Technical Report

Advanced combustion control – the basis for NO_x reduction and energy saving in glass tank furnaces

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1. Early intervention method for NO_x reduction and energy saving

The formation of nitrogen oxide in glass tank furnaces is a result of high local temperatures and high local concentrations of nitrogen and oxygen in the furnace chamber, mostly as a consequence of ingressed air infiltration into the furnace chamber.

Both overtemperatures and air infiltration are not required to make good glass, but they are often the consequence of inappropriate input of gas, oil and combustion air into the furnace. They can also be the consequence of insufficient control of temperatures, combustion (gas, oil, and air flows), furnace pressure, as well as reversal systems and batch charging.

Energy Saving $DeNO_x$ ($EsDeNO_x$) Technology of Software & Technologie Glass GmbH (STG) is a typical early intervention method to reduce NO_x formation and energy consumption, based on the following general ideas:

- Keep excess oxygen levels low and well controlled.
- Improve energy transfer from flames to glass and batch.
- This decreases the flame and furnace temperatures, keeping the glass temperature at an optimum level.
- This, in turn, reduces NO_x formation due to the cooler flames, and also reduces flue gas energy losses.

Therefore, this early intervention results in a decrease in NO_x formation with a decrease in energy consumption and furnace temperatures, while maintaining a high glass pull rate and high glass quality. STG $EsDeNO_x$ technology includes different process steps:

a) Lambda control based on STG lambda sensors;

b) Advanced process control solutions, such as energy profiler, fuel temperature control (BTR);

c) Optical melting control (OMC), i.e. use of batch pattern analysis in process control;

d) STG $DeNO_x$ oil and gas burners;

e) STG air curtain system to control combustion air distribution (only in the case of missing separate regenerators).

The NO_x target values reached for different types of glass, furnace and fuel as well as different burner position using $EsDeNO_x$ technology are shown in table 1.

Energy savings in the first two years of employment can completely pay for this NO_x reduction technology. Reaching these results not only requires advanced process control, but also the appropriate furnace and injector design. But either way intelligent process control is an indispensable element for this kind of technology.

Results of the STG $EsDeNO_x$ technology for different glass furnaces are shown in tables 2 and 3.

Table 1. NO_x target values for different glass, furnace and fuel types and burner position employing STG $EsDeNO_x$ technology

glass type	furnace type	burner position	fuel type	target NO_x in			target energy saving or pull increase in %	other effects
				mg/m^3 [1]	ppm NO_2 [a]	lb/t glass		
float/TV	cross fired	underport	heavy fuel oil	600 to 800	135 to 180	3.2 to 5.5	2 to 4	lower temperatures in crown and regenerator, longer service life of furnace
container	cross fired	underport	heavy fuel oil	500 to 800	115 to 180	2.5 to 4.0	2 to 4	lower temperatures in crown and regenerator, longer service life of furnace
container	endport	underport	heavy fuel oil	500 to 700	115 to 155	1.7 to 3.5	2 to 4	lower temperatures in crown and regenerator, longer service life of furnace
float/TV	cross fired	underport	natural gas	500 to 800	115 to 180	2.5 to 5.5	4 to 6	lower temperatures in crown and regenerator, longer service life of furnace
container	cross fired	underport	natural gas	500 to 800	115 to 180	2.0 to 4.5	5 to 8	lower temperatures in crown and regenerator, longer service life of furnace
float/TV	cross fired	sideport	natural gas	600 to 1000	135 to 225	3.0 to 6.0	4 to 6	lower temperatures in crown and regenerator, longer service life of furnace
container	cross fired	sideport	natural gas	600 to 900	135 to 200	2.1 to 4.5	5 to 10	lower temperatures in crown and regenerator, longer service life of furnace
container	endport	underport	natural gas	400 to 600	90 to 135	1.6 to 2.8	4 to 10	lower temperatures in crown and regenerator, longer service life of furnace

[1] Referred to standardized flue gas conditions: dry, 8 % O_2, at 1013 mbar and 273 K. These conditions will be assumed also in tables 2, 3 and 4.

[2] Referred to 15 % O_2.

Table 2. Characteristic data of a patterned and a container glass end fired furnace with burner in underport position reached after using STG $EsDeNO_x$ technology

characteristic data	starting at	changed to	result in %
patterned glass furnace:			
6 port cross fired furnace 175 m^2 melter size 330 t/d melter capacity			
NO_x	1200 mg/m^3 (8 % O_2) 268 ppm (15 % O_2) 5.48 lb/t	700 mg/m^3 (8 % O_2) 155 ppm (15 % O_2) 3.06 lb/t	−42
CO		<50 mg/m^3 (8 % O_2)	
energy saving	5320 MJ/t	5100 MJ/t	−4
heavy fuel oil burner		30	
burner maintenance		3.9 of 30/month	
average service period		7.7 months	
container glass end fired furnace:			
36 m^2 melter size 95 t/d melter capacity			
NO_x	2500 mg/m^3 (8 % O_2) 560 ppm (15 % O_2) 11.21 lb/t	285 to 350 mg/m^3 (8 % O_2) 70 ppm (15 % O_2) 1.18 lb/t	−86
CO		<88 ppm	
natural gas consumption	570 m^3/h	510 m^3/h	−10
boosting	350 kW	100 kW	−70
glass pull	95 t/d	113 t/d	18
crown temperature	1550 °C	1500 °C	
total saving by side effects		0.3 mill. US$	
return of investment		0.4 a	

Table 3. Characteristic data of a container and a float glass furnace with burner in underport position reached after using STG $EsDeNO_x$ technology

characteristic data	starting at	changed to	result in %
container glass furnace:			
5 port cross fired furnace 102 m^2 melter size 325 t/d melter capacity			
NO_x	1350 mg/m^3 (8 % O_2) 302 ppm (15 % O_2) 5.79 lb/t	680 mg/m^3 (8 % O_2) 152 ppm (15 % O_2) 2.92 lb/t	−42
CO		100 mg/m^3 (8 % O_2)	
heavy fuel oil burner		24	
burner maintenance		0.7 of 30/month	
average service period		34.3 months	
float glass furnace:			
7 port cross fired furnace (only 4 ports equipped with $DeNO_x$ technology) 460 m^2 melter size, 650 t/d melter capacity			
NO_x	1500 mg/m^3 (8 % O_2) 335 ppm (15 % O_2) 8.25 lb/t	750 mg/m^3 (8 % O_2) 168 ppm (15 % O_2) 4.05 lb/t	−50
CO		<50 mg/m^3 (8 % O_2)	
energy consumption		6180 MJ/t	
natural gas and heavy fuel oil burner		24	
burner maintenance		5/month	
average service period		4.8 months	

2. Process control in $EsDeNO_x$ technology

Energy Saving $DeNO_x$ technology (see figure 1) is concerned with

- furnace temperature control,
- well controlled input and distribution of gas and oil,
- well controlled combustion air input and distribution,
- furnace pressure control,

Table 4. Basic elements of STG EsDeNO$_x$ technology

STG EsDeNO$_x$ burner system	STG Lambda control	STG optical melting control
optimum port design*)	advanced process control system (Siemens PCS7)	
gas burner oil burner	zirconium dioxide sensor	TV picture processing PC as ProfiBus client
parameter change:		
increase in heat flow flame/glass increased emissivity of flame increased heat exchange area	constant combustion air minimized and compensated for air infiltration minimized energy loss and NO$_x$ formation	control of batch coverage control of stable glass recirculation control of optimum hot spot position
results:		
reduction of NO$_x$ to 300 to 900 mg/m^3, 5 to 15 % energy saving, 5 to 10 % glass pull, lower temperature, return on investment: 0.4 to 0.5 years by only side effects		

*) For new furnaces.

- reversal operation,
- use of video processing for energy and hot spot control,
- reliability, redundancy and backup of control system elements.

Table 4 presents three basic elements of the STG DeNO$_x$ technology.

3. BTR proprietary furnace temperature control

For regenerative type furnaces standard proportional integrated differential (PID) control of the furnace crown temperature (thermocouple) leads to unacceptable fluctuations and asymmetries of energy input. In contrast, EsDeNO$_x$ technology allows you to keep stable temperatures with as low as possible fluctuations of energy input. To achieve this, BTR type temperature control compensates for the typical temperature drop-down-and-increase with reversal operation by a self learning mathematical temperature control algorithm. BTR control actually compares the predicted final temperature to the temperature setpoint during the reversal time period. It uses a three setpoint system consisting of a temperature setpoint, a short distance energy setpoint and a long distance setpoint of energy input. The historical trend shows a 24 h period, keeping the temperature in a ±1 K temperature tolerance band around the setpoint.

4. Energy control and energy profiler

Based on continuous measurement of calorific value or Wobbe index it is a standard to control energy input gas and/or oil in terms of MW, automatically responding to the actual drift of natural gas composition and providing real constant input of energy for melting and refining.

For cross fired furnaces optimum use of energy and furnace temperature control requires the energy profiler block, which allows good handling of either percentage or MW energy input per port optionally, keeping the total energy setpoint constant or modifying it with the MW input.

For typical deviations between total and single gas measurements there is a flexible compensation available, using a virtual software controller to fix necessary compensation factors for left and right firing.

5. Combustion air cross limit ratio control

It is the typical target of ratio control to keep combustion air in a fixed optimum ratio to gas or oil. Following the idea that energy control is better than gas or oil flow control, an air to gas ratio in terms of air per energy unit as standard cubic feet (SCF) of air per kWh of gas or oil is used. Higher calorific value of gas or oil requires consequently higher input of combustion air to keep constant combustion. The ratio of SCF of air per energy unit is not really, but quite close to, a constant value. Remaining differences may be compensated for easily by Lambda trimming of ratio value.

The old question whether gas should follow air or air should follow gas is no real alternative. But cross limit ratio control makes sure that for increasing energy, air is increased first and gas follows, and for decreasing energy, air follows the decreasing gas flow. Only this type of control allows stable energy flow with very low excess air, assuming that for any change – up or down – there will be a temporary increase in excess air. This control strategy combines optimum combustion and safety requirements and avoids a reducing atmosphere even during modification of energy input — up or down.

6. Lambda control trimming of air ratio

Pure ratio control provides automatic control of the inputs of combustion only. But there is a typical uncontrolled input of cold air inspiration into the furnace and regenerator which also takes part in combustion and is not controlled by the ratio control. It is in the range of 5 to 10 % of total air and may have a real influence on NO$_x$ formation and energy efficiency. Therefore, only Lambda control may provide really constant optimum combustion – reading the excess air downstream of combustion by means of Lambda sensors in the regenerator crown at the exhaust side of the furnace.

In contrast to pure ratio control, Lambda control provides a real feedback of combustion result to combustion

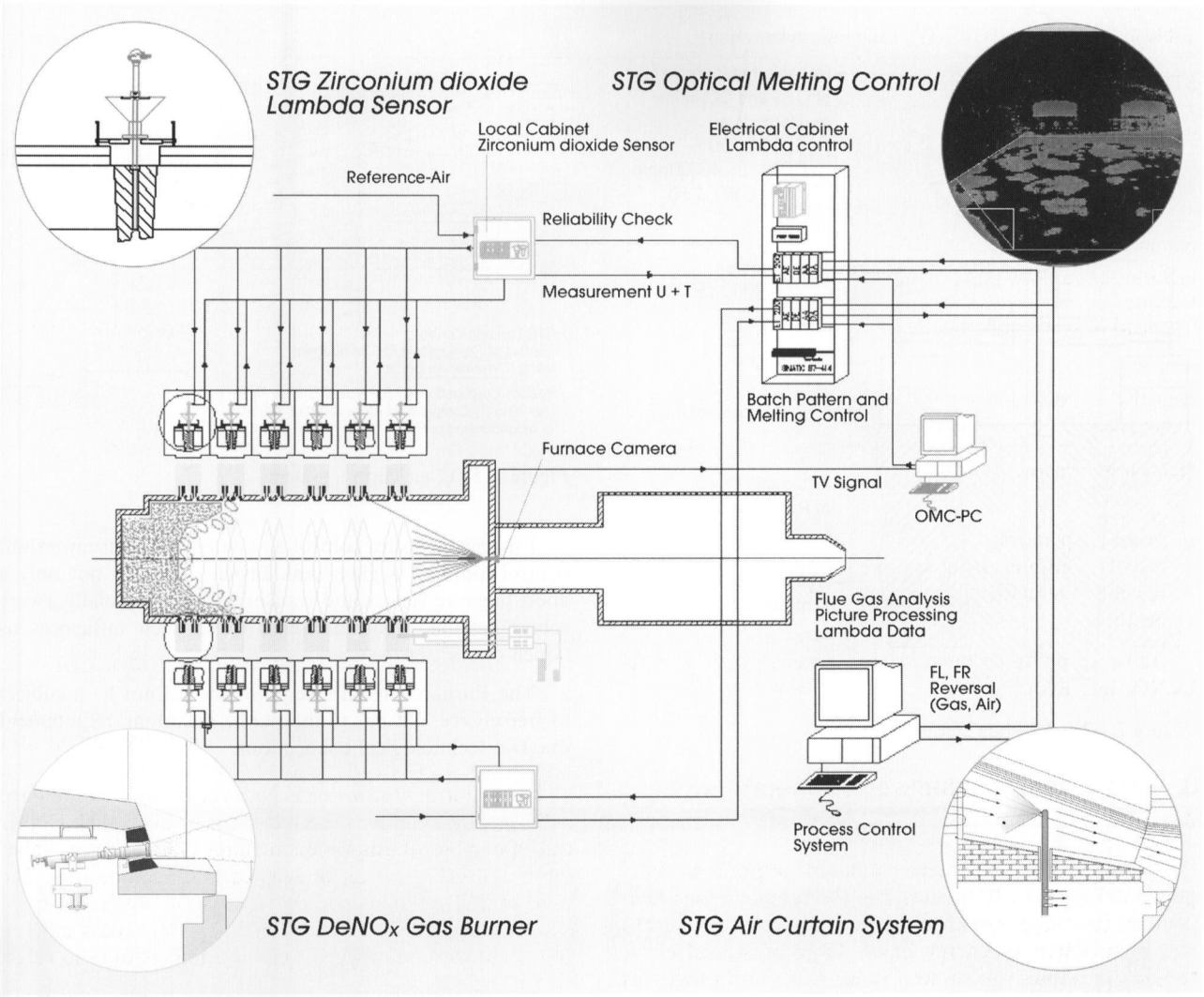

Figure 1. EsDeNO$_x$ technology of Software & Technologie GmbH (STG).

air input. Lambda is defined as the quotient of combustion air available totally divided by stoichiometric minimum of combustion air. The optimum range of Lambda equals 1.02 to 1.15. The better you are able to measure and control the Lambda value, the lower the Lambda setpoint which you can choose without causing technological problems. Lower Lambda values result in lower NO_x formation and lower energy consumption.

The target of Lambda control is: minimize air infiltration – and compensate for the remaining air infiltration which cannot be avoided.

Lambda control requires reliable sensors and software tools to organize control even under the condition of a regenerator furnace. STG zirconium dioxide lambda sensors have been developed and improved over the last 15 years (figure 2). So today we expect a service life of four years or more with the accuracy and reliability good enough for automatic control purposes. These sensors are usable up to 1600 °C even under strongly reducing flue gas conditions. Standard installation is on top of the regenerator, which gives the best performance and service life. The additional input of gas or oil fuel composition signal processing in the SIMATIC control system delivers complete flue gas analysis and it calculates the exact amount of infiltrated air flow as a result of the combustion calculation.

Any direct PID control of percentage of O_2 content in flue gas very likely produces an unstable combustion situation worse than pure ratio control and cannot be used to reduce NO_x. So for most regenerative furnaces Lambda control software requires a mix of PID control and predictive control, based on the analysis of measured results of the last five firing periods.

Typical problems of uncontrolled cross mixing between neighbouring ports in cross fired furnaces, due to unsealed separating walls in the regenerator, or influence of dog house just close to exhaust port of an endport furnace, are subject to individual solutions and discussion.

The air curtain system, based on water or air cooled dynamic air baffles, is used as a tool to control combustion air distribution over the ports of a block type regenerator without separating walls between the ports of a cross fired glass tank furnace. It is used for the typical excess air ports 5 and 6: about 300 SCF/h of compressed air helps to redirect about 3000 SCF/h of preheated combustion air to neighbouring ports, which allows for the reduction of total air (figure 3).

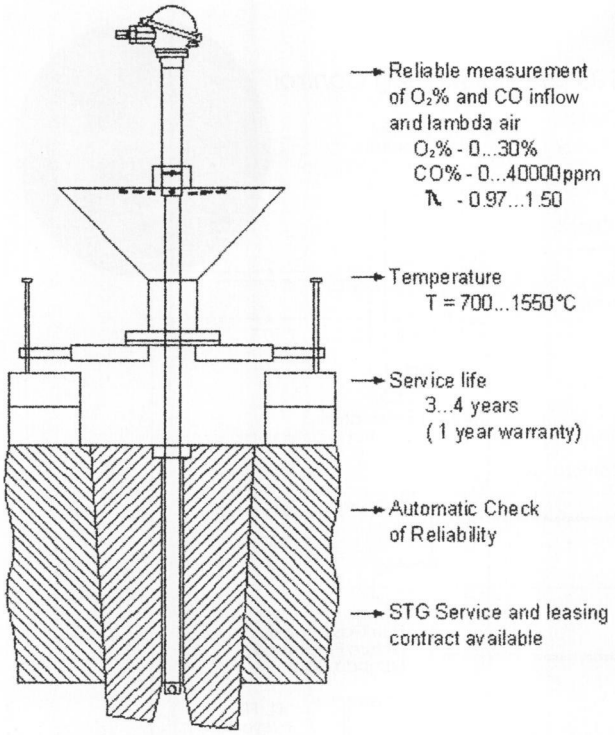

Figure 2. STG Lambda sensor.

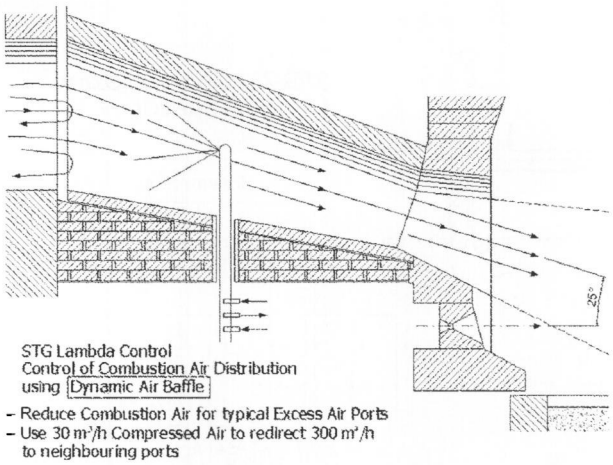

Figure 3. STG air curtain system.

Furnace pressure control as one of the most important control loops of a glass tank furnace requires not only a good pressure sensor and transmitter, but especially a very robust reference pot, nonsensitive to such influences as "open doors", etc.

The Furnace pressure setpoint should not be a subject of free choice, but has to follow the maximum requirement due two technological connections:

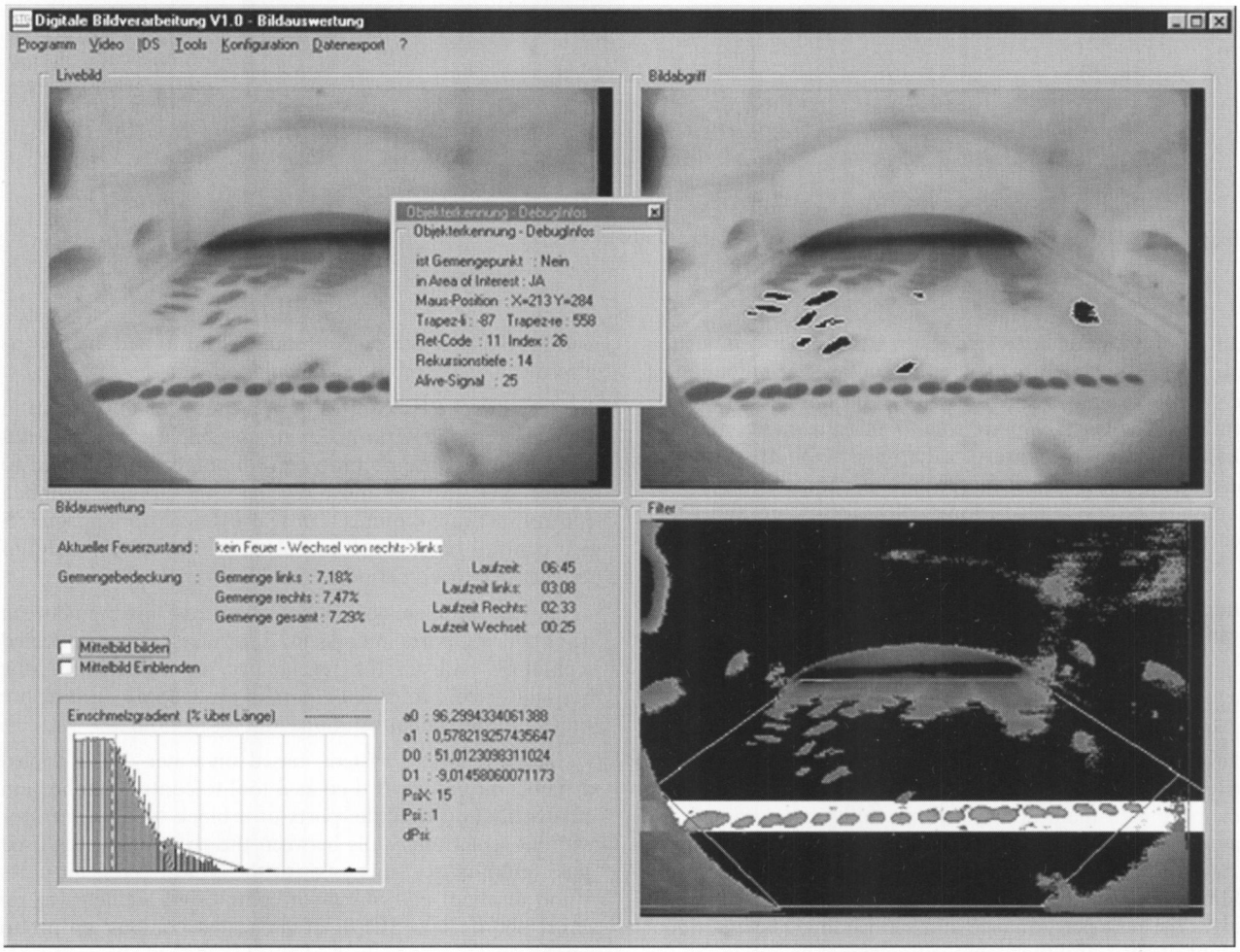

Figure 4. Illustration of optical melting control.

a) find the minimum value of furnace pressure which provides no more real decrease of ingressed air infiltration;

b) find the minimum value of furnace pressure just creating a small flow of flue gas outwards from the doghouse. This may be measured by the use of a temperature sensor at the doghouse area.

The reversal operation has a real influence on how to avoid extreme values of NO_x or SO_x at restart of fire just after reversal. There is a so called YNF software block used for gas, oil, furnace pressure and other reversal effected loops. The YNF block memorizes typical fire left and fire right position and provides ramping up after reversal to the saved former actuator positions of left or right firing.

Reversal timer system and reversal actuator time recording, combined with the turbo-mode operation, allows fine tuning of reversal sequence to reach a short time from fire to fire in a range of only 20 s, even for double use of oil and gas simultaneously. Shorter reversal time from fire to fire results in lower actual energy input during firing period.

Optical melting control (OMC) means the use of video picture processing of a standard type furnace camera to extract additional information from what was formerly only used as an optical picture, and opens a new window to the furnace process.

Measuring temperatures is not really the target of OMC. But it yields a lot of detailed information about the melting process, its stability and optimum situations, e.g. it determines

- the area covered by unmolten batch giving a measure of real energy transfer to the batch (batch pattern analysis);
- the degree of foam, which is a real handicap for energy transfer;
- the point and intensity of the highest flame temperature;
- the hot spot position on the glass surface;

and controls

- the size and number of bubbling spots.

The introduction of video based information into automatic furnace control seems to be a real step forward for the future, and will help to keep the optimum conditions for low NO_x formation and low energy consumption under control.

In such a system we have to understand the OMC-PC as a smart transmitter, taking the video signals, digitally processing them, and providing the results into the process control system. This OMC-PC works as a profi-bus client in the complete system architecture (figure 4).

Reliability, redundancy and backup of major system elements are not directly related to the questions of NO_x reduction and energy saving, but they become important when the furnace operation is pushed to its limits in order to achieve best results of $EsDeNO_x$ technology as well as low energy consumption.

It is a general rule to have the system designed to be able to operate in a "switch-off-and-continue" as well as in a "switch-on-again-and-continue" situation without real disturbance of the process. Use of redundant central processing unit (CPU) or independent backup hardware controllers for main control loops, automatically taking over in case of system failure, makes sure that there will be a solution which, on the one hand, is sophisticated enough for the purpose of NO_x reduction and energy saving, but, on the other hand, also robust, reliable and simple enough to use in an emergency situation.

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