines ; theory (with dissociation) : dot lines)

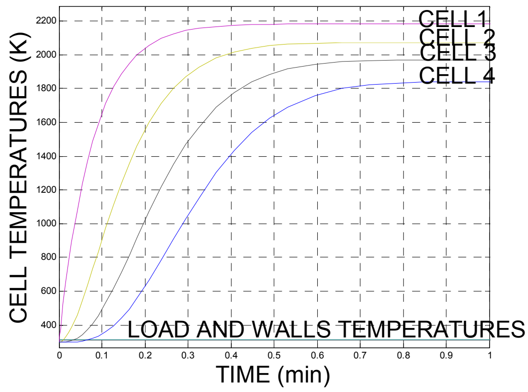


fig. e : transient volume temperatures in a 4 cells combustion section

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 jor with wall element j) presenting a common area A_{ij} is very simply computed by :

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

At the current time, we estimate the forced convection coefficient h_{ij} (around 12W/m²/K for flow/wall exchanges f.e.) but we will include a more sophisticated method in the future, as the Lebedev estimation method [5]. In the figure e, the decrease in temperature observed with the cell index is due to convective transfers to the walls and load.

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, 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 valid.

We use the Gebhart formalism [7] 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. For volume-volume and volume-surface view factors, we had to compute them by using a simple form that possesses all influences in its structure (absorption along a path, conservation of flux and volume influence). So, the influence factor between the volume element *j* emitting toward volume element *i* distant of d_{ij} through a gas of absorption coefficient K is given by :

$$g_i g_j = \delta_i \cdot V_j \cdot K^2 \cdot \frac{\exp^{-K d_{ij}}}{d_{ij}^{\;2}} \quad (7)$$

Where V_j is the volume of element j. We compute all volume view factors and we tune the coefficients δ_i so that the classical reciprocity and complementarity relations are verified. Special attention has to be paid for self-irradiation influence factors.

Finally, the radiant heat fluxes (W) of all elements are written in a very simple vector form :

$$q_{rad} = W - BW \quad (8)$$

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

We are now able 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 model, that we describes now.

B. Modelling of the bath

At our level of complexity, we are interested in flow pattern and temperatures in the glass bath. Temperature is a quality index for the final product. To determine it, we have to consider the flow induced by batch charging and by natural convection streams, the heat transfers by convection, radiation and conduction in the walls. These are the principal phenomenon in the bath. Of course, we negligate many other, like melting chemical, glass foaming, bubbling and 2 phase flow in the batch zone, but this is namely the compromise we seek between simulation rapidity and reality.

One time again, we apply a spatial decomposition of the bath space. The model is then articulated around mass and energy balances in each zone, as for the combustion chamber. The heat source terms are due to radiation and convection, and we are working out the implementation of Rosseland model.

The challenge lies in the determination of the spatial decomposition because the flow pattern is complicated. We are currently using following method. We assume a typical 2D float glass flow pattern with two main convection streams (solid lines in fig. f) according to experience and CFD simulations, and we fit to it a coarse spatial decomposition.

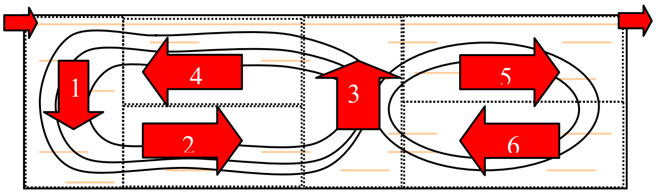
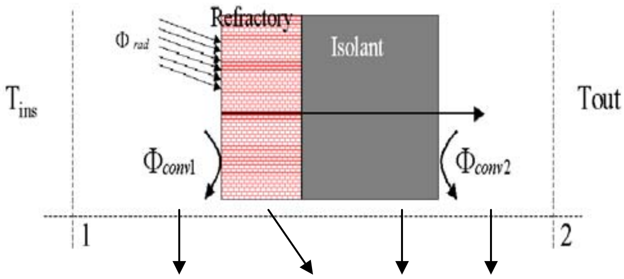


fig. f : coarse spatial decomposition in the bath

C. Modelling of the walls

The phenomenon to consider are the diffusion of heat in the walls, and the convective and radiative transfers at the sufaces. We use the method of thermal quadrupoles [11], 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 simpler to implement than usual finite-differences schemes for heat diffusion equation.

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 depth of the wall, which is of particular interest to predict temperature point at thermocouples sensors location inside the walls. Figure g shows the quadrupole for a wall element (the different transfer matrices are not explicited in this document).



$$\begin{pmatrix}\theta_{ins}\\ \phi_{ins}\end{pmatrix}=\begin{pmatrix}1 & \frac{1}{(h_{ins}S)}+\frac{1}{(h_{rad}S)}\\ 0 & 1\end{pmatrix}\begin{pmatrix}A_1 & B_1\\ C_1 & D_1\end{pmatrix}\begin{pmatrix}A_2 & B_2\\ C_2 & D_2\end{pmatrix}\begin{pmatrix}1 & \frac{1}{(h_{out}S)}\\ 0 & 1\end{pmatrix}\begin{pmatrix}\theta_{out}\\ \phi_{out}\end{pmatrix}$$

fig.g : Conductive transfers modelling

IV. Applications

We are currently working out the use of the model in two different applications, together with a German division of Siemens.

The first is to extract from the non linear model linear sub-models valid for particular operation conditions. The goal is to use these linear sub-models in model predictive control (MPC) algorithms of the furnace. In classical MPC actually, the models are obtained thanks to very expensive and uncomfortable identification campaigns on the actual plant [13]. Therefore, an interesting way to circumvent this problem is to use first principles models for the low frequencies, and shorter identification campaigns for the relevant fast dynamics [10], [6]. Such models can support the operator in its decision by predicting on long time scales the influence of its actions, or by proposing optimal commands.

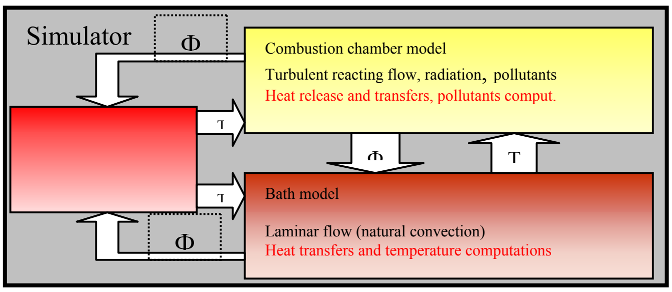


fig.h : Global structure of the simulator

The second application is to introduce the model in a simulator of an Operator Training System (OTS). The model has to be simulated faster than real time, to allow short training sessions. The complexity lies in the correct coupling of different solvers to ensure convergence of the simulation [9] (see fig. *h*). We have done a prototype of an OTS which allows different furnaces configurations to be tested, with a "repeat scenario" function to train particular transients.

V. Conclusion and Perspectives

Modeling is widely used in the glass industry, and the need of simple models is important. In this document, we have shown the development of a simplified glass furnace model based on the zonal approach applied in the whole system. The challenge is to model complex physical phenomenon with a coarse approach.

The perspectives of our work are numerous. First, in the modeling, some physical phenomenon of importance could be taken into account to better fit the reality : Among them are chemical dissociation at high temperatures and estimation of glass flow pattern in the bath. Then, the most interesting perspective is the use of the model in model-based control structures. Rapid simulation for Operator Training is a key area too and other applications like rapid optimization are also very interesting. Using the model for test series would allow to make parametric studies for optimization purposes.

VI. References

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