Energy Savings and Glass Quality Improvement by Mathematical Modelling and Advanced Furnace Control

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Introduction

The goal of the latest strategy in glass companies is to decrease the cost of production while maintaining or increasing the glass quality. There are several perspective ways leading to this goal: Optimization of the heating system, Modification of the furnace design, or Installing the new advanced control system. Optimization of the heating system can be achieved by installing modern burner system, re-arranging the burner locations, changing the type of fuel, or installing the electric boosting into the existing furnace. Using the advanced control system leads mainly to the stabilization of the furnace operation which results in energy saving and glass quality enhancement.

The use of the **CFD** modeling capability represented by Glass Service Glass Furnace Model (**GS-GFM**) and the use of advanced control represented by GS **Expert System *ES III*$^{\mathbf{TM}}$** are presented in this contribution.

Simulation of the glass furnace by mathematical modelling

Modern mathematical model is fast, variable and yields multiple results at relatively low cost. The advantage of mathematical approach lies in simultaneous solution of many production, design, and technological tasks by using just one universal tool which is called mathematical modeling. Mathematical modeling is performed by CFD code. One of the world leading companies in CFD code development including sophisticated methods of results applications is Glass Service Inc. Its CFD code - **Glass Service-Glass Furnace Model (GS-GFM)** has been developed since 1990 and it is based not only on excellent usage of modern numerical methods but ,moreover, on long-term experience of furnace engineers and on knowledge base of technology and design of plenty of furnaces operating all over the world. This knowledge has been collected by multiple usage of the **GS-GFM** during 15 years of industrial application. The **GS-GFM** code calculates three-dimensional glass flow- and temperature-distribution, batch melting, and Joulean heat generation in glass space as well as fuel combustion, radiation, heat transfer and turbulence gas behavior in combustion space. The glass space and combustion space are simulated by different mathematical methods and they are iteratively coupled by using heat and mass transfer between these parts. The heat balance and energy consumption of the whole furnace are recorded during this calculation. At the end there is generated a list of energy and mass balance. Another set of post-processors enables to calculate refining ability (bubble behavior), melting ability (sand cores dissolving), various particle tracking and graphical display (2D,3D) of physical quantities distribution (temperature, velocity, pressure, electrical potentials, Jouean heat, species concentration, etc.) including animation of flows.

The **GS-GFM** code is being applied in many glass plants for solving various tasks within Float, Fiber, Container or Technical glass furnaces. The solving of each task starts with simulation of base case which is called “tuning phase” for reaching the best operation coincidence between the model and the real furnace. Further process consists of simulation of several new cases involving required furnace modifications (design, operation, heating system, etc.) followed by post-processing which involves using various tracking, melting, and refining criteria for practical interpretation of the results. At the end, all the direct and indirect results and indicators are evaluated and compared and the optimal solution for given task is selected.

The **GS-GFM** code is capable to accept lot of furnace parameters as glass pull variations, furnace detailed dimensions (full design), material composition incl. insulations of walls, bottom, and crown, glass properties in form of temperature functions (based on user specification), way of glass heating (direct heating by all types of electrodes, indirect heating by gas and/or oil burners with oxygen and/or air). The **GS-GFM** code is able to simulate all furnace types and sizes, for example regenerative, recuperative, end-fired, melters, and accepts all practical glasses as flint, amber, green, borosilicate, float, etc.

The **GS-GFM** code was used in glass industry for solving many kinds of tasks such as:

- Optimization (pull, glass quality, fuel saving) of float furnace, of container furnace, of borosilicate glass furnace, and of fiber furnace by modifying the burner location and fuel distribution.

- Study of glass level heat coverage by applying the staggered and the opposite burners arrangement in melter for fiber production.

- Optimization of float furnace by modifying the glass depth in melting part, refiner and in working part (variation of step-bottom design), by modifying the bottom insulation, and by variation of cooler position.

- Optimizing the glass melting in fiber furnace by choosing the best space correlation of electric boosting and of bubbler rows.

- Optimizing the glass melting in glass furnace by variation of boosting electrodes (location, number, phasing).

- Air- to oxy-conversion in container and in float furnace.

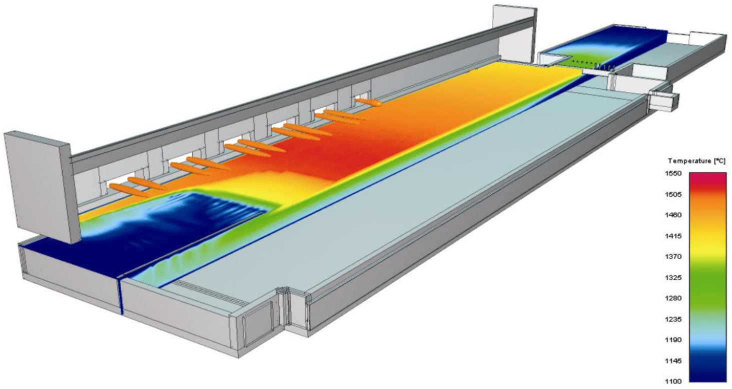

Fig. 1 Mathematical model of float furnace – design optimization

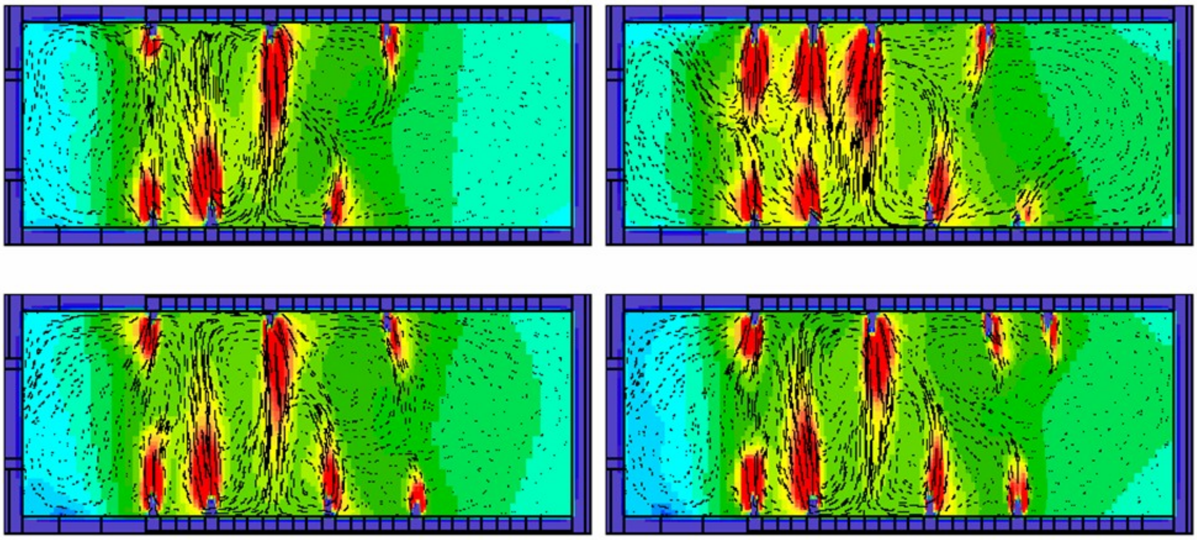

Fig. 2 Example of case study of burner locations optimization resulting in fuel saving and glass quality enhancement

During the energy optimization it is important to maintain the glass quality on same or higher level. The glass quality is estimated by calculation of residence time parameters, silica dissolution and bubbles behavior inside the glass-melt. Various criteria as melting index, refining index, and critical trajectory are investigated.

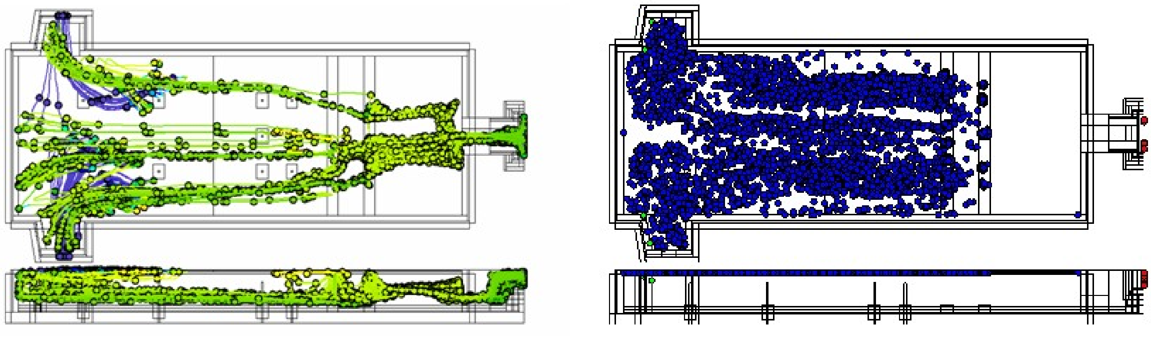

Fig. 3 Critical trajectory and fining ability investigation by postprocessors

One of the important energy optimizations means is calculation of Joulean heat distribution in glass according to the values of prescribed electrical power associated with given groups of electrodes (volume heating zones). The optimal solution can be estimated by adjusting the electrical power in each zone. On Fig.4. there is an example of 5-zone electrical boosting of a glass tank and the Fig.5 shows electrical, temperature, and flow quantities distribution in one selected cross section.

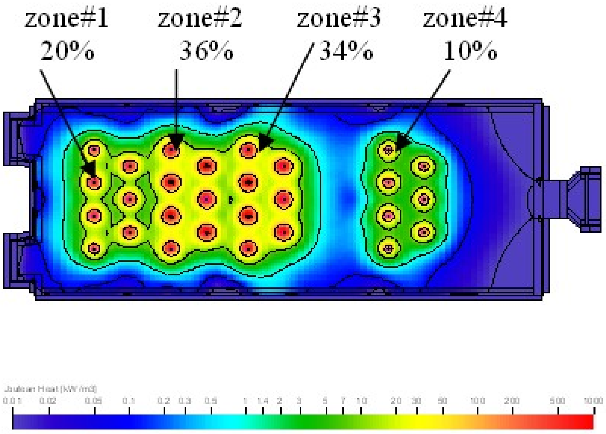

Fig.4. Zonal el.heating – Joulean heat distribution in horizontal layer 150 mm below electrodes tips

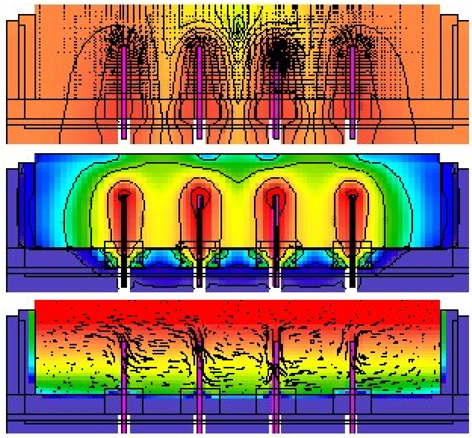

Fig.5. Values distribution in vertical section through electrodes of zone #3 (El.potential and current; Joulean heat [kW/m^3] ; Temperature and Flow)

Advanced Glass Furnace Process Control

The control is one of most important tools to increase glass quality, production, and life time of existing furnaces. There were 3 basic steps in development of control: (a) manual control based on experience, (b) system of PID loops, and (c) modern advanced control system based on multivariable predictive adaptive models.

The traditional furnace control is based on PID concept. It is typically used to control primary single input - single output loops for gas and air-flow, glass levels, or temperatures. Usually, behavior of PID results in variation around SP in some range. Reasons for limited ability of PID control are hidden in long dead time, interacting dynamics, non-linearity of processes in glass furnace, and lack of external influences information. The control based on PID loops is unable to target main goal of the whole process e.g. optimized melting, ecology, and conditioning as one task because of using large group of separated loops. The main problem with manual control lies in the huge amounts of information related to the process behavior such as the interdependence between all inputs and outputs, dynamics of those relations, outside influences, technological aspects of production, restrictions on inputs and outputs etc.

Advanced control combines the advantages of manual and PID controls as well as eliminates their faults. All information about process relationships between inputs and outputs are taken into account at the same time. It means that all interactions are considered and optimal control actions are calculated and performed. Such algorithms are independent of furnace operator strategies.

The advanced control principles will be demonstrated on function of commercial control system called ***Expert System ES III™*** (***ES III™***)developed in Glass Service, Inc. which achieves the supervisory multi-variable model based control in time and space. It is characterized by several important features:

Supervisory character means a higher level of process control. ***ES III™*** usually keeps existing control hardware and partly also the well running PID loops. The main target is to stabilize the whole process above all to improve the stability of the most important (technologically critical) process areas.

Multi-variable character (multi input – multi output (**MIMO**)) allows to specify interaction of all manipulated variables (MVs) and controlled variables (CVs), for example several temperatures (CVs) in glass together with throat temperature are influenced by adjusting all the burners (MVs).

Model based predictive control (MPC) uses dynamic numerical models of the process. In common sense the model describes outputs (vector *y* composed of temperatures, pulls, glass level,…) as function of inputs (vector u composed of fuel, oxidizer, batch charging, electric power …) via matrix form $\vec{y} = M.\vec{u}$. In general, the controller will solve a dynamic optimization problem for u_{future} that minimize the difference e_p between predicted y_p and desired behavior y_{sp}

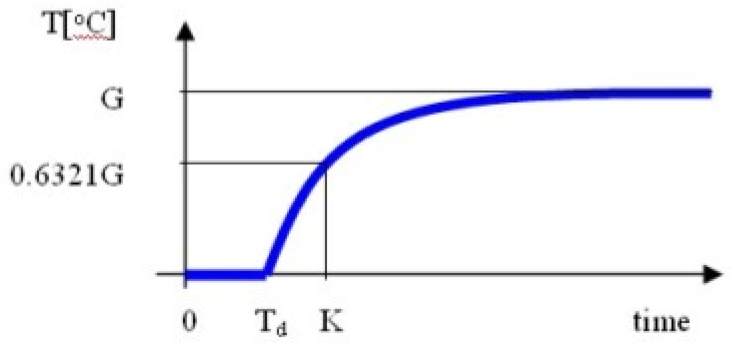

Fig.6. Model Example of the first order step response

Identification is way of obtaining the model parameters by measurement responses on small variations of input variables on existing furnace.

External Influences describe long time furnace behavior changes caused by influence of outside factors as furnace ageing, changes in batch composition, humidity, etc.

Disturbances (D) describes short time external influences as a day-night cycle in temperatures, gas calorific value changes, pressure changes etc. In each time step predicted value $y_m(t)$ is compared with actual value $y(t)$ and the error is then used again in new prediction.

Fuzzy logic control (FLC) uses empirical process data as a control tool. That means it uses a knowledge base consisting from logical rules applied to error (*e*), change of error (Δe), and change of control output (Δu). This concept uses verbal expressions as *PB* (positive big), *PS* (positive small), *Z* (zero), *NS* (negative small), *NB* (negative big) for characterizing the values of *e* ,*Δe*, *Δu* and knowledge base (matrix) given by table of all possible combinations of logical expressions. The concrete meaning of verbal values (usually with numerical overlapping) has to be created by control engineers.

Expert System ES III™ is a compact SW code connecting all the above mentioned control algorithms (MPC, D, FLC) together with the sensors, furnace outputs, and control inputs and with identification processes into one coherent system which is prepared to be implemented to any glass aggregate. ***ES III™*** has been installed using supervisory PC on industrial lines as float process, TV furnaces, container glass furnaces, and forehearths during last 10 years. A good example is applying the ***ES III™*** control to the forehearth where output glass homogeneity is characterized by 9-position temperature set-point, see Fig.7. The overview control screen composed of 4 window is presented on Fig.8. The situation of transition from manual control (red circles) to advanced control (blue circles) is demonstrated by temperature development in zones 1-4 (window#1), by heating and cooling course in zones 1-4 (window#2), by development of 9 temperatures in zone 5 (window#3), and by heating and efficiency in zone 5 (window#4). The fast action of ***ES III™*** is well visible on window#3 and #4 where the temperature homogeneity was changed from 92% to 99.5%.

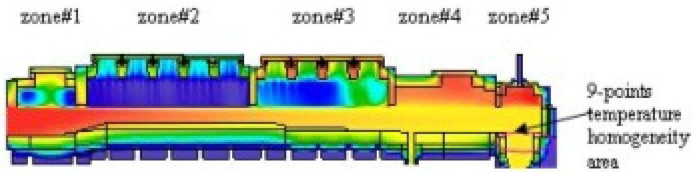

Fig.7. Forehearths with 5 controlled zones and 9-position temperature homogeneity set-point

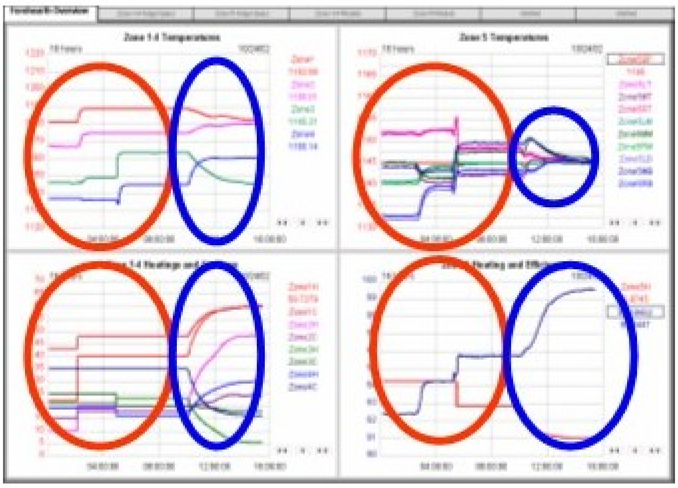

Fig.8. Four-window control screen of ESIII ™ implemented to forehearth

Glass Service Expert System ***ES III™*** belongs to advanced glass furnace control systems. Except for advantages described above, the following benefits can be expected:

- Reduced defects and increased production (1 - 5 %)
- Continuous optimized heat input distribution leads to reduced energy use (1 - 3 %)
- Reduced losses during product change (20 - 50%)
- Reduced fluctuation of furnace temperatures (40 – 80%)
- Reduced fluctuation of glass level (40 – 60%)

- Safety of operation, independent of the operator (eliminating the human factor)

On the Fig.9 there is example of the installed ***ES III™*** application on float furnace showing real numbers of energy savings up to around 2-3% which represents cost saving about 130 US$ per year.

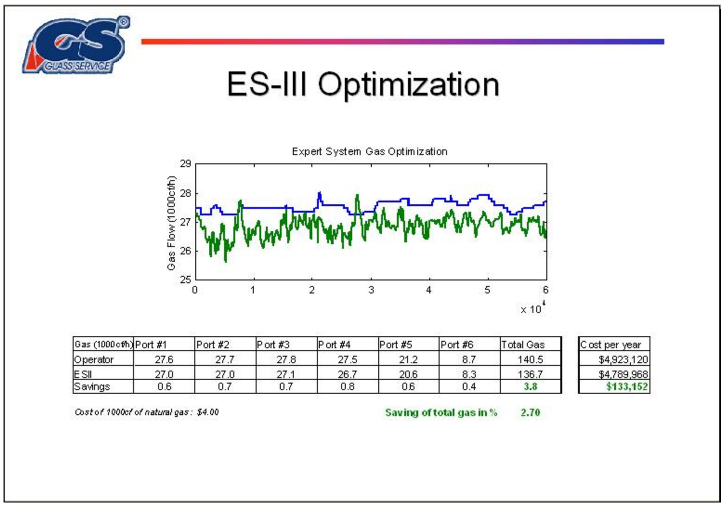

Fig.9: ***ES III™*** Gas Fuel Optimization Compared With Manual Operator's Control

Conclusions

The present stage of mathematical modeling and advanced control are able to handle with most of the melting and operational processes in all glass furnace types and complicated designs. The main goal of applying of these commercial mathematical codes is significant saving energy during glass production by keeping or increasing the glass quality at the same time. The Glass Service-Glass Furnace Model is successfully used for simulation of industrial glass furnaces for 15 years and the advanced control system ***ES III™*** is successfully operating on many industrial glass lines for more than 10 years.

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